Geoengineering and abatement: a 'flat' relationship under uncertainty*

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Abstract

The potential of geoengineering as an alternative or complementary option to mitigation and adaptation has received increased interest in recent years. The scientific assessment of geoengineering is driven to a large extent by assumptions about its effectiveness, costs, and impacts, all of which are highly uncertain. This has led to a polarizing debate. This paper evaluates the role of Solar Radiation Management (SRM) on the optimal abatement path, focusing on the uncertainty about the effectiveness of SRM and the interaction with uncertain climate change response. Using standard economic models of dynamic decision theory under uncertainty, we show that abatement is decreasing in the probability of success of SRM, but that this relation is concave and thus that significant abatement reductions are optimal only if SRM is very likely to be effective. The results are confirmed even when considering positive correlation structures between the effectiveness of geoengineering and the magnitude of climate change. Using a stochastic version of an Integrated Assessment Model, the results are found to be robust for a wide range of parameters specification.

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1 Introduction

The slow progress in climate change mitigation policies aimed at reducing greenhouse gas emissions has fueled the discussion about alternative policy options in order to cope with the impacts from climate change. In particular, geoengineering (GE) options which either remove carbon dioxide from the atmosphere (carbon dioxide removal or CDR) or counteract the temperature increase by managing incoming solar radiation (Solar Radiation Management or SRM[1]) have been proposed and become increasingly debated over recent years.

These two geoengineering options differ fundamentally in terms of costs and effectiveness. While CDR strategies tend to be costly and slow in terms of temperature response [38], Solar Radiation Management has been argued to be a more cost-effective solution since it can reduce the effects of global warming relatively quickly [34, 19] and hence provides a potential game-changing option for climate policy [37, 43]. In this paper we focus on the latter geoengineering option of SRM and in particular we consider the most widely discussed strategy of reducing solar radiation through stratospheric aerosols, although our formulation is sufficiently generic to represent a broader set of SRM strategies. The reduction in solar radiation after volcanic eruptions have provided natural "experiments" as a basis for this strategy. For instance, in 1991, the eruption of Mount Pinatubo led to the injection of including around 20 megatons of sulfur dioxide into the stratosphere leading to a decrease of global temperatures of about 0.5°C in the years after the eruption [35]. This illustrates the potential power of reducing the global temperature through the periodic and continued injection of sulfate particles, or aerosols, into the lower stratosphere. The extent to which SRM can compensate the radiative forcing of greenhouse gases and the associated climate damages is still debated; the most recent literature suggests that SRM cannot reverse climate change [29], but that it has the potential to compensate temperature and precipitation patterns even regionally (though not simultaneously) [25, 7]. On the other hand, this technology brings about substantial risks such as ozone depletion, side effects of the implementation itself [32], as well as region-specific impacts such as increased droughts in the Sahel region [15]. Moreover, it does not reduce damages from increased CO_2 concentration such as ocean acidification, and once implemented, it could not be suddenly discontinued as otherwise an abrupt temperature is likely to happen [6].

[1] In this article, we will use the terms Solar Radiation Management (SRM) and geoengineering (GE) interchangeably.

One common feature of geoengineering is that it tends to be speculative. First of all, no (large-scale) experiments have been conducted in order to assess the full potential to counteract global warming. Second, the implementation is challenging in many respects. And even if geoengineering could have the desired effect on the climate and were technically feasible to implement, virtually nothing is known about potential side effects along many dimensions. Still, geoengineering appears appealing notably facing potentially high costs of mitigation of climate change and the political difficulties in climate policy negotiations. In particular, given the general uncertainties about the expected temperature change and the magnitude impacts in the future, it has been argued tit can provide a valuable option for a situation where climate change turns out to be extremely costly. Apart from the scientific and economic uncertainties, ethical considerations, moral issues regarding the manipulation of the climate, and issues in international law regarding unilateral actions in this field provide a strong barrier towards even proceeding in research in this field.[2] It is therefore save to say that if ever it would be considered as an option, it will take decades if not more before a great deal of the surrounding uncertainties could be resolved, see also the recent contributions of Robock, MacMartin, Duren, and Christensen [31].

Notwithstanding the challenge of modeling geoengineering, the literature examining it has been growing exponentially in the most recent years [22]. Economists have contributed to the debate about risks and virtues of geoengineering, unsurprisingly finding mixed results, see Klepper and Rickels [17] for an overview. On the one hand, geoengineering can provide a viable strategy and might be the lesser of two evils in particular if climate change might be very harmful in the future [3]. On the other hand, geoengineering itself would come with highly uncertain but potentially high costs in terms of potential damages and its unknown effectiveness in the long run, so that it might look too costly at least at the current state of knowledge as to give up on emissions reductions and rely on geoengineering for the future, see e.g. the applications of Nordhaus' DICE model in Gramstad and Tjøtta [14] or Goes, Tuana, and Keller [13]. The fundamental driver of the divergence of opinion in this polarizing debate reside in the assumptions about relative costs, damages, and the uncertainty about the parameters characterizing SRM [36]. However, very few papers have provided an explicit modeling of the uncertainty of geoengineering, with

[2]The cancellation of the Stratospheric Particle Injection for Climate Engineering (SPICE) project in 2012 provides an example of the difficulties research faces in this field including due to public opinion or the governance of such projects.

the exception of Moreno-Cruz and Keith [24]. Their paper is probably most related to this one as they consider the dynamic decision problem using a simplified model and a numerical implementation based on DICE with convex mitigation and linear GE cost functions. Their numerical results suggest that the lower the side-effects of GE and the higher its effectiveness, the lower will be the mitigation effort in the first stage. Moreover, GE will be more likely to be used if the climate sensitivity is going to be higher. This illustrates the insurance effect of geoengineering. Their results, however, are purely numerically based on a simple integrated assessment model. Moreover, they do not investigate the impact of the correlation between climate and geoengineering uncertainties.

