Climate Engineering Economics

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Abstract

This article reviews and evaluates the nascent literature on the economics of climate engineering. The literature distinguishes between two broad types of climate engineering: solar radiation management and carbon dioxide removal. We review the science and engineering characteristics of these technologies and analyze the implications of those characteristics for economic policy design. We discuss optimal policy and carbon price, interregional and intergenerational equity issues, strategic interaction in the design of international environmental agreements, and the sources of risk and uncertainty surrounding these technologies. We conclude that climate engineering technologies, similar to mitigation and adaptation, should be a fundamental part of future domestic and global climate policy design. We propose several avenues in need of additional research.

1. INTRODUCTION

tted carbon dioxide (CO_2) and other greenhouse gases into the atmosphere for centuries. With population and economic output growing, atmospheric concentrations of CO_2 are rising at an increasing rate.[1] Moving the remainder of humanity out of poverty and into the middle class is expected to exacerbate this trend if policy actions are not taken to decarbonize the global energy system. The threat of climate change has influenced both domestic policy (e.g., the US Clean Power Plan) and international negotiating bodies like the United Nations Framework Convention on Climate Change (UNFCCC). Policy discussions and negotiations around climate change have focused mostly on actions to reduce emissions of greenhouse gases. Emission reductions are referred to as abatement or mitigation. Negotiations have started to pay dividends but only slight ones. At the current pace, the world is headed toward atmospheric CO_2 concentrations between 550 and 1,000 ppm by the end of this century, making the goal of restricting global temperature change to 2°C increasingly unlikely to be met and a 4.0°C change increasingly plausible. Scientific evidence suggests that the amount of warming caused by even moderate continued emissions will affect human and natural systems for many generations (IPCC 2014).

There are two alternative approaches to reducing risks from climate change besides abatement: adaptation and climate engineering. Adaptation reduces risk by making systems more resilient to climate change. Recognizing that climate impacts will be heterogeneous and often regressive, the international community has elevated adaptation on the agenda with the goal of helping poor nations cope with existing and inevitable climate change.

Climate engineering, also known as geoengineering,[2] is a more recent addition to academic and policy conversations about climate risk. The economics literature on climate engineering is nascent. Here, we review that literature and discuss its implications for how this new set of instruments could help deal with climate change.

We start by briefly reviewing the scientific concepts related to the two broad categories of climate engineering: carbon dioxide removal (CDR) and solar radiation management (SRM).[3] We describe the more salient characteristics of both sets of technologies, but the bulk of this review focuses on SRM, due to its fundamental differences from abatement and adaptation and its potential to disrupt the standard thinking about climate change policy.

Three characteristics make SRM the focus of most climate engineering economics literature: (*a*) SRM is inexpensive compared to abatement; (*b*) SRM allows rapid action, which could circumvent some of the inertia of the Earth's carbon cycle; and (*c*) SRM imperfectly (or ineffectively) compensates for carbon dioxide–driven warming, and it may introduce unintended consequences. Because it is cheap, SRM offers the possibility of drastically reducing the costs of climate risk mitigation. But it is so cheap that it can feasibly be implemented by individual nations pursuing their own self-interest. Because it is fast, it may be able to serve as an insurance against uncertain future climate damages and climate tipping points (CTPs). But because it can be rapidly implemented at any time, it has the potential to be used strategically by some actors and induce suboptimal behavior in others. Our goal with this review is to explore these and other trade-offs. The review considers the main modeling frameworks and extensions that are currently used in the literature,

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[1] The average growth rate of CO_2 concentrations during the 1960s was 0.85 ppm/year, whereas the average rate between 2004 and 2014 was 2.11 ppm/year.

[2] Although the term geoengineering is perhaps more commonly used and recognizable, this review uses the term climate engineering to clarify that these technologies specifically address climate change. Geoengineering is also occasionally used to refer to geological engineering or geotechnical engineering. Another proposed term for climate engineering is climate intervention (NRC 2015a,b).

[3] CDR is also known as direct air capture (DAC); SRM is also known as albedo modification or solar geoengineering.

the implications of those modeling choices, and the current set of conclusions. We then identify pathways for future research.[4]

2. SCIENCE AND ENGINEERING

Climate engineering has novel risk mitigation properties, in terms of both technological feasibility and physical effects on the climate system. These properties are what drive the distinct economics of climate engineering compared to abatement and adaptation. Although climate engineering may refer to technologies as disparate as sun-deflecting mirrors in space and orchestrated algal blooms, most approaches fall into two classes of technologies, which have little else in common than an unconventional approach to reducing climate change risks. The first class, SRM, counteracts the warming effects of anthropogenic greenhouse gases by deflecting sunlight back into space before it can be absorbed by the Earth. The second class, CDR, reduces concentrations of the greenhouse gas CO_2 in the atmosphere directly.

In the remainder of this section, we introduce the basic scientific and technical properties of each of these climate engineering technologies and then compare and contrast those properties with those of abatement. As we show after introducing our economic model of climate engineering, the specific spatial and temporal properties of SRM and CDR drive their unique economics. Because our main focus is the economics of climate engineering, we limit our citations in this section to only the most essential; an exhaustive review of the state and prospects of the science of climate engineering, including extensive literature citations, was published as a two-volume National Research Council report (NRC 2015a,b).

2.1. Solar Radiation Management

Approximately 30% of the incoming solar radiation is reflected back into space, whereas the rest is absorbed and reemitted by the Earth. The radiative properties of the Sun and Earth's radiation are quite different. The greatest portion of the Sun's radiation is in the short wavelength visible spectrum, whereas the Earth emits radiation in the longer wavelength infrared. Although the atmosphere does not interact much with incoming visible light from the Sun, its greenhouse gases do interact substantially with infrared radiation emitted by the Earth's surface. This is why rising concentrations of greenhouse gases such as CO_2 are causing the atmosphere and oceans to warm up. SRM would cool the Earth by reflecting a larger fraction of incoming solar radiation back into space before it can be absorbed and reemitted by the Earth, thereby offsetting some or even all global-scale warming.

