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Why is geoengineering so tempting?

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Abstract

Geoengineering can be defined as the technologies that aim to deliberately alter geophysical mechanisms in order to alleviate the impacts of climate change. It has received increasing attention by economists and the public but remains deeply controversial. This paper studies the *potential benefits* from geoengineering in a standard one-sector growth model augmented with a carbon cycle and a climate system. These benefits can be interpreted as a lower bound for the *direct and indirect costs* which would make geoengineering less preferable to abatement. In the planner's solution to the model, exogenous geoengineering in the future increases investment in physical capital and reduces abatement, both today and in the future. The central result of the paper is that the direct and indirect costs of geoengineering must be large for geoengineering not to be tempting. Nevertheless, substantial abatement is optimal even when geoengineering does not entail any costs. A sensitivity analysis establishes how the results change in a world with a lower initial capital stock; an earlier availability of geoengineering; and under different parameter values for the discount rate and the curvature of the damage function. Together these results show how the temptation to use geoengineering can be different for developing and advanced countries.

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1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) defines geoengineering as "a broad set of methods and technologies that aim to deliberately alter the climate system in order to alleviate the impacts of climate change." A distinguishing feature of geoengineering is that it interferes with planet-level processes to reduce climate change impacts, whereas mitigation and adaptation operate relatively more locally to change human behavior. The term made its first appearance in the literature in the 1950s. More recently, it has received increasing attention in the context of the debate on climate change and the appropriate response to it. The fact that the IPCC (2013) explicitly mentions it has generated much discussion because the intentional manipulation of natural process at such a large scale remains deeply controversial. As a consequence, it is not surprising that scientists and economists are keenly interested in various aspects of the issue, with academic papers and reports being published on the topic. Books are cropping up outlining the pros and cons of various geoengineering proposals. Using an unorthodox approach to identify global investment priorities, a group of top economists convened by the Copenhagen Consensus Center in 2012 ranked geoengineering research and development 12th among the 40 projects they were presented with, putting it ahead, for example, of efforts to develop an HIV vaccine. Popular media references capture public attention with such headlines as "UN warms to idea of using giant mirrors in fight against climate change effects" in the Financial Times and "How to save the planet: Moon mining, iron filings and fake volcanoes" in the Telegraph of the UK.

Against this background the research question of the current paper is how exogenous, costless and permanent deployment of geoengineering affects the endogenous evolution of key macroeconomic variables over time. My analysis relies on the planner's solution to the one-sector growth model augmented with a carbon cycle and a climate system. While this approach appears naive, I argue that calculating the economic benefits of geoengineering in a dynamic model is a useful exercise because the estimates of the direct and indirect costs of these technologies vary widely, and so the computed benefits can be interpreted as a lower bound on geoengineering costs such that welfare is lower with geoengineering than without. With the aid of the model I conclude that these costs would have to be sizable.

The model I use to calculate these benefits is simple, but flexible enough to study the two broad categories of geoengineering methods known as solar radiation management (SRM) and carbon dioxide removal (CDR).[1] SRM technologies work by reflecting some of the incoming solar radiation back to space and thereby reduce the solar forcing. The Royal Society (2009) and an overview by Vaughan and Lenton (2011) list surface and cloud albedo enhancement methods, stratospheric aerosol injection and space-based methods as examples of SRM technologies. These technologies reduce the warming associated with a given stock of CO_2 in the atmosphere but do not address the

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[1] Vaughan and Lenton (2012) study CDR and SRM strategies together taking emissions trajectories as given in a carbon cycle-climate model, i.e. without an economy component.

root cause of the problem, i.e. the build-up of CO_2 and other greenhouse gases in the atmosphere. As a consequence, the climate change damages which are not related to temperature increases, e.g. ocean acidification, and those that may emerge as side effects of SRM, e.g. changes in precipitation patterns, continue to exist, and may become worse if emissions with geoengineering increase. Nevertheless, SRM's effect on temperatures can be rapid and the direct costs of individual methods vary from negligible to high relative to abatement.[2]

CDR technologies, on the other hand, target the stock of CO_2 in the atmosphere directly. Among these technologies the Royal Society (2009) and Vaughan and Lenton (2011) consider large scale land use changes, enhanced land and ocean weathering methods, ocean fertilization and direct air capture as possibilities. The key limitation of these methods, except perhaps an extremely ambitious direct air capture initiative, is that they operate on century to millennial time scales. Moreover, given the enormity of the task at hand, implementing them is costly at the current level of technological development and require the building and maintenance of extensive infrastructure.[3]

Rather than focusing on specific methods, I work with abstract (representative) SRM and CDR technologies in the model. Once in operation, the model counterpart of real world SRM technologies reduces the radiative forcings by a fixed amount. Similarly, the CDR technologies are incorporated by increasing the rate at which CO_2 diffuses away from the atmosphere. The parametrization of these technologies in the model are well within the feasibility bounds provided in Lenton and Vaughan (2009).

The main results obtained from the model are about the sizes of the *gross benefits* of geoengineering, measured relative to a business as usual (BAU) scenario, and of the *net benefits* of optimal abatement in the absence of geoengineering, also measured relative to the same BAU scenario. I explicitly consider scenarios where CDR and SRM technologies are exogenously implemented either individually or jointly at a known point in the future. I distinguish between scenarios where abatement responds optimally to geoengineering and where it is restricted to be zero, and compute i) investment and emissions, which are always chosen optimally; ii) the optimal level of abatement when it is not restricted by assumption; and iii) the implications of the preceding variables on welfare.

When abatement is chosen optimally, investment and emissions are always higher in scenarios with geoengineering relative to those without. Geoengineering reduces abatement effort but does not eliminate it. In the benchmark parametrization, the optimal abatement effort is delayed somewhat but continues to be substantial with geoengineering. When abatement is restricted to be zero, emissions are higher than BAU emissions in scenarios with geoengineering.

Turning to welfare, the equivalent variation (EV) in BAU consumption that would make the BAU scenario generate the same present discounted value of utility as the scenario where both CDR

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[2] See Robock et al (2009) and Table 3.6 in Royal Society (2009).

[3] See Socolow et al (2011), Mcglashan et al (2012), Socolow and Tavoni (2013) and references therein.

and SRM technologies are deployed in 2050 but where no abatement takes place is 0.80%. In other words, providing 0.80% additional consumption each and every period to someone in the BAU scenario makes her as well off as living in the geoengineering-only scenario, when geoengineering costs are assumed to be zero. To get a sense of whether 0.80% is large or small, it is useful to compare it to the EV of a scenario which many climate change researchers have worked with, i.e. one with optimal abatement but no geoengineering. Using the same parameter values, the EV in this case is 0.43% which measures the benefits of abatement net of its costs.

When comparing these two figures it is important to keep in mind that they measure different things. By construction, the former figure for geoengineering captures the benefits of geoengineering only. It provides information on the size of the direct and indirect costs of geoengineering which would make the scenario with geoengineering but no abatement less preferable to a world with optimal abatement but no geoengineering. Considering the total abatement costs are approximately 0.21% when also measured in units of EV in BAU consumption, the total cost of geoengineering would have to be about $(0.80 - 0.43)/0.21 \approx 1.8$ times as large as the total abatement costs for the scenario with no geoengineering to be preferable. I also calculate the analogous figures for the cases where SRM and CDR technologies are deployed individually and when abatement is allowed to respond optimally. The broad conclusion is that the benefits of geoengineering are sizable, especially for SRM technologies.

However, as the sensitivity analysis with respect to the initial capital stock and the deployment date of geoengineering demonstrate, a given set of costs can have different implications on the value of geoengineering scenarios relative to the abatement-only scenario, highlighting the importance of research on the known, anticipated and yet-to-be-discovered costs of geoengineering technologies, which can be a challenging task.[4] Regardless, given the size of the benefits identified in this paper, geoengineering is likely to receive increasing attention and feature more prominently in the public debate on our response to anthropogenic climate change.

It is in this context that the following, admittedly speculative, scenario is conceivable: faced with immediate abatement costs, a subset of developed countries, egged on by the geoengineering and fossil fuel lobbies, decide to use stratospheric aerosol injection to rapidly cool the planet. The direct costs of this method are trivially low — Keith (2013) compares them to the budget of a Hollywood blockbuster — and its effectiveness in cooling the planet has been argued with the use of data from volcanic eruptions acting as natural experiments. Its potentially large and heterogeneous indirect costs, on the other hand, will take time to emerge, quantify and agree upon.[5] In developing countries, geoengineering deployed elsewhere increases the incentives to pursue a carbon-intensive but 'tried-and-tested' growth path which spares them the abatement

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[4] See Robock et al (2010) who argue that it is not possible to test stratospheric geoengineering without full scale implementation.