Our paper aims at advancing this thin literature by focusing explicitly on the uncertain features of GE. We study the role of the uncertainties surrounding geoengineering and climate change as a whole to see whether geoengineering could or should be used in the future and under which conditions and how it could shape climate change policies today. We analyze how much of the near term optimal abatement should be carried out for different subjective probabilities of success of a large scale geoengineering program in the future, and for different correlation structures with the overall uncertainty about climate change. Our paper uses standard models of dynamic decision theory under uncertainty to analyze what conditions of the geoengineering option can be derived from an economic perspective. We first introduce a two-period model of abatement and geoengineering, where the latter is only available in the second stage and with uncertainty characterizing both the uncertainty of GE as well as the climate, and derive a complex but innovative analytical solution under both a cost effectiveness (CEA) and cost benefit framework (CBA). We show that under fairly general conditions, today's mitigation effort is decreasing but concave in the probability of success of geoengineering. As a result, current abatement is significantly reduced only under very optimistic assumptions about geoengineering. We also investigate the potential insurance effect of GE using a copula approach to model the relationship between the uncertainty about climate response and geoengineering, and are able to confirm the results for reasonable correlation structures between the climate and the effect of geoengineering. An "insurance" effect of GE arises only if the relatedness between GE becoming effective and severe impacts from climate change is very high and moreover if the probability of GE becoming a viable option is sufficiently large.

In order to quantify the effects of the analytical results, we use a stochastic programming version of a large scale integrated assessment model with a rich description of the mitigation strategies, integrating the possibility of geoengineering as an alternative policy option to mitigation, which becomes available in the future with a certain probability. The numerical results confirm the theoretical results in that we find that the optimal path of does not deviate too much from the standard optimal abatement path as long as the probability of geoengineering being implemented and effective is not very close to one. If we consider a fixed climate stabilization target, the optimal abatement becomes even stronger prior to the resolution of uncertainty. The results are found to be robust to different timing of resolution of uncertainty, different climate stabilization targets, and different level of comononicity of the climate and geoengineering random variables. From a policy perspective, our results suggest that uncertainty provides a strong argument for abatement as opposed to a "wait and see" policy relying on potential large scale geoengineering in the future, but does not rule out the possibility of deploying geoengineering in the future.

This paper is structured as follows. We first present the general model considering only uncertain effectiveness of geoengineering in both in a in a CEA and CBA framework. In section three, we allow for simultaneous uncertainty about climate change as well as GE. Using the integrated assessment model WITCH, we provide a quantitative assessment of geoengineering in section four. Section five concludes.

2 Unknown effectiveness of geoengineering

We begin by sketching out a simple analytical framework which captures the interplay between GE and abatement in sufficiently general terms. We model SRM geoengineering as an uncertain process: as of today we do not know how effective it will be in substituting mitigation to control global warming. While mitigation of climate change can be implemented already now, as noted above the limited evidence on the risks and impact of GE are such that considerate amount of time will be needed to establish the scientific background in order to implement large scale geoengineering. The question we try to answer in this chapter is how this uncertainty affects our decision today to mitigate climate change. Moreno-Cruz and Keith [24] have highlighted the uncertainty and its importance for the optimal decisions about the implementation of geoengineering. They argue that even if geoengineering is potentially not very effective in offsetting global warming caused by CO_2 emissions, it might considerably shape climate change policies due to the comparably quick response geoengineering policies imply.

We use a simple model to analyze this question aiming at deriving some general conclusions which economic theory can give as guidance in this polarizing debate. Empirical calibration and specific assumptions will ultimately determine the best guess estimates of the potential crowd out between the two competing climate strategies, and we tackle this with the numerical integrated assessment model. The aim of this section is to test whether using general functional forms something can be said about the trade-off between geoengineering and abatement under uncertainty. This is a novel contribution to the literature.

In a simple two period setup, denote by A_t the level of abatement in period $t = 1, 2$ and by G the level of geoengineering that will be implemented only in the second period since it is not available as a large scale alternative today. Therefore we will solve the model backwards starting in period two.

In order to simplify notation, we will express all variables in terms of their radiative forcing potential (as e.g., in Moreno-Cruz and Keith [24]). In a simple energy balance model, the changes in the global mean temperature ΔT are a linear function of radiative forcing R: $\Delta T = \lambda R$ where λ denotes the climate sensitivity, typically considered to be around $0.8\frac{K}{W/m^2}$. We denote by S^{bau} the business-as-usual radiative forcing from CO_2 emissions and express abatement A_t in the same units. Since the global temperature increase can also be approximated as a linear function of cumulative emissions Matthews, Gillett, Stott, and Zickfeld [20], the final temperature increase can be written as a linear function of $S^{bau} - A_1 - A_2$.[3] Similarly we measure geoengineering G in terms of its radiative forcing potential; we also take into account that its effectiveness is not perfect and moreover uncertain and its effect on effective radiative forcing can be expressed by the random variable $\widetilde{\varphi}$ with support $\left[\underline{\varphi}, \overline{\varphi}\right]$. Overall, the increase of global mean temperature can then be written as:

$$\Delta T = \lambda(S^{bau} - A_1 - A_2 - \widetilde{\varphi}G).$$

2.1 Cost Effectiveness Analysis (CEA)

For the case of a climate stabilization policy, we specify a ceiling in terms of maximum temperature increase over pre-industrial periods ΔT^{max}, which can be directly converted into a goal in terms of maximum radiative forcing for a given value of climate sensitivity. The Social Planner then minimizes the cost of attaining this stabilization goal of the induced change in world average temperature. The cost

[3] The authors find a linear response of temperature to cumulative emissions in trillion tons of carbon emitted of 1.0 – 2.1°C/TtC. In our model, scaling λ and $\widetilde{\varphi}$ appropriately would allow to calibrate the model to these values.