2.1.1. Brief description of different technologies. A number of engineering approaches have been proposed for disrupting the Earth's radiation balance to counteract the warming effects of greenhouse gases. These different technologies would be implemented anywhere from the surface of the Earth up to far outside the Earth's atmosphere. However, two types of technology currently discussed are considered both scalable and technically and economically feasible in the near future: stratospheric aerosol albedo modification (SAAM) and marine cloud brightening (MCB).

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[4] Our review complements recent reviews on the economics of climate engineering. Barrett (2014) focuses on governance issues and just studies SRM, not CDR. Klepper & Rickels (2012, 2014) provide overviews of both the science and economics of CDR and SRM. We synthesize the science/engineering and economic/policy literatures on CDR and SRM, and we compare both CDR and SRM to abatement. Wagner & Weitzman (2015, ch. 5) provide a nontechnical introduction to the economic issues associated with climate engineering.

SAAM is inspired by a natural analog: large volcanic eruptions that periodically reduce global temperatures by injecting large amounts of sulfate aerosol precursors into the stratosphere. This layer of the Earth's atmosphere is convectively stable; therefore, it allows injected particles to remain, reflecting light back into space for an average of 1–2 years, rather than the few days such particles reside nearer the Earth's surface. The long lifetime of these particles means that the effectiveness of SAAM would be fairly insensitive to day-to-day disruptions in implementation schemes, though to optimize stratospheric aerosol concentration and distributions, a continuous program would likely be preferred (Rasch et al. 2008). The most likely approach to implementation is high-flying aircraft outfitted with aerosol precursor dispensing systems (McClellan et al. 2012), but other dispersal systems involving technologies such as balloons, pipes, and artillery have also been evaluated (NRC 2015b).

MCB would exploit a phenomenon called the Twomey effect, whereby the addition of small particles into low-lying clouds over the ocean creates more, smaller cloud droplets that are more reflective. Implementing MCB at scale would require constructing a fleet of ships to spray salt or other fine particles into the lower atmosphere over areas of the ocean amenable to this type of intervention. A number of designs for such ships have already been developed (Salter et al. 2008). Unlike SAAM, these particles would be short-lived, so continuous deployment is necessary for continuous effect.

2.1.2. Overview of costs, benefits, risks, and impacts. Direct costs for proposed SRM technologies range from very expensive (space mirrors) (Angel 2006) to very cheap (SAAM). Because the costs are so low and the physical mechanisms so well understood, SAAM is presently considered the most feasible and likely approach to SRM. No significant innovations to existing technology are required for SAAM dispersal. Crutzen (2006) estimates a cost of \$20–25 billion/1–2 years, based on the balloon and artillery gun technologies. Robock et al. (2009) provide an overview of approximate costs of various technologies, ranging from \$0.2 billion/year to \$30 billion/year. Katz (2010) uses both data compilation and derivation to obtain estimates of some SRM technologies within a broader technology discussion. McClellan et al. (2012) provide an overview of costs related to specific technologies, finding lower estimates of the cost to counteract the warming effects of a doubling of atmospheric CO_2 using existing technology at \$1.1 billion/year and for new technology at \$0.6 billion/year.[5] Although estimates differ, using airplanes is commonly considered the lowest-cost technology. Although not nearly as deployment ready as MCB using existing technology, current cost estimates for MCB indicate that the direct costs for achieving global temperature reductions are also likely to be low relative to the cost of abatement (NRC 2015b).

Extensive climate modeling research shows that even relatively unsophisticated implementations of SAAM appear to work surprisingly well to counteract the temperature and precipitation changes projected to occur with global warming, even at the regional scale (Caldeira & Wood 2008, Ricke et al. 2012). The mismatch, however, between countering warming from an increase in the Earth's radiation with cooling from a reduction in the Sun's radiation inevitably results in an imperfect reversal of global warming's impacts. These imperfections include relative overcooling of equatorial regions and undercooling of polar ones, an overdrying of the global hydrological cycle with the restoration of global temperatures (Bala et al. 2008), and accompanying shifts in global circulation patterns that result in continuing regional climate change even with global temperature stabilization (Ricke et al. 2010). SAAM would increase the share of diffuse, as opposed to

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[5] These various cost estimates are not directly comparable to each other, as all are for different amounts of SRM intensity (radiative forcing).

direct, sunlight reaching the Earth's surface, resulting in small but potentially significant changes in sky color (Kravitz et al. 2012), solar power capacity (Murphy 2009), and ecosystem productivity (Kalidindi et al. 2014).

SRM approaches also present the possibility of novel environmental risks. Introducing particles into a stratosphere that still contains significant amounts of chlorofluorocarbons creates the potential for stratospheric ozone destruction (Tilmes et al. 2008). Large-scale deployment of SAAM could slow or even reverse the recovery of the stratospheric ozone hole. SRM also does nothing to address threats from ocean acidification, the process by which the atmosphere-to-ocean exchange of CO_2 reduces the pH of the surface ocean, leading to a multitude of effects on marine life (Orr et al. 2005).

2.2. Carbon Dioxide Removal

One of the main challenges associated with reducing the risks of higher CO_2 concentrations in the atmosphere is this pollutant's long lifetime. Because the ocean and biosphere are natural sinks that uptake a portion of new CO_2 emissions, the uptake rate is limited and it saturates as high atmospheric CO_2 concentrations persist. A significant fraction of emitted CO_2 remains in the atmosphere for thousands of years (Archer et al. 2009). CDR technologies are a way of artificially increasing the capacity and uptake rate of carbon sinks.

2.2.1. Brief description of different technologies. A number of approaches for CDR are potentially viable. They include bioenergy with carbon capture and sequestration (BECCS), which captures carbon in plant biomass and subsequently sequesters the CO_2 produced in using the biomass to produce energy; direct air capture (DAC), in which a chemical sorbent such as an alkaline liquid is exposed to ambient air, removing CO_2; enhanced weathering, in which the carbonate or silicate reactions that naturally sequester atmospheric CO_2 over millennial timescales could be accelerated or supplemented; and ocean fertilization, in which large amounts of nutrients, most notably iron, would be dispersed on the ocean surface to enhance phytoplanktonic growth that would sequester CO_2 in biomass (NRC 2015a).