[5] After decades of research, a consensus is yet to emerge regarding the extent and time path of climate change damages. Some even question the sign of the damages in the near term as a result of increased primary productivity.

costs but results in higher emissions. If indeed the events unfold along these lines, the actions of the remaining developed countries, who may prefer abatement over geoengineering, are largely irrelevant. In summary, the world as a whole can be burdened with non-temperature climate change damages and geoengineering costs as well as climate change damages related to warming if geoengineering is interrupted for some reason.

The rest of the paper is structured as follows. The next section provides a brief overview of the literature focusing primarily on the more recent economic studies. In Section 3, I describe how I incorporate geoengineering in an otherwise standard macroeconomic model. Section 4 outlines my quantitative strategy. The discussion of the key results under alternative geoengineering scenarios is in section 5, which also contains a discussion of the sensitivity of the results to a number of model features and parameters. The final section highlights the limitations of my approach and concludes. All figures and tables can be found at the end.

2 Related literature

The early scientific literature on geoengineering goes back to the 1950s and is reviewed in Keith (2000). Accelerating global CO_2 emissions, our improved understanding of their climate change and economic impacts and two seminal articles on geoengineering by Nobel laureates Schelling (1996) and Crutzen (2006), have generated more interest in the topic more recently. The scientific basis and governance issues raised by geoengineering are summarized in IPCC (2012) and the Royal Society (2009) both of which also contain an excellent set of references. Lenton and Vaughan (2009) and Vaughan and Lenton (2011) provide a technical review of the available options with an explicit focus on potential effectiveness and feasibility.

More recently, economists have taken an active interest in the impact these technologies can have on the mainstream climate change policy debate. Barrett et al (2014) argue that stratospheric aerosol injection may not be the silver bullet it appears to be in responding to climate emergencies, or when used as a stop gap measure. Their conclusion follows from the observation that when the intervention is likely to be effective, it is unlikely to be politically feasible, and vice versa.[6] The authors' conclusion has been challenged in Irvine et al (2014). Moreover, their notion of political feasibility does not preclude the use of geoengineering "unilaterally or minilaterally", much along the lines discussed in Barrett (2008), which identifies the governance of the technology as the main challenge given its "incredible economics." Victor (2008) makes a similar point and discusses various ways of regulating geoengineering research and implementation. Manousi and Xepapadeas (2013) go a step further and formally model the interaction between countries when there are two possible responses to climate change, mitigation and geoengineering. They find that geoengineering reduces

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[6] In this context, political feasibility is loosely defined as "a reasonable prospect that the international political system ... allow[s] geoengineering to be used to achieve [its] ... goal."

incentives to mitigate and that in a non-cooperative solution the incentive to use geoengineering is greater.

The implications of the uncertainty over the parameters characterizing geoengineering, the climate system and/or the economy-climate interaction have been the focus of a number of recent papers. Goes et al (2011) find that SRM does not pass the cost benefit test for a wide range of parameter values when uncertainty over intermittent technology deployment, climate sensitivity, abatement costs and climate change damages are introduced. However, in a follow-up paper Bickel and Agrawal (2013) cast substantial doubt on the robustness of their results. Whether and when abatement is allowed to respond optimally, and the specification of the discount factor, turn out to be crucially important for the results.

Emmerling and Tavoni (2013) focus on the uncertainty regarding the effectiveness of an SRM technology. The authors study how this uncertainty affects the incentives to abate and find that abatement always declines, but does so substantially only when SRM is very likely to be effective. Uncertainty is also the focus of Bahn et al (2014) who analyze the implications of a stochastic sequence of damages associated with SRM. The authors use an integrated assessment model where the response to climate change can take the form of mitigation, proactive and reactive adaptation, and SRM. They conclude that unless damages associated with it are low, SRM is part of the optimal policy mix in only a minority of cases. Using a simple two period model of learning, Moreno-Cruz and Keith (2013) study how uncertainty about the impacts of SRM and climate sensitivity come together to imply that geoengineering research is cost-effective, even if the technology is to be used as an emergency measure only.

In all of these studies, the direct and indirect costs of geoengineering are crucial but vary in a wide range. On the one hand, the deployment costs of some SRM methods, e.g. stratospheric sulfur injection, are small relative to the size of abatement costs or the global economy.[7] On the other hand, SRM technologies can have substantial indirect costs. Robock (2008) and the Royal Society (2009) count heterogeneous regional climate impacts, ocean acidification, ozone depletion, greater acid deposition as well as risks associated with program interruption and unknown unknowns among the key indirect costs of SRM methods. Some of these can be very large. For example, the disruption of the Asian monsoon patterns following the implementation of SRM would be a matter of life and death for hundreds of millions of people living near the subsistence level.[8] Quantifying such costs is a difficult task where research is much needed. Incorporating them into the cost-benefit framework of this paper is all the more difficult because potentially catastrophic geoengineering impacts must be weighed against potentially catastrophic climate change impacts, which the framework is ill-equipped to deal with.[9]

In the case of some CDR technologies, the situation is reversed. Socolow et al (2011) show that the

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[7] See Crutzen (2006) and Robock et al (2009).

[8] See Robock et al (2008).

[9] See Weitzman (2009) and Millner (2013).

direct costs of deployment are currently high, particularly at the scale required, whereas indirect costs, at least in the case of some technologies such as direct air capture, are likely to be low. A more comprehensive treatment of the direct costs of the most popular CDR methods can be found in McGlashan et al (2012) and the Royal Society (2009). Since these technologies directly target the root cause of anthropogenic climate change, there are large incentives to develop cheap, scalable technologies that can remove large quantities of carbon from the atmosphere and store it safely. How wide the range of CDR costs is then becomes a matter of how optimistic one is regarding technological progress specific to CDR in the face of these large incentives.

3 Theoretical model

My starting point is the neoclassical one-sector growth model in which the primary drivers of growth are capital accumulation and productivity growth. I modify it to incorporate climate change and geoengineering. In the model, climate change causes a proportional loss in output, $D(\tau_t)$, as a function of the increase in the average surface temperature relative to pre-industrial times. The damages can be reduced by controlling emissions but doing so is costly because some of the output must be devoted to abatement activities. Denoting the share of emissions abated with $\mu_t \in [0,1]$, $\Lambda(\mu_t)$ is the total abatement cost expressed as a share of available output. In other words, net output after the climate change damages and the cost of abatement activities are accounted for is given by the left hand side of (2), where A_t is an exogenous productivity parameter. Output can be used as consumption (c_t) or investment (x_t). Augmented by x_t, the capital stock (k_t) accumulates according to the law of motion (3). Emissions in each period are given by (4), where σ_t is the exogenous emission intensity of output.

Geoengineering enters the model exogenously through the relationships describing the climate system (5) and the carbon cycle (6). The climate system determines the relationship between a sequence of CO_2 stocks in the atmosphere ($\mathbf{s^t} \equiv\{s_0, s_1, ..., s_t\}$) and a sequence of atmospheric temperature increases ($\tau^{\mathbf{t}} \equiv \{\tau_0, \tau_1 ..., \tau_t\}$) according to (5). The natural state of the climate system is characterized by $T(\mathbf{s^t})$ and under an abstract SRM technology the relationship is given by $\tilde{T}(\mathbf{s^t})$. Similarly, a sequence of anthropogenic emissions ($\mathbf{e^t} \equiv \{e_0, e_1, ...e_t\}$) determines $\mathbf{s^t}$ through the carbon cycle described by (6). The natural state of the carbon cycle is given by $S(\mathbf{e^t})$ and under a CDR technology the carbon cycle is transformed to $\tilde{S}(\mathbf{e^t})$. Below I provide more details on how CDR and SRM technologies alter the working of the carbon cycle and the climate system. Here it suffices to note that their use results in a more favorable damage profile for a given emissions path.

The initial states for the economy, carbon cycle and the climate system are k_0, s_0, τ_0. It is known whether SRM and/or CDR technologies are used at the outset. In other words, the values of SRM and CDR are exogenous, known in period 0 and fixed permanently. These are important assumptions and I discuss them in more detail below.