functions of mitigation and geoengineering are assumed to be increasing, convex, and three times differentiable. The total cost of achieving the target can be written as $V(A_1, A_2, G) = C_A(A_1) + \beta \left(C_A(A_2) + C_G(G)\right)$ where β denotes the discount factor and hence the problem of a risk-neutral social planner can be stated as follows:

$$\min_{A_1,A_2,G} E\left[C_A(A_1) + \beta\left(C_A(A_2) + C_G(G)\right)\right] \;\; s.t. \;\lambda(S^{bau} - A_1 - A_2 - \tilde{\varphi}G) \leq \Delta T^{max} \tag{1}$$

The cost function $C_A(A)$ are the standard cost functions of abatement whereas $C_G(G)$ is the cost function of geoengineering. It is noteworthy to stress that while we do not include potential damages from geoengineering, they could be easily included and would simply increase the cost of geoengineering. While we don't impose any functional forms, we need to make some basic assumption about the relative costs of abatement and geoengineering. Throughout the paper, we deliberately take an optimistic view about the costs of GE vis à vis with abatement. We assume that -if successful- GE will be cheaper than mitigation, for every level of abatement. This is motivated by the literature which portrays GE as a climate strategy with 'incredible economics' [2]. In reality, though, the risks and impacts associated with GE, as well as the public opposition and the difficult governance process, are likely to limit GE to meet only a fraction of the climate solution space. Our analytical framework captures this by depicting GE as an uncertain process: as defined above, the probability of success of GE can be interpreted as its effectiveness as a substitute for abatement. This characterization of GE allows us to explore a 'limiting' case which provides an important benchmark which is extended in the numerical analysis which follows in the paper: in particular, most of the results we find here would be -if at all- strengthened by assuming a more pessimistic view of GE.

Since we express all variables in its potential to limit the increase of forcing generated by the CO_2 stock in the atmosphere,we assume that abatement is in general more costly per unit. In particular, we impose that if geoengineering is effective, or that $\tilde{\varphi} = \overline{\varphi}$, it will be the only policy that will be employed in the second stage. Formally, this can be ensured by assuming that marginal cost of geoengineering are never higher than the initial marginal abatement cost.

Assumption 1. $C'_G(x) \leq C'_A(x) \; \forall x$

With the assumption that there are no fixed costs ($C_A(0) = C_G(0) = 0$), this ensures that $C_G(x) \leq C_A(x) \; \forall x$. Since we are assuming that in the last period only one policy alternative will be used, we strengthen it to assume $C'_G(x) \leq C'_A(0)\ \forall x$, which is sufficient for the analysis below. Based on estimates of abatement policies compared with cost estimates of geoengineering implementation such as McClellan, Keith, and Apt [21], this assumption seems reasonable. Moreover, we will consider the case in which geoengineering will either be completely effective or not be feasible at all, i.e., we assume that $\tilde{\varphi}$ can take on values of $\overline{\varphi}$ (with probability p) or $\underline{\varphi}$ (with probability $1-p$).[4] By Assumption 1, this ensures that if geoengineering turns out to be most effective, it will be the strictly preferred policy to rely on while if it is the least effective, it will never be used. Moreover the effectiveness of geoengineering is learned before the second period's decision.

With regard to the total expected cost of attaining the stabilization goal it is clear from (1) that an increase in the probability of success of geoengineering reduces the expected costs. In this sense, geoengineering can be seen as an alternative option in the portfolio of actions against climate change which has a strictly positive effect in this stylized model.

Given that the second period's decision is either abatement or geoengineering, we can rewrite $E_{\varphi}V(A_1, A_2, G)$ and get the first order condition of the program (1) as

$$C'_A(A_1^*) = \beta \left(pC'_A(S^{gap} - A_1^*) + (1-p)C'_G(S^{gap} - A_1^*)\right)$$

and the second order condition as

$$D_{CEA} \equiv C''_A(A_1^*) + \beta \left(pC''_G(S^{gap} - A_1^*) + (1-p)C''_A(S^{gap} - A_1^*)\right) > 0$$

where $S^{gap} = S^{bau} - \lambda \Delta T^{max}$ represents the forcing reduction needed to meet the temperature objective.

By totally differentiating the first order condition and using the second order condition we immediately find that the optimal level of abatement in the first period is decreasing in the probability p of success of GE or that $A_1^{*\prime}(p) < 0$ if Assumption 1 holds[5].

That is to say, a more likely effective geoengineering program does reduce abatement today. This result is not surprising given the assumed substitutability between

[4]In the following we will simply assume that $\overline{\varphi} = 1$ in order to simplify notation. One could however rephrase the formulation with a general value for $\overline{\varphi} < 1$, in which case the clear distinction between abatement and geoengineering policies needs to strengthen assumption 1 by additionally imposing that $\frac{1}{\underline{\varphi}}C_G(x) < C_A(x) < \frac{1}{\overline{\varphi}}C_G(x)\ \forall x$.

[5]Note that this would hold even in the case in which both GE and abatement are used in the second period.

both policies, and confirms the results of Moreno-Cruz and Keith [24]. What is more important for the sake of this paper, however, is to explore how effective geoengineering would need to be to reduce today's abatement efforts considerably. To that end, we need to understand the curvature of the function $A_1^*(p)$. To that end, we impose the following assumption which will be discussed below:

Assumption 2. *The marginal total welfare loss by increasing today's abatement above optimal* $h(A_1) \equiv C_A'(A_1) - \beta[pC_G'(S^{gap} - A_1) - (1-p)C_A'(S^{gap} - A_1)]$ *is convex or less concave than the difference between abatement and geoengineering costs in the second period* $g(A_1) = C_A(S^{gap} - A_1) - C_G(S^{gap} - A_1)$*, in the sense that* $\frac{h''(x)}{h'(x)} > 2\frac{g''(x)}{g'(x)}$.

The cost gap between geoengineering and abatement in the second period $g(A_1)$ is always decreasing in first-period abatement if Assumption 1 holds since the amount of abatement or SRM is reduced. Moreover, it is concave given that the cost function of abatement is steeper than that of geoengineering, $(C_G'(x) \leq C_A'(x))$. Function $h(A_1)$ on the other hand is always increasing due to the second-order condition; it is also very likely to be more concave than $g(A_1)$ based on the fact that the first-order condition is given by $h(A_1) = 1$ if we assume the local optimum is a global one.