2.2.2. Overview of costs, benefits, risks, and impacts. All CDR technologies are estimated to have high direct costs, generally on par with or exceeding the costs of abatement. However, because CDR counteracts the root cause of emissions–driven climate change rather than masking its influence as SRM does, it has the same climate effects as abatement. Its notable improvement upon these more conventional approaches to controlling atmospheric CO_2 is the greater potential for reversibility of change, because CDR can remove past emissions and reduce concentrations faster than simply ceasing CO_2 emissions. Risks associated with CDR technologies tend to be localized, with the exception of ocean fertilization, for which studies indicate that deployment at scale would significantly disrupt ocean ecology.

The CDR technology with more potential to serve as a pure backstop technology is industrial air capture. The primary constituent cost is expected to be for carbon-free energy to power these machines. Estimates of the cost vary from \$30/tCO_2 (Lackner & Sachs 2005) to over \$600/tCO_2 (Socolow et al. 2011). Lackner et al. (2012) extensively survey publications dealing with costs of CDR, but they do not suggest any specific estimates. Lackner (2009) provides the estimate of CDR costs at \$200/tCO_2 during the prototype use and at \$30/tCO_2 in the commercial stage. House et al. (2011) estimate the current costs of CDR to be \$1,000/tCO_2, and the costs are expected to decrease to \$300/tCO_2 by 2050. The authors also provide the energy costs of capturing and compressing CO_2. The variations in these estimated costs have a substantial impact on potential deployment.

At \$30/tCO_2, this technology could fundamentally alter optimal climate risk mitigation pathways. It is a marginal player at \$600/tCO_2, whereas it is a thought experiment at \$1,000/tCO_2.

Other technologies offer the same general story of high costs and uncertain ranges. Kriegler et al. (2013) provide a cost overview of BECCS. The authors compare the costs of BECCS with existing CDR technologies and find that the cost is less than \$0–1,000/tCO_2 for capture volumes of under 14,000 Mt/year. Rickels et al. (2012) estimate the unit costs for ocean iron fertilization at \$22–119/tCO_2.

2.3. Characteristics of Abatement Versus Solar Radiation Management Versus Carbon Dioxide Removal

The standard approach suggested for addressing climate change is eliminating the source via decarbonization of the energy system, that is, abatement. Because CO_2 is a long-lived global pollutant (Archer et al. 2009), CO_2 abatement by one actor has a planetary effect but one that is minuscule compared to all other emissions released or avoided. The only risks from CO_2 in the atmosphere that an emitter can reduce via abatement are those caused by their own future emissions. Each climate engineering technology provides a new point of leverage in this regard. SRM allows a single actor to counteract some of the effects from all emissions, both past and present, on a very short timescale and at low cost. CDR allows actors to reduce concentrations of CO_2 in the atmosphere, and thus the root cause of climate change, by removing both past and future emissions of themselves and others.

With the exception of this potential for removing past emissions from the atmosphere, CDR technologies share many characteristics of traditional abatement approaches. They have high direct costs, are limited by relatively long timescales of effect, and perfectly reduce impacts of climate change (mostly by avoiding further change). However, the constraints and characteristics of SRM differ vastly from abatement in several economically significant ways beyond the obvious implications of low direct costs. First, there is spatial heterogeneity in its effects and, to an extent, its potential deployment. This physical characteristic equates to inefficiency in SRM's effectiveness in managing climate risks and creates the potential for novel strategic behaviors. Second, the timescales for effective deployment, planned cessation, or abrupt termination of SRM are much shorter than those for abatement or CDR (at least in amounts physically feasible by currently known or imagined technologies). Finally, because of its imperfect compensation for the effects of CO_2 –driven change, any SRM deployment will be accompanied by much larger scientific and technical uncertainties and risks than emissions reductions or CDR technologies. These scientific and technical uncertainties and risks translate into economic ones as well.

2.3.1. Spatial heterogeneity. The long atmospheric lifetime of CO_2 relative to tropospheric mixing timescales results in relatively little leverage over the distribution of forcing characteristics for anthropogenic emissions reductions and CDR. SRM, however, would likely allow for some control over the spatial distribution of sunlight-reflecting effects. In the case of SAAM, although strong stratospheric winds make management of the longitudinal distribution of reflective aerosols infeasible, there is potential for control over latitudinal distributions of aerosols, making it possible to reflect more sunlight in one hemisphere than another or over the poles than at mid-latitudes (Robock et al. 2008). In the case of MCB, only certain areas of the atmosphere over the sea are likely to be amenable to large increases in marine cloud reflectivity, limiting spatial control (Latham et al. 2012), though given these constraints, geoengineers would likely have a great deal of control over the relative magnitude of implementation between such regions. The end result of these spatial degrees of freedom is a certain amount of potential "tunability" in the regional climate effects of SRM (see, e.g., MacMartin et al. 2013).

Whereas the impacts of climate change itself exhibit abundant spatial heterogeneity (Walther et al. 2002), the regional responses to emissions reductions and CDR are generally straightforward: The regional climate change is diminished or reversed. Although this is not necessarily true for impacts due to irreversibility and threshold behavior of certain human and natural systems (IPCC 2014), to the first order, an increase or decrease in atmospheric CO_2 concentrations results in relatively linear scaling of regional climate effects.

In the case of SRM with a uniform application, temperature changes in all regions are reduced, as are precipitation changes in most regions (Kravitz et al. 2014). However, the amount of reduction in these changes proceeds at different rates for different regions as the amount of SRM is increased. As a result, it is almost certain that different regions, countries, and sectors would prefer different amounts and distributions of SRM. In addition, these preferences would be expected to diverge further if SRM is increased to compensate for rising atmospheric greenhouse gas concentrations (Ricke et al. 2010). In some regions, hydrological changes caused by climate change are exacerbated by the application of SRM (Kravitz et al. 2014).

2.3.2. Timescale asymmetry. Abatement is a process subject to a great deal of inertia. Political and social inertia are associated with implementing effective policies, particularly if such policies depend upon international coordination. Infrastructural inertia is associated with transitioning the energy system to low- or no-carbon technology (Davis & Socolow 2014). Finally, there is carbon cycle inertia whereby a substantial fraction of past emissions remains in the atmosphere for thousands of years (Archer et al. 2009).