The problem facing the planner is to maximize (1) by choosing sequences of investment and emissions control rates subject to (2)-(6) given the initial conditions and exogenous variables.

$$\underset{\{x_t,\mu_t\}}{max}\sum_{t=0}^{\infty}\beta^t U(c_t) \qquad subject\,to \tag{1}$$

$$\begin{aligned}
[1-D(\tau_t)]\,[1-\Lambda(\mu_t)]A_tF(k_t) &= c_t+x_t & (2)\\
k_{t+1} &= (1-\delta)k_t+x_t & (3)\\
\mathbf{e^t}\ni e_t &= (1-\mu_t)\sigma_tA_tF(k_t) & (4)
\end{aligned}$$

$$\tau_t\in\tau^{\mathbf{t}} = \begin{cases} T(\mathbf{s^t}) & if\,SRM=0\\ \tilde{T}(\mathbf{s^t}) & if\,SRM=1\end{cases} \tag{5}$$

$$\mathbf{s^t} = \begin{cases} S(\mathbf{e^t}) & if\,CDR=0\\ \tilde{S}(\mathbf{e^t}) & if\,CDR=1\end{cases} \tag{6}$$

$$Given \qquad A_t,k_0,s_0,\tau_0,SRM\in\{0,1\},CDR\in\{0,1\}\,and\,\sigma_t.$$

The various functions in this problem and their key properties are summarized in Table 1. The idea is to solve the model under various scenarios regarding geoengineering and compare the solutions across the scenarios. These scenarios are summarized in Table 2.

BAU in Table 2 is the scenario where no abatement takes place by assumption and the problem above has the additional constraint that $\mu_t = 0$ for all t. Moreover, there is no geoengineering so the damages that result from the emissions under this scenario are the greatest. It is important to note that the investment decisions take full account of the these damages and are optimally chosen given the assumptions of this scenario. OPT relaxes the restriction that $\mu_t = 0$ so that this variable can take any value in $[0, 1]$. The next three rows consider the addition of CDR and SRM to the problem, first individually and then jointly. The final three rows describe the scenarios where no abatement takes places but geoengineering can nevertheless make the damages associated with emissions less severe.

Next, I describe how geoengineering alters the carbon cycle and the climate system in the model. To do so, fix an arbitrary emissions sequence, $\mathbf{\hat{e}} = \{e_0, e_1, e_2...\}$ and assume that geoengineering takes effect in period t^*. Focus first on the scenario where $CDR = 1$ and $SRM = 0$. Then the relationship between $\mathbf{s^t} = S(\mathbf{\hat{e}})$ and $\mathbf{\tilde{s}^t} = \tilde{S}(\mathbf{\hat{e}})$ is such that for $0 \leq t \leq t^*$, $s_t = \tilde{s}_t$ and for $t > t^*$, $s_t < \tilde{s}_t$. In words, following the implementation of the CDR technology, the CO_2 stock implied by $\mathbf{\hat{e}}$ is smaller. Since $T(\mathbf{s^t})$ is increasing in each s_t, and $D(\tau_t)$ is increasing in τ_t, relatively less output is lost to climate change damages with CDR than without it under $\hat{\mathbf{e}}$.

Focus next on the opposite scenario where $CDR = 0$ and $SRM = 1$ and maintain the same emissions sequence $\hat{\mathbf{e}}$. The stock of carbon dioxide implied by $\hat{\mathbf{e}}$ is $\mathbf{s^t} = S(\hat{\mathbf{e}})$. Then the relationship between $\tau^{\mathbf{t}} = T(\mathbf{s^t}) = T(S(\hat{\mathbf{e}}))$ and $\tilde{\tau}^{\mathbf{t}} = \tilde{T}(\mathbf{s^t}) = \tilde{T}(S(\hat{\mathbf{e}}))$ is such that for $0 \leq t \leq t^*$, $\tau_t = \tilde{\tau}_t$ and for $t > t^*$, $\tau_t > \tilde{\tau}_t$. That is, given $\hat{\mathbf{e}}$, the temperatures and climate change damages are lower with the SRM technology than without it.

Finally, if $CDR = 1$ and $SRM = 1$, then $\tilde{T}(\tilde{\mathbf{s}}^{\mathbf{t}}) = \tilde{T}(\tilde{S}(\hat{\mathbf{e}}))$, generates lower temperatures and damages relative to the scenario when there is no geoengineering or those when CDR or SRM methods are deployed individually in period t^*. The implications of the deployment of none, one or both of the geoengineering methods are summarized in Table 3.

To provide intuition, Figure 1 provides a schema of the model and illustrates how geoengineering affects the system. The blue arrows show the domain of the representative CDR technology and the red arrow does the same for the representative SRM technology. Figure 2 illustrates qualitative points in Table 3 under alternative geoengineering configurations using the benchmark parameter values for geoengineering and assumes it is deployed in 2050.

By incorporating geoengineering in the model this way I make the following four assumptions:

1. *Exogeneity:* Geoengineering is exogenous, binary and permanent.
2. *Zero cost:* All direct (e.g. R&D, initial deployment and operation) and indirect (e.g. known and unknown externalities) costs of geoengineering are zero.
3. *Perfect information:* All relevant properties of geoengineering, including the date of implementation and effectiveness, are known.
4. *No uncertainty:* All parameters describing the climate system, carbon cycle, damages and geoengineering technologies are deterministic.

Clearly, these assumptions are strong and limit the set questions the model can answer. However, they also allow me to work with a simple and tractable model which treats geoengineering as a feature of the economic environment and focuses on the planner's response to changes in various aspects of this feature. For example. using the model it is possible to illustrate the dynamics of investment and abatement. Reasonably parametrized, the model can provide guidance on the relative size of welfare benefits associated with various geoengineering technologies. Of course, it is not possible to say whether geoengineering is welfare improving or not using this model because the costs of geoengineering are entirely absent from the model. However, the computed welfare benefits can be interpreted as an estimate for the lower bound of the costs that would render geoengineering welfare-reducing.

It is useful to note that the exogeneity is not as unrealistic as it initially appears. As Barrett (2008), Victor (2008), and Manousi and Xepapadeas (2013) point out, these technologies can be deployed by a single nation or a small coalition, even though the consequences of such deployment are global. As such, assuming some actor will eventually be tempted by geoengineering and therefore treating it as an exogenous feature of the environment is a sensible strategy. Moreover, given the fact that the goal of the model is to bound the costs beyond which geoengineering is inferior to abatement, the zero cost assumption is consistent with the question the model is designed to answer. Obviously, no such argument exists for the perfect information and no uncertainty assumptions.

It helps intuition to highlight that the model is equivalent to a one-sector growth model with climate change if $SRM = 0$ and $CDR = 0$. Moreover, the one-sector growth model with climate change is equivalent to the standard one-sector growth model if temperatures are unrelated to damages, i.e. $D(\tau_t) \equiv 0$ for all τ_t. That is, if there are no economic consequences of climate change, (5) and (6) do not affect utility maximization and it is optimal to set $\mu_t = 0$ in all periods.

In order to illustrate the tradeoffs facing the planner under different scenarios, I derive the first order conditions for the model with no geoengineering, i.e. $SRM = 0$ and $CDR = 0$ and follow this with a discussion of how these conditions are altered in scenarios with geoengineering. To avoid clutter, I subsume the carbon cycle and the climate system under the function $D(\tau_t)$ with the understanding that $\tau_t \in \tau^\infty = T(S(\mathbf{e}^\infty))$ where $\mathbf{e}^\infty$ is consistent with the planner's choices $\{\mu_t, x_t\}_{t=0}^\infty$. I also use (3) to substitute out x_t which allows me to write consumption c_t as a function of the μ_t and k_{t+1}. Then

$$c_t \;=\; [1 - D(\tau_t)]\,[1 - \Lambda(\mu_t)]\,A_t F(k_t) - k_{t+1} + (1-\delta)k_t \tag{7}$$

and the first order conditions for this problem are given by

$$\begin{aligned}\mu_t : \quad & -U'(c_t)\Lambda'(\mu_t)\,[1 - D(\tau_t)]\,A_t F(k_t) \\ & - \textstyle\sum_{s=0}^{\infty} \beta^s U'(c_{t+s})[1 - \Lambda(\mu_{t+s})]\frac{\partial D(\tau_{t+s})}{\partial \mu_t} A_{t+s} F(k_{t+s}) \quad = 0\end{aligned} \tag{8}$$

$$\begin{aligned}k_{t+1} : \quad & -U'(c_t) + \beta U'(c_{t+1})\left[[1 - \Lambda(\mu_{t+1})]\,[1 - D(\tau_{t+1})]\,A_{t+1} F'(k_{t+1}) + (1-\delta)\right] \\ & - \textstyle\sum_{s=1}^{\infty} \beta^s U'(c_{t+s})\left[[1 - \Lambda(\mu_{t+s})]\frac{\partial D(\tau_{t+s})}{\partial k_{t+1}}\right] A_{t+s} F(k_{t+s}) \quad = 0\end{aligned} \tag{9}$$

where $\frac{\partial D(\tau_{t+s})}{\partial \mu_t}$ and $\frac{\partial D(\tau_{t+s+1})}{\partial k_{t+1}}$ for $s = 0, 1, 2...$ denote the implications of an increase in abatement in period t and in capital stock in period $t+1$ for the climate change damages.