Thus, for all specifications we applied numerically (quadratic and several power specifications), Assumption 2 is always satisfied. While a characterization based only on the primitives of the problem would be preferred, this condition can thus be considered rather weak and is satisfied by standard cost functions applied in this context. We are now able to state our first main result.

Corollary 1. *Under the assumptions 1 and 2, the optimal abatement in the first period is decreasing and concave in the probability of geoengineering being effective, i.e.,* $A_1^{*\prime}(p) < 0$ *and* $A_1^{*\prime\prime}(p) < 0$.

Proof. The first part holds as noted above: totally differentiating the first order condition yields $\frac{dA_1^*}{dp} = \beta\frac{C_G'(S^{gap}-A_1^*)-C_A'(S^{gap}-A_1^*)}{D_{CEA}}$ which is negative due to Assumption 1 and the second-order condition. For the second part, we compute $\frac{d}{dp}\left(\frac{dA_1^*}{dp}\right)$ taking into account A_1^* itself depends on p as computed before and after some manipulations and using the fact that $D_{CEA} > 0$, we find the equivalence of this term being negative with the condition in Assumption 2 or that it is a necessary and sufficient condition so that overall $A_1^{*\prime\prime}(p)$ is negative. □

While the condition of 2 might seem hard to interpret, there is an economic meaning to it. Roughly speaking, the derivative of the value function with respect to the first-period decision, i.e., initial abatement, needs to be convex or at least not too concave compared to the difference between abatement and geoengineering cost in the last period. In other words, marginal costs need to increase sufficiently fast in today's abatement. Given the extremely differing cost estimates for abatement and geoengineering, this seems a justifiable assumption. Considering some frequently used specifications, we find that condition 2 holds for most widely discussed parametrization.

Firstly, let's consider quadratic cost functions (or equivalently damage functions if damages of geoengineering and of the CO_2 concentration are included) as it is typically the case in numerical models. In this case, having a higher marginal cost at any level of abatement compared to geoengineering is sufficient to ensure that $A_1^*(p)$ will be concave, that is, abatement will be reduced slower than linearly and optimal first-period abatement is only slowly decreasing. Similarly, a linear (as in Moreno-Cruz and Keith [24]) or even quadratic cost function of geoengineering together with quadratic or cubic abatement cost functions (with $C_A'''(A) \geq 0$) all meet the assumption and thus provide sufficient conditions for initial abatement to be concave in the probability of effectiveness of the geoengineering option. With a linear geoengineering cost function, an exponent of the abatement cost function between two and three (implying $C_A'''(A) \geq 0 \geq C_A''''(A)$) also satisfies Corollary 1.This case covers widely used abatement cost functions such as the one in used in RICE with an exponent of 2.8 or estimates for EU countries in Eyckmans and Cornillie [12] with an exponent between 2.1 and 2.9. In multi-model ensembles which have used a large suite of integrated assessment models [8, 18], marginal abatement costs (as measured by carbon prices) have been shown to be convex with respect to cumulative emission reductions, which are themselves linearly related to radiative forcing[6]. These results suggest that for a fairly general specification of the costs of achieving a stabilization goal of global warming, the results shown in Corollary 1 hold. Geoengineering does provide an alternative to abatement, but the uncertainty around its effectiveness makes abatement today respond slowly to the probability of success of GE. This 'flat' relation between initial abatement and GE for a large parameter set provides an argument to rely more on mitigation today.

[6]According to reduced complexity climate carbon cycle models such as MAGICC, available at http://www.magicc.org/.

2.2 Cost-Benefit Analysis (CBA)

So far, we considered a fixed stabilization goal in terms of global temperature in a cost-effectiveness framework. In this case, the possibility of geoengineering not being a viable solution implies high late abatement costs due to the fixed stabilization goal. One might thus ask if the results hold true if we were to replace a basically infinitively steep damage function (as in the case of CEA) by a smooth damage function. In order to address this question, we now turn to a Cost-Benefit Analysis framework comparing different costs of climate policies with expected damages. In this subsection, we focus on the differences to the previous results.

Since we expressed all variables in terms of their radiative forcing potential, we can simply introduce a convex and three times differentiable damage function $D(S^{bau} - A_1 - A_2 - \widetilde{\varphi}G)$ instead of the constraint in the problem (1). The objective of the Social Planner now can be written

$$\min_{A_1, A_2, G} C_A(A_1) + \beta E\left[C_A(A_2) + C_G(G) + D(S^{bau} - A_1 - A_2 - \widetilde{\varphi}G)\right].$$

As before, first we will consider that geoengineering will either be completely effective or not be feasible at all, i.e., we assume that $\widetilde{\varphi}$ can take on the values of $\overline{\varphi}$ (with probability p) or $\underline{\varphi}$ (with probability $1-p$). Starting from the last period, now the optimal decision does not only depend on the previous period but also the relative shape of cost and damage functions. As previously, we impose that either of the two policy options is employed exclusively imposing Assumption 1.

The first-order conditions of the last period's problem are the equalization of marginal costs and damages in both policy options. That is, in the case of geoengineering being a viable and effective policy option we have that $C'_G(G^*) = D'(S^{bau} - A_1 - G^*)$ and similarly for the case when abatement is the only option. Using these conditions and by the application of the envelope theorem we can compute the first-order condition of the first-period decision as

$$C'_A(A_1) - \beta\left(pD'(S^{bau} - A_1 - G^*) + (1-p)D'(S^{bau} - A_1 - A_2^*)\right) = 0$$

and the second-order condition as

$$D_{CBA} \equiv C''_A(A_1) + \beta\left(pD''(S^{bau} - A_1 - G^*) + (1-p)D''(S^{bau} - A_1 - A_2^*)\right) > 0.$$

As before, relying on the unambiguous ranking of marginal costs due to Assumption 1 and the convexity of the damage function, the amount of geoengineering -if successful- will always exceed the equivalent amount of abatement or that it must always be the case that $G^* > A_2^*$.