Climate engineering technologies can be viewed as tools for circumventing some of these inertial issues. They can circumvent political inertia because they do not necessarily require international coordination to be physically effective, and because they do not require overturning the powerful interests associated with the status quo energy economy. They can circumvent infrastructural inertia because they do not require technology in use to become obsolete or retired early before implementation. And to differing degrees, they can circumvent carbon cycle inertia as well.

CDR artificially supplements the natural carbon sinks that remove CO_2 from the atmosphere over time, making it possible to reduce atmospheric CO_2 concentrations within several decades without an instantaneous transition to a carbon-neutral economy. But it is still critically limited by the second law of thermodynamics, which makes it difficult to remove CO_2 molecules from an atmosphere made up mostly of oxygen and nitrogen.

SRM is not subject to the above constraints and can reduce global temperatures on very short timescales. As with large volcanic eruptions, a temperature response could be achieved within a year of deployment. This rapid response is the reason some have suggested that SRM is a tool that could be deployed in response to a so-called climate emergency (Blackstock et al. 2009), though the scientific evidence about whether SRM would be effective under such conditions is sparse (Sillmann et al. 2015).

The rapid response of the climate to SRM cuts in two directions. It can achieve rapid cooling with its deployment but could also produce rapid warming with termination. Numerous modeling studies have shown that if SRM is used to counteract effects of global warming and then terminated without accompanying reductions in greenhouse gas concentrations, the climate would warm very rapidly, perhaps at rates many times those that would have been experienced absent SRM.

Matthews & Caldeira (2007) were the first to highlight the rapid warming that could be expected if SRM were abruptly terminated, and Jones et al. (2013) model uncertainty in the potential physical effects of abrupt termination of SRM use through a multimodel ensemble analysis. They find that the amount of warming that would occur depends upon its length of use, the amount of carbon emissions during the period of use, and the relative efficiency of SRM in reducing global temperatures. Because some climate change impacts may depend as much on rates of temperature change as on magnitudes (Diffenbaugh & Field 2013), this "termination effect" represents a novel climate-related risk. Some discussion of the risks associated with the termination effect is also presented in Robock et al. (2009) and Betz (2012).

The risk of termination effects is much higher for SRM than abatement or CDR. Reducing carbon emissions through abatement or CDR affects the stock of carbon and therefore has long-lasting effects. Reducing temperatures through SRM, however, is temporary; the aerosol sulfates will leave the stratosphere within 1–2 years and must be nearly continuously replaced for SRM to be effective in the long term. This leads to complications from termination effects that apply to SRM in a way that does not apply to CDR or to abatement.

2.3.3. Risk and uncertainty. Our understanding of the Earth's climate is replete with uncertainty, and all policy options are plagued by this. Abatement provides the lowest level of uncertainty, as avoiding emissions will prevent the future change they otherwise would have caused.[6] CDR works by the same mechanism as abatement, but its effectiveness for any given technology type may be less certain, because we do not yet know how well that technology will work.

Uncertainty associated with the effectiveness of SRM is very high. There is also uncertainty associated with the technological efficiency of both SAAM and MCB. Moreover, because SRM does not address the root of the problem (greenhouse gas concentrations), the outcomes will certainly be different than with the other two technologies. The extent of this difference is unknown. We can expect some significant regional hydrological anomalies associated with an SRM temperature-stabilized world. However, because even state-of-the-art climate models have difficulty predicting changes to regional precipitation and other hydrological indicators, let alone ecosystem impacts, uncertainty over the magnitude and distribution of the effects is large.

Although the effectiveness of SRM is uncertain relative to abatement or CDR, SRM may reduce uncertainty relative to inaction under business as usual. One source of uncertainty in estimating climate impacts is the value of climate sensitivity, that is, the amount that the Earth will warm for a given amount of additional atmospheric CO_2. Although the regional distribution of SRM and CO_2 forcings may be asymmetrical, a climate more sensitive to CO_2 is still similarly sensitive to other forcings, such as those from SRM. Thus, canceling CO_2 forcings with SRM would narrow the potential range of future global temperature changes considerably (Ricke et al. 2012).

3. THE BASIC ECONOMICS OF CLIMATE ENGINEERING

3.1. Analytical Model

In this section, we present a simple, baseline economic model that can provide a framework for how to think about the economics of climate engineering. This model is similar to that of SRM presented in Heutel et al. (2015a), though here we include both SRM and CDR.

We consider a representative agent model in an economy where there are external damages from pollution that can be alleviated either by reducing pollution (abatement or CDR) or by reducing the harmful effect of pollution (through SRM). There is a fixed stock of capital k that

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[6] There is still uncertainty over inertia in the climate system and how much change would occur even with an instantaneous and total cessation of all greenhouse gas emissions.

can be allocated toward production (k_p), abatement (k_a), CDR (k_CDR), or SRM (k_SRM), so that $k_\mathrm{p} + k_\mathrm{a} + k_\mathrm{CDR} + k_\mathrm{SRM} = k$. Gross output is $f(k_\mathrm{p})$, but net output can be reduced because of damages from pollution x. This is a static model without saving, so all net production is consumed: $y = c = f(k_\mathrm{p})(1 - d(x; k_\mathrm{SRM}))$. The function $d \in [0, 1]$ is the damage function, expressed as the fraction of gross output that is lost due to pollution damages. We assume that d is increasing and convex. SRM affects how pollution reduces gross output: $d_k < 0$ and $d_{xk} < 0$, so that SRM reduces total and marginal damages.[7]

Baseline or business-as-usual pollution is normalized to be equal to the capital stock k, but it can be reduced through abatement or CDR. Thus, pollution x is equal to $(1 - \mu)k - \gamma$, where μ is the fraction of pollution abated, and γ is the pollution removed through CDR. Pollution abated μ is modeled as a fraction of total pollution k, and pollution removed from CDR is modeled as an absolute quantity.[8] The fraction of pollution that is abated is a function of the capital stock devoted to abatement, and the pollution removed through CDR is a function of the capital stock devoted to CDR: $\mu = g(k_\mathrm{a})$ and $\gamma = h(k_\mathrm{CDR})$. We assume that both cost functions g and h are increasing and concave.