All else constant, (8) is the costs and benefits associated with marginally increasing abatement in period t. The first line is the value of the decline in consumption due to lower net output in period t because abatement costs are higher. The second line is the net present value of the avoided damages that result from the implied decline in damages in the future.[10] Similarly, (9) summarizes the costs and benefits of marginally increasing investment in period t, holding everything else constant. Such

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[10] Note that $\frac{\partial D}{\partial \mu} < 0$.

an increase is costly because it reduces consumption in period t. However, in period $t+1$, the greater capital stock increases output and the second term in the first line captures this benefit. Higher output in $t+1$ also increases emissions in period $t+1$ which has climate change consequences for the infinite future. These costs are given in the second line of the expression. The solution that maximizes utility ensures that in each period investment and abatement choices are such that these costs and benefits are equal at the margin.

Recall that in the discussion above there is no geoengineering. At this level of abstraction little can be said about how SRM and/or CDR technologies affect these tradeoffs the planner faces. This is because the effects of SRM and CDR technologies are ultimately about the changes in the evolution of climate change damages over time relative to the damages without geoengineering, which itself exhibits rich and persistent dynamics. Nevertheless, the entire path of $\{\mu_t, k_{t+1}\}$ depends on geoengineering.

To see this, consider a perfect SRM technology which makes $\tau_t = 0$ feasible for all s_t after period t^*. Such a technology would break the link between the stock of CO_2 in the atmosphere and damages, and imply $\mu_t = 0$ for all $t > t^*$ because there is no longer any need to abate and incur the associated costs. After t^*, the economy would converge to a steady state unconstrained by climate change damages. The perfect SRM technology would also affect abatement incentives before t^* because the benefits of abatement would be reduced relative to the case with no geoengineering, i.e. the infinite sum in the second line of (8) would be truncated in t^* for $t < t^*$. As a consequence, the model with a perfect SRM would feature less abatement even before the deployment of the technology.

Investment would also be higher under the perfect SRM technology. To see why, note that the marginal product of capital in period $t^* + 1$ is greater relative to the case with no geoengineering because $D(\tau_{t^*+1}) = 0$. The higher marginal product provides a greater incentive to invest in t^*. Moreover, there are no longer any costs associated with a greater capital stock in the future, which also increases incentives to invest. A similar argument can be used to show that in periods before t^* investment is also higher.

It is not difficult to construct analogous arguments for the effects of a perfect CDR technology, i.e. one that would remove sufficient CO_2 from the atmosphere so as to 'force' the climate system to deliver $\tau = 0$. Neither does the argument depend crucially on these technologies being perfect. In other words, the same qualitative results can be obtained under partially effective SRM or CDR technologies that do not eliminate but only reduce climate change damages. Indeed it is precisely the quantitative properties of the damage function and the geoengineering technologies that make the main research question of this paper interesting. However, in order to answer this question, I need to impose more structure on the model.

4 Quantitative strategy

The main goal in this section is to describe my quantitative strategy. The departure point is a simplified version of the DICE model described in Nordhaus (2013). It is simplified in the sense that I abstract from labour input into production as well as population growth. Moreover, I use constant, rather than declining, rates of change for the exogenous TFP, abatement cost and emissions intensity sequences. Remaining aspects of the DICE model are maintained.

The first decision period in the model is 2015 and one model period equals to 5 calendar years. The utility function is given by $U(c) = c^{1-\eta}/(1-\eta)$. The production function is Cobb-Douglas $F(k_t) = k_t^{\alpha}$. There are two sources of growth in the model, exogenous productivity improvements and endogenous capital accumulation. The latter is implemented by starting the economy from an initial capital stock that is half the implied level in the balanced growth path. Damages, and abatement costs are determined by

$$\begin{aligned} D(\tau_t) &= \psi_1 \tau_t + \psi_2 \tau_t^{\psi_3} \\ \Lambda(\mu_t) &= \theta_{1t} \mu_t^{\theta_2} \end{aligned}$$

where θ_{1t}, is the exogenous marginal abatement cost which changes at constant rates g_θ over time. I assume, as does Nordhaus (2013), that a zero-emissions backstop technology arrives 50 periods into the future to eliminate emissions thereafter.

The carbon cycle, $\mathbf{s^t} = S(\mathbf{e^t})$, takes a sequence of emissions as input and produces sequences of stocks of carbon in the atmosphere, upper oceans and lower oceans. The carbon cycle is an extremely slow moving process in human time scales and takes several centuries to reach equilibrium after anthropogenic emissions decline to zero. The climate module $\tau^{\mathbf{t}} = T(\mathbf{s^t})$ determines the average surface temperature increases $\tau^{\mathbf{t}}$ by determining the endogenous radiative forcings associated with a given sequence of carbon stocks in the atmosphere. It then traces out the implications of these endogenous forcings for the average temperature increases in the planet's surface and its lower oceans. Nordhaus (2013) contains a much more detailed discussion of all the components of the DICE model.

It remains to specify how geoengineering is implemented in the quantitative model. When it is used, geoengineering is first deployed in 2050 and maintained forever. In a scenario with an SRM technology, radiative forcings are reduced by a fixed amount, $1.75\,W/m^2$, in each period after 2050 by the application of the technology. There is little guidance in picking this value and I simply assume it. It is in line with the calibration in Emmerling and Tavoni (2013) for SRM.[11]

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[11] Royal Society (2009) notes that the technical potential of SRM in reducing solar forcings is unlimited. Consequently, without any direct or indirect costs associated with SRM in the model, it would be optimal to offset 100% of both endogenous and exogenous forcings so as to set $\tau_t = 0$.

In scenarios with CDR, the diffusion rate of carbon from the atmosphere to the upper oceans as well as its diffusion rate from upper to lower oceans increases by a given factor, namely 1.247. I obtain this value by targeting the average value of the cumulative CDR to 2100 in Table 1 of Socolow and Tavoni (2013). Loosely speaking, the assumed values of these parameters are neither too conservative, so as to make CDR and SRM appear unattractive, nor are they too Panglossian, so as to violate the technological potential of the technologies discussed in Lenton and Vaughan (2009).

The parameters of the quantitative model are summarized in Table 4. I solve the model in Matlab using a time horizon of 125 model periods corresponding to 625 years.[12] The presentation below focuses on the first 50 periods but the full set of results is available upon request.

5 Results and discussion

5.1 Benchmark model results

Figure 3 presents the solution to the model using the benchmark parameters. The top panel shows the levels of investment and abatement from which it is possible to calculate all other endogenous variables. The lower panel emphasizes two which are of primary interest, namely climate change damages as a share of GDP and the total emissions which underlie those damages.

By construction, under BAU $\mu_t = 0$ for all t. The investment decision takes this into account and follows the non-monotonic pattern in the top left panel. The resulting sequence of investment is the result of two opposing forces: the desire to accumulate capital and the desire to minimize the impact of damages. In the benchmark calibration the economy is 'poor' initially and so the incentives to postpone consumption and increase investment are strong. Moreover, the damages are relatively low so that their effect on future marginal product of capital is minimal. Over time, the capital stock, and emissions along with it, increase rapidly so that the former incentive declines and the latter becomes stronger. Eventually the damages rise sufficiently so that high levels of investment which prevail early on are no longer optimal and investment is reduced.

Allowing the planner to choose abatement optimally in scenario OPT produces rather different results. Abatement starts at about 20% of emissions and steadily increases to 100% in 2170. The associated emissions peak in 2030 and imply that temperatures and damages reach their peak in the mid 22nd century at about 3 degrees Celsius and 2.4% of output, respectively. The behavior of investment is determined by the two opposing forces mentioned above, however, investment does not decrease by as much as it does under BAU thanks to abatement.

The scenarios BAU and OPT are familiar to most climate change researchers and little about the results presented are novel or surprising. The contribution of the current paper is in studying

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[12] Using a longer planning horizon has negligible influence on the results.

geoengineering in this otherwise standard setting. Accordingly, I next discuss the results in which CDR and SRM technologies are individually or jointly implemented, and where both investment and abatement are allowed to respond to their introduction.