Applying similar techniques to study the curvature of $A_1^{*\prime}(p)$, *one can easily show that* $A_1^{*\prime}(p) < 0$ *and that it is moreover concave* ($A_1^{*\prime\prime}(p) < 0$) *if and only if the following assumption holds*:

Assumption 3. *The marginal total welfare loss by increasing today's abatement above optimal* $h(A_1) \equiv C_A'(A_1) - \beta[pD'(S^{bau} - A_1 - G^*) + (1-p)D'(S^{bau} - A_1 - A_2^*)]$ *is convex or less concave than the difference between damages under abatement and geoengineering policies* $g(A_1) \equiv D(S^{bau} - A_1 - A_2^*) - D(S^{bau} - A_1 - G^*)$ *in the sense that* $\frac{h''(x)}{h'(x)} > 2\frac{g''(x)}{g'(x)}$.

The argument is similar to the case of CEA. The notable difference is that rather than having different cost curves, in a CBA framework the difference comes from lower climate change damages in the future in the situation where geoengineering is available and effective. This additional feature of the model makes unambiguous statements of the effect more difficult in the general case.

However, when looking at some specifications used in practice we find several cases that provide sufficient conditions for Assumption 3 to hold. Firstly, a quadratic specification of cost and damage functions implies both sides of the condition to be zero so that initial abatement is linearly decreasing in the probability of success of geoengineering. Using damage functions as discussed in the previous section with $C_A'''(A) \geq 0$ and maintaining a quadratic damage function, the left-hand side is strictly positive or that initial abatement is concave in p. For other combinations, no general sufficient condition can be derived, and from these two examples it is clear that the conditions for a concave relationship between A_1^* and p are less stringent than in the case of a fixed stabilization goal. This is to be expected, given the less restrictive conditions imposed by the CBA on the total abatement.

In the next section, we look at a quadratic specification including uncertainty about the climate and allowing for both abatement and geoengineering to co-exist even after the uncertainty is resolved in order to analyze the robustness of these first results.

3 Unknown effectiveness of geoengineering and uncertain Climate Change impacts

Since uncertainties are pervasive in the field of climate change, it seems reasonable to take into account much of this uncertainty and to see how the result with respect to geoengineering might change. Indeed, the strongest argument in favor of geoengineering is that it might provide an hedge against climate change, should this turn out to be more damaging than expected. In this section we tackle this issue and model uncertainty also around key parameters of climate change or its impacts. The basic decision problem becomes deciding about optimal abatement today and, in the future, about both abatement and geoengineering after learning the state of the world. Conceptually, this framework could be related to the theory of endogenous risks [16] where the distribution of climate change damages is affected by different actions of the decision maker. However, the dynamics of the present problem together with the joint decision on mitigation and geoengineering renders this problem much more complex. We therefore concentrate our attention to a fully quadratic model; though restrictive, this still allows us to capture the fundamental trade-offs in the decision problem we are examining.

A risk-neutral social planner can in this case be characterized by the following general program

$$\underset{A_1}{min} C_A(A_1) + \beta E \left[\underset{A_2,G}{min} V_2(A_1, A_2, G, \widetilde{\varphi}, \widetilde{x}) \right] \tag{2}$$

where the second period's objective function is either the cost of achieving a specified stabilization goal (CEA) or minimizing the sum of costs and damages (CBA). We now consider two sources of uncertainty, the effectiveness of geoengineering ($\widetilde{\varphi}$) and the magnitude of damages or the stringency of the stabilization goal ($\widetilde{x}$); we denote by $F(\widetilde{x}, \widetilde{\varphi})$ the cumulative distribution of the pair of random variables. Without loss of generality, we restrict the random variables to some meaningful domains, namely that $0 \leq \widetilde{\varphi} \leq 1$ and moreover assume that, in expectation, $\widetilde{x}$ equals to one so we can easily compare the results to the certainty case.

As in Section 2, uncertainty is fully resolved before period two so that the second period's decision is deterministic. Given the higher overall level of uncertainty, we moreover allow for both simultaneous mitigation and geoengineering implementation in the future. Also, we again consider both the CEA and CBA case in order to compare the results.

3.1 Cost Effectiveness Analysis (CEA)

First we need to specify the program for this case. In the second period geoengineering and abatement must be such that that the stabilization target in terms of the allowed temperature change must be met. This target is now considered to be uncertain; if the climate sensitivity turns out to be high due to some positive feedback in the climate system, then more forcing reduction is needed to achieve the same temperature objective. Since we expressed all variables in their radiative forcing potential, we know that the forcing reduction of the climate policies (achieved via both geoengineering and abatement) must be greater or equal than $S^{bau} - \frac{\Delta T^{max}}{\widetilde{x}\lambda}$ where the certain value for climate sensitivity is now random. The term $\frac{\Delta T^{max}}{\widetilde{x}\lambda}$ can be interpreted as the cumulative emissions (taking into account geoengineering as effective negative emissions) which are allowed in order to meet the temperature stabilization target ΔT^{max}. The climate sensitivity is now a parameter unknown ex ante and equal to $\widetilde{x}\lambda$. Higher values of $\widetilde{x}$ correspond thus to states with a higher climate sensitivity or equivalently a more stringent climate policy. The social planner's decision program in the second period for the CEA case can be written as:

$$V_2^{CEA} = C_A(A_2) + C_G(G) \text{ s.t. } \widetilde{x}\lambda(S^{bau} - A_1 - A_2 - \widetilde{\varphi}G) \leq \Delta T^{max} \tag{3}$$

We specify the cost functions to be quadratic with marginal abatement costs c_A and marginal costs of geoengineering c_G. We solve the model backwards starting in the second period. Given that the climate sensitivity $\widetilde{x}\lambda$ and hence the effective emission target and the effectiveness of geoengineering are learned before taking the decisions on abatement and geoengineering, we know that marginal costs are equalized between abatement and geoengineering.