The planner's problem is to maximize net output subject to the resource constraint:

$$\max_{k_\mathrm{p}, k_\mathrm{a}, k_\mathrm{SRM}, k_\mathrm{CDR}} f(k_\mathrm{p})(1 - d(x; k_\mathrm{SRM})), \tag{1}$$

such that

$$k = k_\mathrm{p} + k_\mathrm{a} + k_\mathrm{CDR} + k_\mathrm{SRM}, \tag{2}$$

$$x = [1 - g(k_\mathrm{a})]k - h(k_\mathrm{CDR}). \tag{3}$$

The solution to this problem can be described by the following set of first-order conditions:[9]

$$f'(k_\mathrm{p}^*)[1 - d(x^*; k_\mathrm{SRM}^*)] = f(k_\mathrm{p}^*)kg'(k_\mathrm{a}^*)d_x(x^*; k_\mathrm{SRM}^*), \tag{4}$$

$$f'(k_\mathrm{p}^*)[1 - d(x^*; k_\mathrm{SRM}^*)] = f(k_\mathrm{p}^*)h'(k_\mathrm{CDR}^*)d_x(x^*; k_\mathrm{SRM}^*), \tag{5}$$

$$f'(k_\mathrm{p}^*)[1 - d(x^*; k_\mathrm{SRM}^*)] = -f(k_\mathrm{p}^*)d_k(x^*; k_\mathrm{SRM}^*). \tag{6}$$

These three equations represent setting the marginal benefit equal to the marginal cost for abatement, CDR, and SRM, respectively. The left-hand side of each equation is the marginal benefit of an additional unit of productive capital k_p, which is the ability to produce and consume more output. It equals the marginal benefit of an additional unit of abatement (k_a), CDR (k_CDR), or SRM (k_SRM).

The first two equations are nearly identical, implying that $kg'(k_\mathrm{a}^*) = h'(k_\mathrm{CDR}^*)$. The marginal cost of reducing a unit of pollution through abatement equals the marginal cost of reducing it through CDR. Because abatement and CDR are (in this model) perfect substitutes, this equimarginal condition must hold at the optimum. SRM, though, is not perfectly analogous to CDR or abatement.

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[7] These assumptions do not imply that there are no direct damages from implementing SRM, but they do assume that in total the benefits exceed the damages.

[8] This is to reflect that CDR is not limited to reductions of present-day emissions but can take on the emissions of others, past and present, even resulting in negative pollution.

[9] We assume an interior solution and that the second-order conditions ensure a unique solution.

The first-order conditions imply that $-d_k(x^*; k^*_{\mathrm{SRM}}) = kg'(k^*_{\mathrm{a}})d_x(x^*; k^*_{\mathrm{SRM}})$. The marginal benefit of an additional unit of SRM, in terms of reduced marginal damages, equals the marginal benefit of an additional unit of abatement in terms of its reduced marginal damages times the cost of achieving those damages.

The model demonstrates how both SRM and CDR both are alternative means of reducing climate change damages, and they should be employed at an efficient level dictated by equating marginal benefits. Of course, this simple model omits many important relevant features of the real world. For example, the model is static, though climate change is a dynamic problem. Moreno-Cruz & Smulders (2007) develop a model that incorporates climate dynamics and economic growth and show that the main trade-offs presented in this simpler model remain true. However, new insights are revealed. They find that for high levels of damages caused directly by atmospheric CO_2, climate engineering and abatement could act as strategic complements in the sense that climate engineering implementation would increase abatement efforts in the economy. For lower CO_2 concentrations, climate engineering is still used, acting as a strategic substitute for traditional abatement with the final objective of boosting the productivity of the economy.

3.2. Numerical Simulation Models

Several articles have gone beyond such a simple analytical model to consider the economics of climate engineering using a numerical simulation model. Several studies have adapted a commonly used integrated assessment model (IAM) called the Dynamic Integrated Climate Economy (DICE) model, described in Nordhaus (2008). The DICE model contains a representative agent model of economic production with exogenous technological growth, combined with a simple model of the Earth's climate and carbon cycle. Production generates carbon emissions, but those can be reduced in the DICE model through abatement. Carbon emissions increase carbon stocks in the atmosphere and the oceans, which in turn increase temperature. The temperature increase causes economic damages. The DICE model can be used to find the optimal dynamic path of abatement intensity and the optimal carbon price over time. However, the original DICE model does not include climate engineering.

Bickel & Lane (2009) adapt the DICE model to include both SRM and CDR [what they call air capture (AC)]. They provide a cost-benefit analysis for various levels of climate engineering intensity and find that climate engineering promises potentially large net benefits, though the uncertainty is substantial. In their model, only SRM passes the cost-benefit analysis; AC is prohibitively expensive. The authors consider three determined levels of SRM intensity, but they do not solve for the optimal SRM intensity level.

Heutel et al. (2015a) also modify the DICE model to include SRM, using it to solve for the optimal level of both abatement and geoengineering. They argue that SRM is a substitute for abatement, but an imperfect one because it lowers temperatures without reducing carbon concentrations. Thus, it does nothing to address damages directly caused by atmospheric carbon, such as the ocean acidification accounted for in their model. They show that the optimal use of SRM depends on how much damage is caused directly by elevated atmospheric carbon dioxide concentrations.

3.3. Optimal Policy

Relatively few economics papers have evaluated how climate engineering factors into broader optimal climate policy schemes, using either theoretical or numerical simulation models. Barrett (2007) argues that climate engineering can be part of an optimal climate policy portfolio, and Barrett (2008) expands on this idea.[10] Moreno-Cruz & Smulders (2010) use a simple theoretical model to discuss optimal SRM policy; Moreno-Cruz & Keith (2013) extend that paper and calculate optimal policy in the presence of uncertainty.