Under scenario OPT+CDR, the rate at which carbon is removed from the atmosphere increases starting in 2050. As a consequence, the planner invests more and abates less because the higher emissions implied by these decisions cause fewer damages relative to the case without CDR. However, in the benchmark parametrization these changes are relatively minor.

When geoengineering takes the form of an SRM technology, and investment and abatement are allowed to respond optimally in OPT+SRM, the causal chain that links emissions to climate change damages is interrupted at a later stage. In this scenario, the carbon stock in the atmosphere decays at the same rate as in BAU and OPT, but the radiative forcings associated with it are partially offset to reduce temperature increases. The effects on investment and abatement are much greater because SRM relaxes the climate change constraint on the economy much more effectively than CDR does. When the environment features both CDR and SRM and the planner abates optimally, the effect of both technologies complement each other, although the results obtained are only marginally different from OPT+SRM.

Notice that abatement is lower and somewhat delayed in the scenarios which include geoengineering. This is shown in the top right panel of figure 3. However, it is still optimal to undertake substantial abatement. For example. the average abatement rate over the first 50 periods is 71.7% for OPT, 70.5% for OPT+CDR, 62.9% for OPT+SRM and 61.4% when both CDR and SRM are used. Even in the latter case, which features the smallest abatement effort, it is optimal to essentially eliminate all emissions by early the 23rd century. By comparison, under OPT, complete abatement starts 40 years earlier in 2170.

Having noted that it is welfare-improving to abate, it may be too strong to assume that the planner's abatement policy responds optimally to the exogenous deployment of geoengineering. If anything, the coordination problems which have so far precluded a strong global effort to contain the ever-increasing global emissions are likely to get worse with geoengineering. The scenarios considered in Figure 4 take an extreme position on this issue by assuming that like in BAU, $\mu_t = 0$ but geoengineering is deployed in the future as in Figure 3. Put differently, in the scenarios BAU+CDR, BAU+SRM and BAU+CDR+SRM, the world's 'response' to climate change is to wait for the deployment of geoengineering in the future. The figure also includes the results for BAU and OPT for reference. It is not surprising that damages are uniformly higher, and investment uniformly lower when compared to the corresponding geoengineering scenarios with optimal abatement.[13]

A less apparent pattern is worth highlighting in Figure 4. It is the fact that emissions under various

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[13] The investment increase in all scenarios without abatement, e.g. BAU, BAU+CDR, etc., in the second half of 2200s is the driven by the emissions-free backstop technology in period 2265. The discrete drop in emissions in this period slows down the increase in damages and improves the future marginal product of capital.

geoengineering scenarios are now higher than under BAU. This is the implication of a greater capital stock under geoengineering scenarios. It is an important point regarding non-temperature climate change damages because higher emissions, and the higher CO_2 concentrations which follow, imply greater non-temperature climate change damages relative to BAU.[14]

While these results highlight interesting dynamics, they are not readily informative regarding welfare under different scenarios. To this end, I use the results to calculate the EV in BAU consumption that would deliver the same utility as a given scenario. The results are provided in Table 5. For example, providing the BAU consumer with 0.43% more consumption in every period makes her indifferent between living under the BAU and OPT scenarios. Geoengineering is absent from both scenarios. The trade-off between these two scenarios is that in the former the abatement costs are zero but a relatively greater share of output is lost to climate change damages. In the latter, abatement costs are positive but damages are lower. Given the benchmark parametrization, it is welfare improving to undertake some abatement and reduce, but not eliminate, emissions.

Consider next the scenario BAU+CDR+SRM, where the EV is 0.80% of BAU consumption. This scenario forms a natural counterpart to OPT. Whereas there is no geoengineering and the planner makes the best use of the available abatement technology under OPT, under BAU+CDR+SRM there is no abatement but both geoengineering technologies are deployed, albeit exogenously and in the future.

It is important to be careful when interpreting the difference between these two quantities because the costs of geoengineering are not modeled. The absence of direct and indirect costs therefore makes geoengineering look more attractive than it is in reality. Put differently, while 0.43% is the net benefit of abatement, 0.80% is the gross benefit of geoengineering. To make this point more clearly it is helpful to define $\bar{C}$ as the difference between the EV of a given geoengineering scenario and that of scenario OPT. $\bar{C}$ can then be interpreted as the lower bound of geoengineering costs, also measured in EV of BAU consumption, which would make the technology generate a smaller present value of utility than that which is achievable by using abatement only. For the scenario BAU+CDR+SRM $\bar{C} > 0.37\%$ would render geongineering-only inferior to abatement-only.

Is 0.37% a large or a small number? In order to get a sense, one needs to compare it to a more familiar quantity, e.g. the total abatement costs under OPT when expressed as EV in BAU consumption. To this end, I construct a hypothetical consumption stream by adding the total abatement costs under OPT to the consumption stream under BAU and calculate the EV. The figure that emerges from this analysis is 0.21%. Accordingly, the unmodeled costs of geoengineering in BAU+CDR+SRM would have to be approximately 1.8 times as large as the total abatement costs under OPT for geoengineering-only to be inferior to abatement-only. When viewed in this light, 0.37% is a very large number. It is the motivation behind the paper's title.

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[14] The most prominent example is ocean acidification. Note that with a more effective CDR these damages need not materialize. However, Vaughan and Lenton (2011) argue that CDR is likely to make a difference only on century- or millennial time scales.

Table 5 provides the EV and $\bar{C}$ for the remaining scenarios. Notice that $\bar{C}$ is negative in the case of BAU+CDR, with the interpretation that the benefits of BAU+CDR are positive but lower than OPT. Under BAU+SRM however, the costs would have to be greater than 0.32% to imply greater net benefits. These figures are another way of illustrating the idea that SRM is a more effective way of relaxing the climate change constraint than CDR in the benchmark parametrization.

Not surprisingly, under scenarios where optimal abatement takes place in addition to geoengineering, the computed EVs are greater. However, one needs to keep in mind that the EV figures for the geoengineering scenarios now express the net benefits of abatement plus the gross benefits of geoengineering, and that the level of abatement, and consequently its costs and benefits, are lower in scenarios OPT+CDR, OPT+SRM and OPT+CDR+SRM.

In summary, three main conclusions emerge from this analysis. First, geoengineering reduces incentives to abate but does not eliminate them. Second, in the benchmark calibration SRM has a much greater impact on the dynamics of key macroeconomic variables because it has a quicker and greater impact on damages. Third, the direct and indirect costs of SRM, but not CDR, would have to be high for SRM to be less preferable to scenarios with abatement.

5.2 Sensitivity analysis

The purpose of this section is to discuss whether and how the conclusions described above change with the following aspects of the model:

- the level of the initial capital stock and the date at which geoengineering is deployed;
- the values of the rate of time preference (ρ); and the convexity of the damage function (ψ_3).

It turns out that the first and second conclusions above are not altered in ways that would call for a detailed discussion. As a consequence, below I focus on how $\bar{C}$ is affected in each case.

5.2.1 A lower initial capital stock and/or an earlier arrival of geoengineering

In the benchmark model the incentive to accumulate capital is driven by the low initial capital stock relative to the long run equilibrium, i.e. $k_0 = 0.5k_\infty$. k_0 also measures how well off the world is in period 0. By starting the economy off with a $k_0 = 0.25k_\infty$ and holding all else constant, I study how the incentives facing developing and advanced countries may be different with respect to geoengineering.[15] Obviously, this is a crude approximation to a complex problem. A lower k_0 in the model means the whole world is considered to be less developed, rather than only a subset of countries. In reality, countries with significantly different capital stocks coexist today and

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[15] With a lower initial capital stock the initial emission intensity σ_0 needs to be recalibrated to match the 2015 emissions.

strategically interact with each other in ways that are relevant for the question at hand. Moreover, the difference between developing and advanced countries is reduced to a single dimension only, and all other crucial differences, e.g. in total factor productivity, production and abatement technologies, endowments, vulnerability to climate change etc., are suppressed.

Table 6 reports the results for scenarios OPT, BAU+CDR+SRM and OPT+CDR+SRM. The top right panel corresponds to the parametrization with a lower k_0. In each scenario, the EV is measured relative to the BAU consumption consistent with the lower k_0. The results from the benchmark model are in the top left panel for ease of comparison.

With a lower k_0, the benefits of abatement and geoengineering are higher. This happens because as the economy grows towards its long run equilibrium, it emits more relative to the benchmark model. In particular, emissions grow faster early on, and peak at a higher level in the economy with a lower k_0. As a consequence, the technologies which can limit the damages associated with these greater emissions, be it abatement or geoengineering, become relatively more valuable.