This allows us using an envelope theorem argument to simplify the first period decision based on (2).We obtain the optimal first-period abatement level expressed as share of the business-as-usual emissions as:

$$A_1^* = \frac{S^{bau} - \Delta T^{max} / \left(\lambda \frac{E\left[\widetilde{x}\Omega(\widetilde{\varphi})\right]}{E\Omega(\widetilde{\varphi})} \right)}{1 + \frac{1}{\beta E\Omega(\widetilde{\varphi})}} \text{ where } \Omega(\widetilde{\varphi}) = \frac{c_G/\widetilde{\varphi}^2}{c_G/\widetilde{\varphi}^2 + c_A}. \tag{4}$$

From this condition it can be seen that the quadratic specification implies among others that we could rather than assuming the uncertain effectiveness of geoengineering specify its costs as uncertain since the tuples $(\widetilde{\varphi}, \widetilde{x}, c_G)$ and $(1, \widetilde{x}, c_G/\widetilde{\varphi}^2)$ are equivalent in this model.[7] The share of abatement of second period's total climate policy is written as $\Omega(\widetilde{\varphi})$ and is decreasing in the effectiveness of geoengineering. Moreover, it is easy to show that it is convex in $\widetilde{\varphi}$ if the lower bound of the domain of $\widetilde{\varphi}$ and the relation between abatement and geoengineering costs ensure that the following condition holds:

$$\widetilde{\varphi} \geq \sqrt{\frac{c_G}{3c_A}} \tag{5}$$

This condition states that the share of geoengineering in second period's climate policy, which is given simply by the expression $(1 - \Omega(\widetilde{\varphi}))$, is concave in $\widetilde{\varphi}$ if abatement is sufficiently more expensive. It can be expected to hold in our context. For instance, if we assume a lower bound of the effectiveness $\widetilde{\varphi}$ of 0.1 and taking the estimate of McClellan, Keith, and Apt [21] who estimate that geoengineering costs are only around one per cent of the equivalent CO_2 abatement costs, this condition is easily met. Basically, this condition states that geoengineering must be cost-effective enough in order to dominate abatement in the future, which seems reasonable given our approach of an optimistic view on geoengineering. Based on analytical the formula of first-period abatement and the curvature of $\Omega(\widetilde{\varphi})$ we can derive some first results:

Proposition 1. *If $(\widetilde{x}, \widetilde{\varphi})$ are independent, an increase in risk in the sense of Rothschild-Stiglitz in $\widetilde{\varphi}$ increases A_1^* if condition (5) holds, while an increase in risk in $\widetilde{x}$ leaves A_1^* unchanged. If $(\widetilde{x}, \widetilde{\varphi})$ are not independent and the distribution $F(\widetilde{x}, \widetilde{\varphi})$ undergoes a marginal preserving increase in concordance, optimal first-period abatement A_1^* decreases.*

Proof. The first part for independence follows since the numerator of (4) simplifies to $S^{bau} - \frac{\Delta T^{max}}{E\widetilde{x}\lambda}$. Moreover, due to the convexity of $\Omega(\widetilde{\varphi})$ ensured by the condition in (5), an increase in risk in $\widetilde{\varphi}$ leads to an increase of $E\Omega(\widetilde{\varphi})$ and hence to an increase in A_1^*. For the second part, first note that the denominator of (4) is not affected by the marginal preserving increase in concordance. However, an increase in concordance implies that $Cov(\widetilde{x}, \Omega(\widetilde{\varphi}))$ decreases (see Epstein and Tanny [11] or Egozcue, Fuentes Garcia, and Wing-Keung [10]) since $\Omega(\widetilde{\varphi})$ is monotonically decreasing. Rewriting the fraction in the denominator of (4) as $\frac{Cov(\widetilde{x}, \Omega(\widetilde{\varphi})) + E\widetilde{x}\Omega(\widetilde{\varphi})}{E\widetilde{x}E\left[\Omega(\widetilde{\varphi})\right]}$ and noting that $E\widetilde{x} = 1$ by assumption thus shows that initial abatement decreases. □

[7] The reason that $\widetilde{\varphi}$ enters as a squared term here as well as in equation (4) can be explained by the fact that an increased effectiveness of geoengineering has both a marginal and inframarginal effect. It lowers marginal costs of geoengineering compared to abatement but at the same time increases the effectiveness of all geoengineering already applied thus lowering the needed amount to reach the same result in terms of radiative forcing.

The independence of first period abatment in the uncertainty about the stabilization target is intuitive given we consider a risk-neutral decision maker. As for the uncertain effectiveness of geoengineering the dynamic decision problem makes compliance with the target more costly in expected terms if geoengineering is more uncertain. This affects the denominator of (4) since it affects the relative costs of effective geoengineering and abatement.

If the effectiveness of geoengineering and the uncertain stabilization target are not independent, this introduces another effect depending on the sign of the correlation. It affects the numerator of (4) which can be understood as the perceived stringency of the stabilization target from an ex-ante perspective. In order to separate both effects, we use the concept of concordance as in Tchen [40]. Considering the (linear) correlation between $\widetilde{x}$ and $\widetilde{\varphi}$ is not sufficient due to the non-linear reaction in the second period. Therefore, we need a stronger criterion of relatedness. Rephrasing the result of the proposition, the perceived stabilization target $\Delta T^{max} / \left(\lambda \frac{E\left[\widetilde{x}\Omega(\widetilde{\varphi})\right]}{E\Omega(\widetilde{\varphi})} \right)$ is more stringent than if it were known with certainty ($\frac{\Delta T^{max}}{\lambda}$) if $(\widetilde{x}, \widetilde{\varphi})$ exhibit negative quadrant dependency[8]implying that ceteris paribus first period abatement will be higher. In the opposite case, we obtain an "insurance" effect of geoengineering: initial abatement can be lower if geoengineering is more likely to be effective when $\widetilde{x}$ is high in the sense of positive quadrant dependency.