Most numerical simulations consider a fixed level of SRM and perform a cost-benefit analysis. The analysis in Goes et al. (2011) mostly focuses on costs and benefits, but they also perform simulations solving for optimal SRM and abatement levels. Their simulations are performed for different levels of damages from SRM. When damages are zero, they find that SRM is employed at full intensity and abatement is abandoned; this represents the corner solution where SRM is the only climate policy tool used. As the damages from SRM increase, the optimal use of SRM decreases, and the optimal use of abatement increases. This demonstrates that in IAMs, SRM and abatement can be substitute policy instruments. In an optimal policy framework, when one is used more intensively, the other will be used less intensively. When SRM damages are zero, SRM is a perfect substitute for abatement, and atmospheric CO_2 concentrations increase throughout the entire simulation period, whereas temperature quickly decreases back to its preindustrial level. When SRM damages are 3% of the gross world product or higher, the optimal use of SRM is near zero.

Gramstad & Tjøtta (2010) modify the DICE model by including SRM and conducting a cost-benefit analysis, finding that SRM passes the cost-benefit test. They also include a public choice model, wherein SRM may fail in practice due to political considerations although it is welfare-increasing. Heutel et al. (2015a) also use the DICE model with SRM to solve for optimal policy paths of both abatement and geoengineering. In their baseline simulations, the introduction of SRM reduces the optimal amount of abatement by up to 25%, relative to the optimal policy in the model without SRM. Abatement eventually reaches 100% (no emissions), albeit a few decades later than in the simulations without SRM, because in their model SRM is not a perfect substitute for abatement. Simulations that vary the parameter values describing how large direct damages from atmospheric CO_2 demonstrate that when carbon concentrations account for a larger fraction of total climate damages, SRM is used less intensively.

Because abatement and SRM can be viewed as substitute policy instruments, including an SRM option allows for less abatement along the optimal policy path. It follows that the optimal carbon price, set to provide an incentive for polluters to abate at the optimal level, will be lower in a model that includes SRM than in a model that does not. In other words, the exclusion of SRM may lead climate IAMs to overestimate the optimal carbon price.

Several papers demonstrate this result. In Bickel & Lane (2009), the carbon price falls by up to 50% relative to its level without SRM, depending on the intensity with which SRM is used. Heutel et al. (2015a) show that the carbon price under the optimal policy path is about 30–45% lower than the model without SRM. Initially, the difference is small, as both abatement and SRM are used sparsely. As optimal SRM and abatement use increases, the difference in the carbon price between the SRM and non-SRM simulations grows. Eventually, abatement reaches 100% both with and without SRM, so the difference between the carbon prices under the two assumptions disappears. Still, their base-case simulation suggests that the optimal carbon price may be substantially biased by the introduction of SRM. The net deadweight loss from ignoring SRM peaks at approximately 1.6% of world output annually under their base-case parameters.

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[10] Barrett's (2008) title, "The Incredible Economics of Geoengineering," is in response to SRM's very low costs relative to mitigation, and the author notes that "most economic analyses of climate change . . . have ignored geoengineering" (p. 46).

4. EXTENSIONS AND COMPLICATIONS

Although the analytical and theoretical models described above provide the basic intuition for thinking about the economics of climate engineering and climate engineering policy, many complicating factors remain. In this section, we describe how the literature has dealt with some such complications, including regional inequalities, strategic behavior, and risk and uncertainty. For the reasons listed above, these complications are almost exclusively associated with SRM, and for this reason we focus on the literature addressing this set of technologies.

4.1. Issues of Equity and Governance

Who, if anybody, can make a decision to implement climate engineering, and what should the temperature target be? In a recent review paper, Barrett (2014) surveys and analyzes the literature of climate engineering governance. We extend that review by explaining how the specific science and engineering characteristics of the different technologies result in unique governance issues.

This literature extends back to the 1990s, when the governance of SRM was first linked to the notion of democracy. Jamieson (1996) examines the basis for a right of all nations, and even individuals, to determine their climate future through global climate policies that adequately address possible damage arising from climate change. The same point was expressed 14 years later by Corner & Pidgeon (2010), who further argue that some of the poorest countries, such as sub-Saharan and Pacific nations, would be those most affected by climate engineering, and therefore their opinions arguably carry greater weight in the decision. Schneider (1996) argues that because of the potential for international conflict caused by implementation of SRM, it would be irresponsible to implement large-scale climate engineering before there is a high level of certainty about its effects and governance. This is further emphasized by Schelling (1996), who cautions that nations may engage in climate wars to defend and impose their preferred climate. That is, climate engineering can in principle create governance problems in excess of those already existing around climate change policy. Victor (2008) suggests specific norms for climate engineering deployment, whereas Ricke et al. (2013) and Weitzman (2015) develop specific mechanisms to determine climate engineering outcomes. The remainder of this section discusses studies that deal with issues of governance and interregional and intergenerational equity.

4.1.1. Interregional equity. Regional climates in a world where climate change is a product of elevated greenhouse gases and SRM will differ from those in a world with the same global temperature but no SRM. Because both greenhouse gas–driven climate change and SRM will have differential impacts across the globe, some countries will be better off than others if SRM is implemented, and different countries will likely prefer different amounts of global cooling.

Moreno-Cruz et al. (2012) use a residual climate response (RCR) model calibrated with climate model output to investigate the regional inequities that arise from the use of aerosol SRM to compensate for elevated atmospheric CO_2 concentrations. As its name implies, the RCR model evaluates the amount of damages that are left uncompensated when SRM is used to restore average regional temperature or precipitation to its baseline level. The authors find consistently high efficiency of SRM in compensating for greenhouse gas–induced regional climate change (70–99%). The effects differ significantly between population-, area-, and economy-based regional weighting criteria and between precipitation and temperature optimization. For example, an SRM scheme can compensate for 97% of population-weighted precipitation changes, but the same scheme only compensates for 69% of output-weighted temperature changes.

Kravitz et al. (2014) extend the analysis in Moreno-Cruz et al. (2012), applying the RCR model to results from the multimodel Geoengineering Model Intercomparison Project ensemble developed in Kravitz et al. (2011). They find that the high efficiency demonstrated in Moreno-Cruz et al. (2012) is robust for modeling climate uncertainty for temperature but less so for precipitation.