Notice also that $\bar{C}$ associated with BAU+CDR+SRM is smaller with a lower k_0. To gain some intuition as to what this means, suppose the planner had access to accurate information about the level of direct and indirect costs of geoengineering and that these costs were independent of the initial capital stock. Also suppose she can make the once-and-for-all choice at time 0 between scenarios OPT and BAU+CDR+SRM. Then for a wide range of geoengineering costs it is conceivable that she chooses the latter in the benchmark, while in the parametrization with a lower k_0 she picks the former. This happens because under benchmark parameters the BAU consumption profile is higher and the benefits generated under BAU+CDR+SRM can be expressed as a greater share of this profile, i.e. $\bar{C}$.

Next, I turn to the comparison of results under scenarios OPT and OPT+CDR+SRM, where $\bar{C}$ is slightly greater with a lower k_0. Here there is a much smaller range of geoengineering costs for which one scenario would be preferable over the other. In other words, when abatement is allowed to respond optimally to geoengineering and assuming a given set of geoengineering costs, the value of the two scenarios are approximately the same regardless of where the economy starts from.

These observations suggests that for a given set of costs, geoengineering can be relatively more attractive in a world which has a greater capital stock to start when abatement is restricted to 0. But how does this result depend on the exogenous arrival date of the technology? A crucial difference between these alternative ways to respond to climate change in the model is that abatement is available at all times but geoengineering becomes available only in 2050. As a consequence, any change that increases the value of addressing the climate change externality in the model, such as a lower k_0, favors the use of abatement.

The bottom left panel of Table 6 takes a closer look at this issue and reports the results under the assumption that geoengineering is available in 2025 rather than 2050. It is obvious that this increases the gross benefits of geoengineering and $\bar{C}$ substantially, but implies no change to abatement costs under OPT. After all, in the model, geoengineering is a pure stream of benefits with no associated costs, so starting to receive these benefits earlier is strictly better. What is more interesting is the interaction between the arrival date and initial capital stock. The results are provided in the lower right panel of the table. They confirm the intuition provided in the preceding paragraphs. Specifically, faced with the choice under the same cost structure but with geoengineering arriving earlier, the planner now would find the geoengineering-only scenario much more tempting regardless of the initial capital stock or whether abatement is restricted to zero or optimal. This is due to the difference in $\bar{C}$s in the top left and bottom right panels which are now dominated by the early arrival of geoengineering.

5.2.2 Crucial parameters

I follow a simple strategy to study the sensitivity of results to parameters whose true values have been the subject of much debate in the literature. For each of the rate of time preference (ρ) and the convexity of the damage function (ψ_3) I chose a reasonably broad range that has been discussed in the literature. While doing so I hold all other parameters fixed at their benchmark values in Table 4. The alternative parameter values I use to solve the model are given in Table 7. That is, in this exercise there are 10 states of the world, and in each of them only one parameter is varied relative to the benchmark.

The analysis uses Figures 5 and 6 to demonstrate the sensitivity of $\bar{C}$ when a given parameter is varied. In each of these figures the top, middle and bottom panels show the results for geoengineering scenarios with CDR, SRM and CDR+SRM respectively, and solutions associated with the benchmark parameters are identified with a vertical line.

The best way to read these figures is as follows: recall from Table 5 that $\bar{C}$ is positive under the benchmark parametrization for all scenarios except BAU+CDR. That is, if geoengineering were a costless technology, it would generate additional net benefits equal to $\bar{C}$ in these scenarios. Similarly, the negative value for $\bar{C}$ in BAU+CDR indicates that where, even with costs unmodeled, CDR without abatement generates fewer net benefits than optimal abatement. Accordingly, if $\bar{C}$ for a given scenario switches signs, I conclude that the results are sensitive with respect to that parameter.

For the parameters considered in this section, one observes a negative $\bar{C}$ for three states of the world which feature a positive $\bar{C}$ under the benchmark parameters. All of these are associated with scenarios in which no abatement takes place (i.e. the only response to climate change is to wait for geoengineering). To be clear, in each of these instances welfare is greater than under BAU but not as high as it could be if there were no geoengineering but the planner undertook optimal abatement.

Starting with rate of time preference in Figure 5, the bottom two panels show that if the rate of time preference is lower than in the benchmark, BAU+SRM and BAU+CDR+SRM result in negative values of $\bar{C}$. Note that although damages are lower in these two scenarios immediately following the deployment of geoengineering, there is no abatement so emissions eventually generate greater damages.[16] With a smaller rate of time preference, these greater future damages eventually reduce consumption so that $\bar{C}$ is negative. In other words, if the planner could choose between two scenarios, one with optimal abatement and no geoengineering and the other with geoengineering and no abatement, she would be more likely to choose the former if the rate of time preference were lower.

When ψ_3 increases and the damage function becomes more convex, $\bar{C}$ becomes negative for BAU+SRM. Once again this is intuitive and is driven by the damages associated with the unabated emissions in these scenarios. Taken together these results suggest that the temptation to deploy geoengineering may not be high as the paper's title suggests, particularly when the rate of time preference is low or the damage function is more convex.

6 Limitations and conclusion

There are a number of limitations of this approach to studying the economic implications of geoengineering. Assuming geoengineering is an exogenous, binary and permanent feature of the model is restrictive. In the real world one would expect investment in geoengineering research and development to be a crucial determinant of when, and the extent to which, the technology is deployed. Although there exist arguments which suggest it would be difficult to stop a geoengineering program once it starts, it can be interrupted or terminated if large unexpected costs materialize. To add a further layer of complication, the decision to deploy or terminate a geoengineering program will be taken in a world of heterogeneous countries which interact with each other strategically regarding the response to climate change as well as many other economic and political issues. By assumption, these margins are excluded from the simple model studied here.

The absence of uncertainty from the model is also an important limitation. The way that the geophysical processes, and the geoengineering interventions in them, are introduced are both deterministic and simple. In light of the many risky and ambiguous aspects of the climate-economy-geoengineering interaction, the deterministic model here may paint too rosy a picture regarding geoengineering.

This conjecture is also true more generally regarding the limitations mentioned above and is partly by design. By abstracting from the direct and indirect geoengineering costs, as well as considerations which would amplify them, the deck is stacked in favor of geoengineering. Against this backdrop, the main contribution of the paper is in quantifying the benefits of geoengineering using a suitably modified one-sector growth model with climate-economy interaction. These benefits can

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[16] See lower left panel of Figure 4 for intuition.

in turn be interpreted as the lower bound for costs which, if realized, would make a world with geoengineering less preferable to the world where optimal abatement is undertaken.

On the one hand, the results suggest that the costs of geoengineering would have to be large for SRM technologies not to be tempting. On the other hand, CDR technologies would have to become much more effective to be a meaningful tool in responding to climate change. In all cases substantial abatement is optimal when responding to climate change. As a consequence, while geoengineering may be tempting, it is also a poor substitute for traditional abatement.

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Tables

Table 1: Key functions and assumptions

Function	**Description**	**Assumption**
$U(c_t)$	Utility function	$U^{'} > 0$; $U^{''} < 0$; $\lim_{c \to 0} U^{'}(c) = \infty$; $\lim_{c \to \infty} U^{'}(c) = 0.$
$\Lambda(\mu_t)$	Abatement cost function	$\Lambda^{'} > 0$; $\Lambda^{''} > 0$; $\Lambda(0) = 0$
$D(\tau)$	Damage function	$D^{'} > 0$; $D^{''} > 0$; $D(0) = 0$
$F(k)$	Production function	$F^{'} > 0$; $F^{''} < 0$; $\lim_{k \to 0} F^{'}(k) = \infty$; $\lim_{k \to \infty} F^{'}(k) = 0.$
$T(\mathbf{s^t})$	Climate system	$\frac{\partial T_{t+k}}{\partial s_t} > 0$ for all $e_t \in \mathbf{e^t}$, $t \geq 0$ and $k = 1, 2...$
$S(\mathbf{e^t})$	Carbon cycle	$\frac{\partial S_{t+k}}{\partial e_t} > 0$ for all $s_t \in \mathbf{s^t}$, $t \geq 0$ and $k = 1, 2...$
SRM	Indicator function for SRM technology	$SRM \in \{0, 1\}$
CDR	Indicator function for CDR technology	$CDR \in \{0, 1\}$

Table 2: Scenarios regarding geoengineering

Scenario	**Abatement** (μ_t)	**CDR?**	**SRM?**
BAU	Constrained ($\mu_t = 0$)	No	No
OPT	Optimally chosen	No	No
OPT+CDR	Optimally chosen	After 2050	No
OPT+SRM	Optimally chosen	No	After 2050
OPT+CDR+SRM	Optimally chosen	After 2050	After 2050
BAU+CDR	Constrained ($\mu_t = 0$)	After 2050	No
BAU+SRM	Constrained ($\mu_t = 0$)	No	After 2050
BAU+CDR+SRM	Constrained ($\mu_t = 0$)	After 2050	After 2050

Notes: In all scenarios investment is chosen optimally.