Summarizing both parts of the proposition, it follows that in general, uncertainty increases initial abatement unambiguously if $(\widetilde{x}, \widetilde{\varphi})$ are independent or exhibit negative quadrant dependency. In this case both effects work in the same direction asking for a higher initial abatement level compared to the level under certainty. Only if geoengineering is more likely to be effective in the case where climate sensitivity is high (implying a more stringent policy), then uncertainty about geoengineering can imply a lower abatement level compared to the certainty case.

But how strong are both effects? In order to assess the relative magnitude, we now turn to a simple calibration of the model. In particular, we specify the geoengineering effectiveness as a binary Bernoulli random variable: $\widetilde{\varphi} \sim \{1 : p; 0 : (1 - p)\}$. The potential of geoengineering is thus either zero or as effective as abatement in order to reduce global temperature. Moreover we assume, as argued in McClellan, Keith, and Apt [21], that the cost of geoengineering is around one per cent of abate-

[8]Positive quadrant dependency and concordance are equivalent concepts, where two random variables are positive (negative) quadrant dependent $(F(\widetilde{x}, \widetilde{\varphi}) < (>) F_x(\widetilde{x}) F_\varphi(\widetilde{\varphi}))$, if and only if the distribution can be obtained by a sequence of marginal-preserving increases (reductions) in concordance starting from both variables being independent [40].

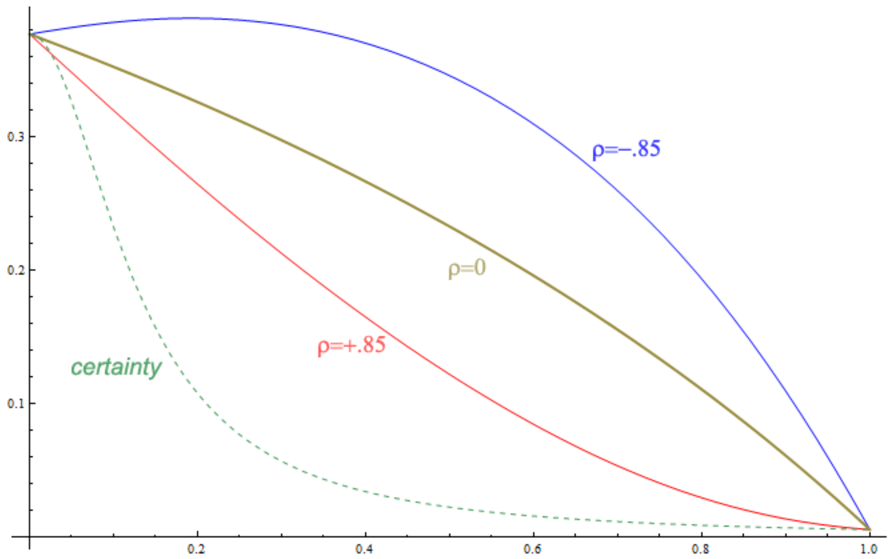

Figure 1: Share of first-period abatement for different values of $p(= E\widetilde{\varphi})$ (CEA)

ment , i.e., $c_A/c_G = 100$, and use a discount factor for the time span of fifty years (considered to be the first period in our model) of $\beta = 0.99^{50}$. Finally, we assume a high degree of uncertainty about the climate sensitivity in that we consider a uniform distribution $\widetilde{x} \sim U[0, 2]$.[9]

Figure 1 shows the optimal first-period abatement, normalized as percentage of total expected abatement for varying probabilities of geoengineering becoming a viable climate policy option. Under certainty ($\varphi = E\widetilde{\varphi} = p$), abatement becomes very low as soon as the effectiveness of geoengineering φ is slightly above zero as shown by the green curve in Figure 1.[10] Considering uncertainty as specified and assuming that both random variables are independent, however, the curve is concave in p–as shown in the previous section– and the reduction in initial abatement A_1^* is substantially reduced.

Let's now consider different degrees of relatedness between the effectiveness of geoengineering and the climate sensitivity. So far, little is known about the correlation between how possible geoengineering strategies work and the fundamental parameters of climate change, in particular, the reactivity of the climate to greenhouse gas emissions. Matthews and Caldeira [19] argue that a priori there is no reason to assume any relation ship between both parameters. On the other hand,

[9]According to IPCC fourth assessment report, the most likely value of climate sensitivity is 3°C, with a likely (= greater than 66% chance of being correct) range of 2-4.5 °C.

[10]Under certainty, optimal abatement is always decreasing in φ. Moreover, it is convex in φ if and only if $\varphi > \sqrt{\frac{c_G(1+\beta)}{3c_A}}$ and implies that for most of the domain of φ on the right, abatement under certainty is decreasing and convex leading to the strong difference to the uncertainty case.