Moreno-Cruz et al. (2012) further define a Pareto-improving criterion to determine the level of SRM that would benefit most regions in the world, without making any particular region worse off. In that work, the first region to reach its optimum as SRM is incrementally increased is Western Africa. In this article, the Pareto-optimal level of SRM compensates for 56% or more of the CO_2-induced damages. Kravitz et al. (2014) extend this analysis to compare results for a variable relative weighting of temperature and precipitation and find that for all but high weightings of precipitation (>0.9), implementations of SRM that reverse 85% or more of global temperature change are all Pareto-improving.

All the previous articles are subject to the critique made explicit in Heyen et al. (2015). These results are highly sensitive to the choice of metrics and baselines for determining regional preferences (e.g., the specification of the damage function and reference temperature).

4.1.2. Interregional strategic behavior. The regional asymmetry of impacts from SRM can motivate strategic behavior. The dynamics of strategic incentives associated with SRM and implications for climate governance have been addressed in several economic theory articles. Weitzman (2015) investigates the idea of a "free driver" effect. Contrary to the usual free rider problem associated with abatement, low technology costs reverse the balance of benefits and burdens of coalition building and create incentives to engage in unilateral climate engineering. This paper develops a model of externalities and incentives and suggests that strong mechanisms, such as a supermajority voting rule, are necessary to reach the social optimum. The ideas put forward in Weitzman (2015) are further developed in Heyen (2015), which incorporates R&D incentives for SRM climate engineering. That study adopts a game-theoretic approach to analyze how the balance of benefits and costs of climate engineering affects country-level incentives to engage in climate engineering R&D. Though the model yields significant behavior restrictions, conclusions are similar to those obtained in other economic models of R&D: There are significant incentives for free-ridership in technology development, but the threat of the free driver effect causes excessive investment in the technology and an R&D race.

A further step is taken by Ricke et al. (2013). The authors investigate the potential effects of climate engineering for a variety of regional players in a game-theoretic model and identify strategic incentives to engage in climate engineering. Diverse regional responses to climate engineering create incentives to form narrow coalitions and exclude excessive members rather than force them to participate. This parallels an idea of Millard-Ball (2012). Although that work is more concerned with the effects of the threat of unilateral climate engineering to global participation in abatement, he raises the question of exclusivity in governance of climate engineering.

Moreno-Cruz (2015) investigates free rider and free driver aspects in climate engineering and mitigation. He finds that in symmetric or low-damage settings, the possibility of climate engineering reduces incentives for mitigation, whereas in a setting in which the damages from climate engineering are asymmetric or high, the incentive to avoid climate engineering causes extremely high levels of mitigation. The author also examines the free driver notion and finds supporting evidence for excessive climate engineering under the free driver scenario, similar to Weitzman (2015).

Manoussi & Xepapadeas (2016) extend the existing line of research by producing a model that is explicitly dynamic and allows for CO_2 accumulation. The paper provides a rich framework to analyze the delayed effect of mitigation on temperature relative to the more immediate effect of SRM on temperature. When the sources of asymmetry are climatic, there is no trade-off between SRM and emissions reduction. When the asymmetries are economic, the most productive country compensates an increase in emissions with SRM, just enough to counterbalance the global warming effects of its increased emissions.

4.1.3. Intergenerational equity. The issue of intergenerational equity and climate engineering has only been briefly touched upon thus far in the literature. Burns (2011) delves into this topic in depth, compiling a body of knowledge on ethics, philosophy, and international law to support the claim that SRM would violate the principle of intergenerational equity by imposing excessive environmental burdens on future generations.

Contrary to Burns (2011), Goeschl et al. (2013) find a net positive effect associated with SRM via the intergenerational transfer of SRM technology. In particular, this study assumes that (*a*) the current generation cares about the future generation sufficiently to be concerned about the stock damages of atmospheric carbon, (*b*) there may be a pro-SRM bias in the future, (*c*) both abatement and R&D on SRM involve a cost today, and (*d*) there is uncertainty about the damages associated with atmospheric carbon. The authors demonstrate that even in the absence of a pro-SRM bias, the presence of an SRM option offsets current abatement. Far from constituting an instance of a "moral hazard" (Bunzl 2009, p. 2), this simply results from the partial substitutability between abatement and SRM that a current generation will rationally want to exploit.[11] Under this model, the presence of a pro-SRM bias constitutes an important source of potentially powerful strategic distortions between generations. Abatement efforts are not reduced by the availability of SRM, but rather abatement increases relative to the benchmark as the bias-driven distortion between generations increases. An altruistic current generation will partially offset a pro-SRM bias among the future generations by providing more abatement today, thus reducing the incentives to deploy SRM in the future.[12]

4.2. Risk and Uncertainty

Risk and uncertainty are of fundamental importance in the consideration of climate engineering because of the large uncertainties surrounding both the effects of climate change overall and those of climate engineering in particular. Here we review the publications in three sections: direct climate risks, termination effects, and CTPs.

4.2.1. Direct climate risks and insurance. Direct risks of climate engineering have received the most extensive treatment in economic models to date. Due to their global nature and lack of similarity with abatement approaches, SRM technologies introduce novel risks.

Moreno-Cruz & Keith (2013) introduce SRM in a simple economic model of climate change that is designed to explore the interaction between uncertainty in the climate's response to CO_2 and the risks of SRM in the face of carbon cycle inertia. They use a two-stage decision framework in which the abatement decisions are made in the first period, and SRM decisions are made in the second. In between periods, the decision maker learns the true sensitivity of the climate. Using this framework, they find that SRM is used in the case of high climate sensitivity, even if the damages from SRM exceed the previously expected damages from climate change. If climate sensitivity is low, SRM is not used much and climate change is dealt with only by abatement. Using the same

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[11] This same argument is made in Keith (2013, pp. 127–35).

[12] Sterck (2011), Goes et al. (2011), and Betz (2012) also raise questions of emissions reductions and burdens from side effects on future generations.

framework, they find that learning about SRM—the value of information associated with reducing the uncertainty about the side-effects of SRM—can reduce the overall costs of climate change on the order of 10%, depending on the amount of learning.