Table 3: Effect of geoengineering on damages

CDR	SRM	**Carbon cycle**	**Climate System**	**Damages**
0	0	$S(\mathbf{\hat{e}})$	$T(S(\mathbf{\hat{e}}))$	$\mathbf{d_{00}}$
1	0	$\tilde{S}(\mathbf{\hat{e}})$	$T(\tilde{S}(\mathbf{\hat{e}}))$	$\mathbf{d_{10}} \leq \mathbf{d_{00}}$
0	1	$S(\mathbf{\hat{e}})$	$\tilde{T}(S(\mathbf{\hat{e}}))$	$\mathbf{d_{01}} \leq \mathbf{d_{00}}$
1	1	$\tilde{S}(\mathbf{\hat{e}})$	$\tilde{T}(\tilde{S}(\mathbf{\hat{e}}))$	$\mathbf{d_{11}} \leq \mathbf{d_{00}}, \mathbf{d_{10}}, \mathbf{d_{01}}$

Notes: All scenarios feature the same underlying emissions sequence $\mathbf{\hat{e}} = \{e_0, e_1, e_2...\}$. Climate change damages are given by $d = D(\tau)$. The indexes of $\mathbf{d_{00}}$ refer to whether or not CDR and SRM are active in a given scenario, respectively. All inequalities in the final column are strict for $t > t^*$. That is, $\mathbf{d^*_{00}} > \mathbf{d^*_{10}}$ where $\mathbf{d^*_{xx}} = \{d^{xx}_{t^*+1}, d^{xx}_{t^*+1}, d^{xx}_{t^*+2}, ...\}$.

Table 4: Parameters of the quantitative model

Parameter	**Description**	**Value**	**Source/Note**
η	Elasticity of substitution of MU	1.45	DICE-2013R
ρ	**Rate of time preference (annual)**	$0.15 \Rightarrow \beta = \frac{1}{1+0.015}$	**DICE-2013R**
α	Capital share in production	0.3	DICE-2013R
δ	Depreciation rate (annual)	0.1	DICE-2013R
A_0	Initial TFP	1	Normalization
g_A	TFP growth rate (annual)	0.758%	Target DICE-2013R analogue
θ_{10}	Initial abatement cost coefficient	0.043	Target μ_{2015}^{opt}in DICE-2013R
g_θ	Abatement costs growth rate	-6.5%	Target DICE-2013R analogue
θ_2	Abatement cost exponent	2.8	DICE-2013R
σ_0	Initial emission intensity	53.7	Target e_{2015}^{bau} in DICE-2013R
g_σ	Intensity growth rate	-4.5%	Target DICE-2013R analogue
ψ_1	Damage function coefficient	0	DICE-2013R
ψ_2	Damage function coefficient	0.00267	DICE-2013R
ψ_3	**Damage function exponent**	**2**	**DICE-2013R**
k_0	**Initial capital stock**	**0.2143**	**Half of implied** k_∞
$\{s_0^{at}, s_0^{up}, s_0^{lo}\}$	Initial carbon stocks	{880.4,1555.210010.9}	DICE-2013R in 2015
τ_0^{at}, τ_0^{lo}	Initial temperatures	{0.93; 0.0274}	DICE-2013R in 2015
CS	Climate sensitivity	2.9	DICE-2013R
t^*	**Geoengineering arrival date**	7	**Assumed as 2050.**
λ^{CDR}	Factor change in diffusion rates	1.247	Assumed
λ^{SRM}	Reduction in radiative forcing	-1.75	Assumed

The parameters in the rows in bold are varied in Section 5.2.

Table 5: Welfare and costs of geoengineering in the benchmark model

	No Abatement		**Optimal Abatement**		
	EV	$\bar{C}$	**EV**	$\bar{C}$	
BAU	na	na	0.43%	na	**OPT**
BAU+CDR	0.08%	*-0.35%*	0.47%	*0.04%*	**OPT+CDR**
BAU+SRM	0.75%	*0.32%*	1.00%	*0.57%*	**OPT+SRM**
BAU+CDR+SRM	0.80%	*0.37%*	1.03%	*0.60%*	**OPT+CDR+SRM**

$\bar{C}$ is the difference between $EV_X - EV_{OPT}$ where $X = BAU + CDR, ...OPT + CDR, ...$. It acts as a measure of the lower bound of geoengineering costs which would make the technology generate a smaller present value of utility than that under OPT.

Table 6: The implications of lower k_0 and earlier arrival of geoengineering

	Benchmark k_0		**Lower** k_0		
	EV	$\bar{C}$	EV	$\bar{C}$	
OPT	0.43%	-	0.57%	-	**Benchmark arrival (2050)**
BAU+CDR+SRM	0.80%	0.37%	0.88%	0.31%	
OPT+CDR+SRM	1.03%	0.60%	1.18%	0.61%	
OPT	0.43%	-	0.57%	-	**Earlier arrival (2025)**
BAU+CDR+SRM	1.08%	0.65%	1.17%	0.60%	
OPT+CDR+SRM	1.28%	0.85%	1.44%	0.87%	

Table 7: Alternative parameter values for sensitivity analysis

Parameter	**Description**	**Value used in sensitivity analysis**
ρ	Discount factor (annual)	{0.001,0.005,0.01,**0.015**,0.02}
ψ_3	Damage function exponent	{1.0;1.5;**2.0**;2.5;33.0}
k_0	Initial capital stock	0.25
t^*	Geoengineering arrival date	2

Bold indicates the benchmark parameter value.