Emmerling & Tavoni (2013) use the World Induced Technical Change Hybrid (WITCH) model, one of the main numerical modeling tools designed to evaluate the impacts of climate change policies. Similar to Moreno-Cruz & Keith (2013), their study is focused on how uncertainty affects policy. They find that the introduction of SRM reduces the optimal amount of abatement but only under the optimistic assumptions about SRM's effectiveness. Notably, their simulations suggest that the optimal level of emissions can be higher than business-as-usual emissions when an SRM option is deemed highly effective. Heutel et al. (2015a) also model uncertainty in climate sensitivity and climate engineering damages, finding that both sources of uncertainty have a larger effect on optimal SRM use than on optimal abatement.

Feichter & Leisner (2009) discuss general risks associated with climate engineering and conclude that, despite risks preventing the deployment of climate engineering technologies immediately, more research is needed to investigate their potential applications. Betz (2012) provides an extensive discussion of risks through a formal logic analysis of debate over whether to invest in climate engineering research, following a similar line of reasoning to that presented through a decision analytical framework in Morgan & Ricke (2011). Galaz (2012) examines climate engineering from a perspective of planetary impacts and Earth stewardship as a technological innovation, and like many, finds that it has both advantages and risks. Most of the above works argue for a cautious and responsible approach to climate engineering's evaluation and development. Regarding CDR, Williamson et al. (2012) discuss ongoing international efforts for climate engineering risk management as a part of a broader study of ocean fertilization technology.

4.2.2. Termination effects. Termination effects are a central topic in Goes et al. (2011). The authors use an extended DICE model to evaluate the risks associated with continuous, then abruptly terminated aerosol SRM deployment and the accompanying rapid increase in global temperature. The models in Goes et al. (2011) and Bickel & Agrawal (2013) consider SRM deployment in conjunction with an exogenous cause of intermittency; SRM is randomly stopped and unable to be restarted. SRM intermittency leads to high costs from climate damages, higher in some periods than even the business-as-usual case of no abatement or no emissions. In Goes et al. (2011), SRM fails cost-benefit tests, but Bickel & Agrawal (2013) argue that this is due to several modeling choices such as the discount rate, form of the damage function, and the exogenous and abrupt intermittency of SRM. Under more general specifications, SRM passes a cost-benefit test.

4.2.3. Climate tipping points. CTPs are uncertain and irreversible events that have large and lasting effects on the climate system and, potentially, the global economy. Some examples of CTPs include the collapse of the West Antarctic ice sheet or a disruption of the thermohaline circulation (Lenton et al. 2008). Most articles about CTPs have focused on climatological effects (Lenton et al. 2008, Lockwood 2011, Zickfeld et al. 2010). The possibility of CTPs can affect optimal climate policy, and IAMs like DICE have been modified to include them (Lemoine & Traeger 2014). Studies that focus on the economics of tipping points and SRM include Bellamy & Hulme (2011), Bickel (2013), Bickel & Agrawal (2013), and Heutel et al. (2015b).

Bickel (2013) uses an extension of the DICE model to investigate different CTP scenarios and the potential efficacy of aerosol SRM technology in averting damage from reaching a CTP. He finds that SRM is a potentially effective technology in countering temperature change and CTPs, but he remains cautious about its effectiveness given uncertainties over the technologies and their indirect costs. Bickel & Agrawal (2013) refer to CTPs as among the potential sources of economic damage from not using climate engineering, and they show that if the uncertainty and risks of business as usual are included in the analysis, SRM may eventually be an economically efficient policy instrument.

By adapting the DICE model to include both SRM and CTP, Heutel et al. (2015b) study how the presence of CTPs affects optimal abatement and SRM policy. Their model considers three rules that govern the use of SRM: banning completely, freely allowing it, and allowing it only after reaching a CTP. They demonstrate that the presence of CTPs leads to more use of both abatement and SRM, because both help insure against the risk of crossing a CTP threshold. Under the rule where SRM cannot be used until the CTP is reached, policy costs are higher than under the rule where SRM can be used without restriction.[13]

5. CONCLUSIONS

Climate engineering has remained at the fringes of climate policy debate and academic economic research. However, the literature is growing, and much of it suggests that climate engineering technologies can have a substantial impact on climate policy and international climate negotiations. This may be especially true given the current difficulty that nations continue to face in coordinating a response to climate change. CDR and SRM are two sets of technologies that offer climate risk mitigation alternatives. CDR offers a path toward decarbonization, with relatively low uncertainty and large benefits, but at very high costs. SRM is available at much lower direct costs, but comes with more uncertainty and does not address the root cause of climate change. The current literature has explored these technologies and identified them as nontrivial additions to the conventional slate of potential climate policy instruments. Literature exploring the economics of CDR is lacking. This is in part due to the high expected costs of CDR technologies and similarities in key characteristics between CDR and standard abatement techniques. The literature on SRM is more evolved, though still relatively small.

There are several directions warranting more research in the near future. More research on the impacts and damages from climate engineering needs to be pursued. Uncertainties are associated with all aspects of climate change impacts, but those associated with climate engineering are exceptionally large. This research should extend not only to physical scientists and engineers but also to economists. Attribution of impacts becomes more pressing once changes to the climate become deliberate. Compensation and liability will likely be important aspects of any climate engineering policy and will require mechanisms for monitoring and adjudication.

A second area of research need is the explicit modeling of SRM and CDR in conjunction with abatement and adaptation. As the climate continues to change, the incentives to invest in any particular form of climate risk mitigation strategy will change as well, and different regions will opt for different strategies. The literature has already started to address this issue, though it has thus far focused solely on effects of abatement, not adaptation.

Finally, we need to begin exploring specific mechanisms to ensure an efficient and equitable implementation of climate engineering technologies. Although some early steps have been taken in this direction, we need to understand from an economic perspective how to create institutions that can accommodate these novel climate risk reduction strategies.

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[13] Bellamy & Hulme (2011) approach the question of CTPs from the perspectives of personal beliefs and societal perception. In a sequence of quantitative and qualitative studies of public opinion on climate change and abatement, the authors refer to CTPs to identify public perception of the most undesirable outcomes of climate change.

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