Figures

Figure 1: Model schema

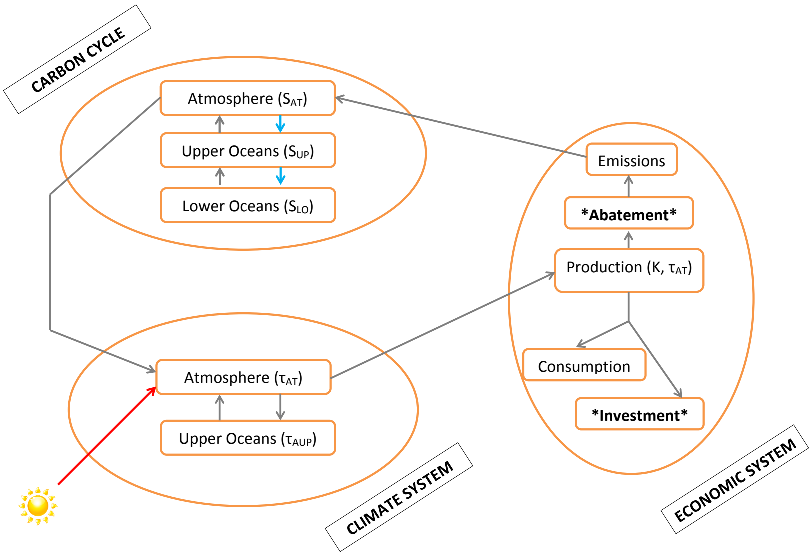

Figure 2: Geoengineering and climate change damages

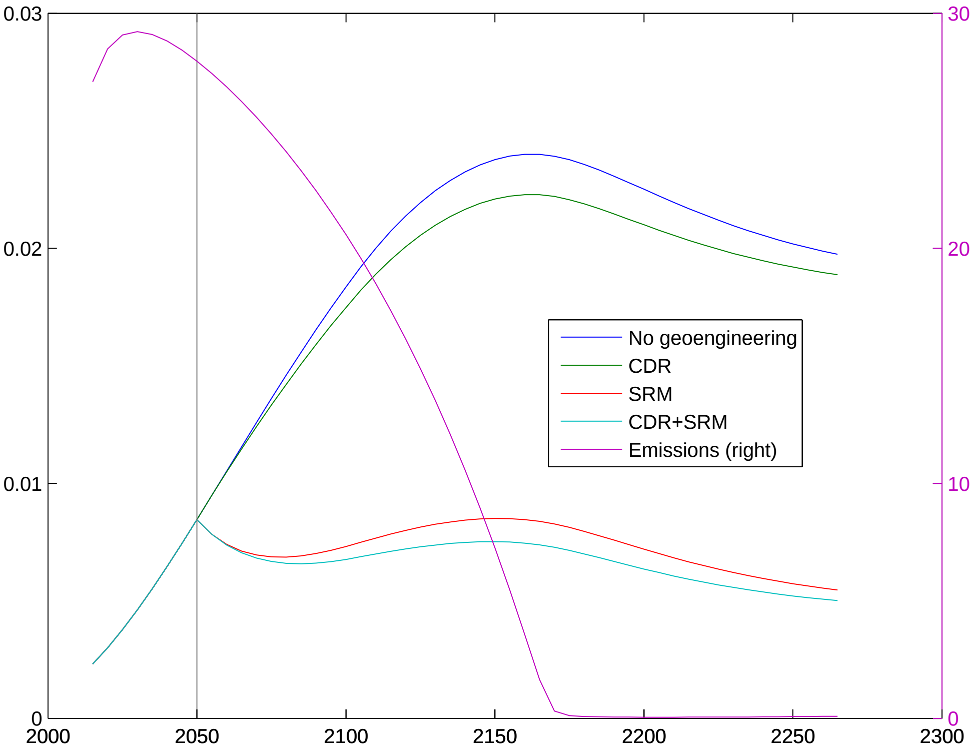

Figure 3: Benchmark results

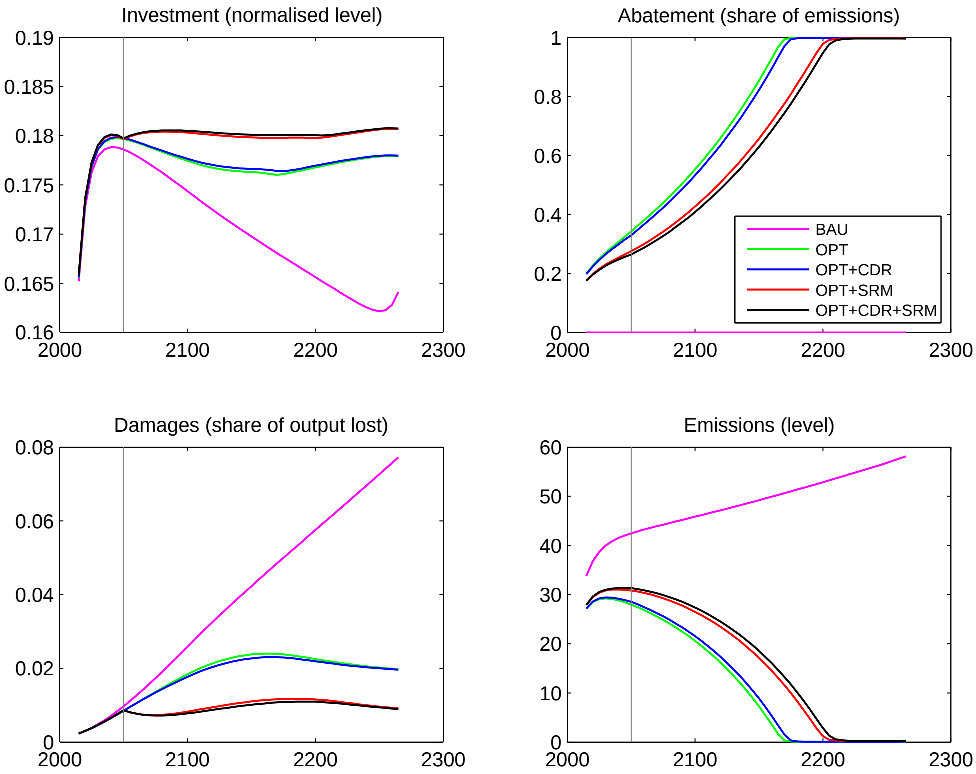

Figure 4: Benchmark results with constraint $\mu_t = 0$

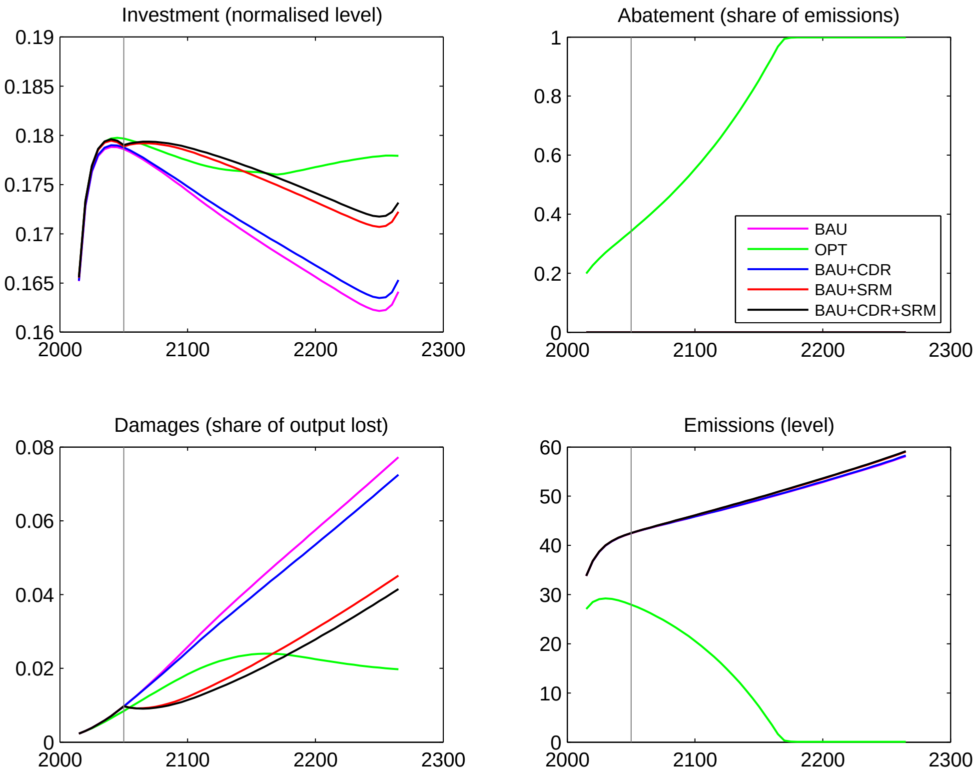

Figure 5: Sensitivity of $\bar{C}$ with respect to ρ

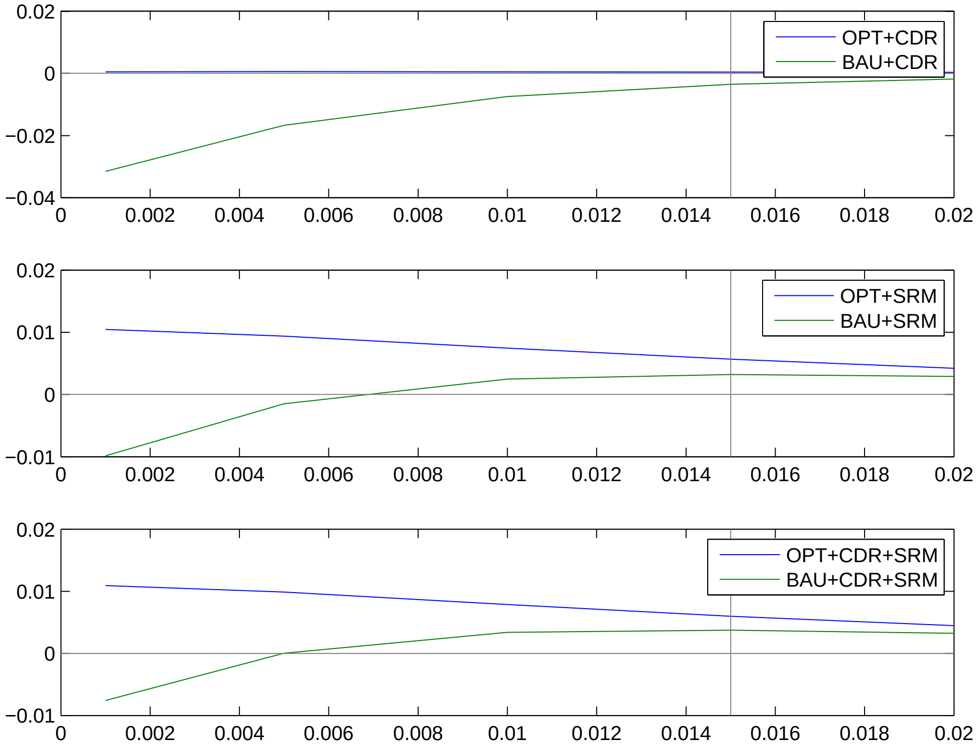

Figure 6: Sensitivity of $\bar{C}$ with respect to ψ_3