taking into account the regional differentiation of climate change and potential difficulty of geoengineering to account for regional differences might give rise to a negative correlation[30]. Overall, as of today it is rather speculative as of how well geoengineering could be used as an alternative climate change policy for different parameters of the climate system. To quantify how this correlation would affect our results, we use a copula approach to allow the joint distribution $F(\widetilde{x}, \widetilde{\varphi})$ to capture different degrees of relatedness. In particular, we consider the Frank copula to capture the relationship between $\widetilde{x}$ and $\widetilde{\varphi}$. It is appropriate to model positive as well as negative relationship, is symmetric and allows including very extreme degrees of relatedness. A copula specifies a joint distribution of uniform marginal distributions u_1 and u_2 which can be recovered from the original marginal distribution via the inverse probability transform, i.e., $F_{\varphi}^{-1}(u_1) = \widetilde{\varphi}$ and $F_x^{-1}(u_2) = \widetilde{x}$. A copula $C(u_1, u_2)$ then fully characterizes the relationship between both distributions and the Frank copula is defined as as $C(u_1, u_2) = -\frac{1}{\alpha} ln \left(1 + \frac{(e^{-au_1}-1)(e^{-au_2}-1)}{e^{-\alpha}-1}\right)$ where the parameter $\alpha \in [-\infty; +\infty]$ captures the degree of relatedness, see, e.g., Trivedi and Zimmer [42].[11] Positive quadrant dependency as used in Proposition 1can be characterized by a copula for which $C(u_1, u_2) > u_1 u_2$ holds, which is the case for the Frank copula for $\alpha > 0$. This approach allows to assess the quantitative impact on the optimal abatement policy. In Figure 1, we also show the optimal first-period abatement for the extreme positive and negative correlation admissible. We take rather extreme values for the parameter of the copula as $\alpha = \{-ln10^{10}, 0, +ln10^{10}\}$ which for $p = 0.5$ yield a rank correlation between $\widetilde{x}$ and $\widetilde{\varphi}$ of ± 0.85 and zero for $\alpha = 0$. As expected, a negative correlation case reinforces the results shown so far, with a pronounced concavity of A_1^* in p. On the other hand, in the case of extremely high positive correlation the profile of A_1^* becomes slighly convex. But even in this case, first-period abatement remains still substantially higher compared to the certainty case for all chances of geo-engineering to be effective.[12]In the next section, we alternatively use a Cost-Benefit analysis in order to see how much of the result holds true if we have a continuous damage function rather than a fixed stabilization target.

[11] Alternatively, using a FGM copula might be reasonable given that the relationship is most likely to be only modest.

[12] In fact, if the rank correlation is positive, it might even be optimal to have zero abatement in the first period if the conditional expected value of climate sensitivity in the case where $\widetilde{\varphi} = 0$ is sufficiently low. Nevertheless, in numerical examples we considered this turned out to be the case only for a very extreme positive correlation structure, which are far beyond realistic values.

3.2 Cost Benefit Analysis (CBA)

Instead of using a fixed stabilization target, we now introduce a damage function D that captures impacts from climate change. Uncertainty surrounding the climate sensitivity is now captured by a multiplicative factor $\widetilde{x}$ of total damages where again we set without loss of generality $E\widetilde{x} = 1$. Using the general formulation of the decision problem in (2), the second period value function now can be written as

$$V_2^{CBA}(A_1, A_2, G) = C_a(A_2) + C_g(G) + \widetilde{x}D(S^{bau} - A_1 - A_2 - \widetilde{\varphi}G).$$

Again solving backwards and using the quadratic specification as in the previous section and moreover a quadratic damage function with marginal damages denoted by d, one can compute the optimal abatement and geoengineering levels in period two where uncertainty is removed. Using an envelope theorem argument yields for the optimal abatement level in the first period:

$$A_1^* = \frac{1}{1 + \frac{1}{\beta E \underbrace{\left[\frac{1}{1 + \frac{c_A}{d\widetilde{x}} + \frac{c_A}{c_G/\widetilde{\varphi}^2}} \right]}_{\Gamma(\widetilde{x},\widetilde{\varphi})}}} S^{bau}. \tag{6}$$

Without the possibility of geoengineering and under certainty, it simplifies to the intuitive level of first period abatement of $A_1^* = \frac{\beta}{1+\beta+\frac{c_A}{d}} S^{bau}$ depending only on the ratio of marginal abatement cost and damages, and the discount factor. Under uncertainty, what matters is the term denominator of (6) and hence the curvature of $\Gamma(\widetilde{x}, \widetilde{\varphi})$. Since $\Gamma(\widetilde{x}, \widetilde{\varphi})$ is always concave in $\widetilde{x}$, it is unambiguously the case that an increase in risk in $\widetilde{x}$ implies a lower initial abatement level if $\widetilde{x}$ and $\widetilde{\varphi}$ are independent. The effect of the uncertainty surrounding geoengineering is as before depending on a condition of relative costs. In particular, $\Gamma(\widetilde{x}, \widetilde{\varphi})$ is concave in $\widetilde{\varphi}$ if the following condition holds:

$$\widetilde{\varphi} \geq \sqrt{\frac{c_G}{3c_A} + \frac{c_G}{3d\widetilde{x}}} \tag{7}$$

Comparing this to (5), it is clear that this condition is more restrictive due to the second term on the right hand side, related to the ratio of marginal costs and benefits. Still, the assumptions about the relative costs of geoengineering and mitigation are crucial for this condition to hold. As long as marginal damages are not too low compared to abatement costs, however, this condition is likely to hold at

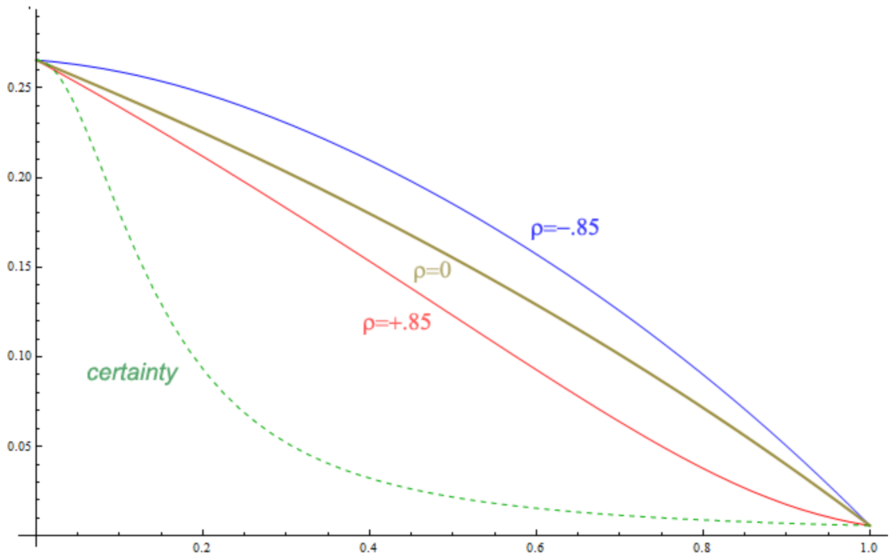

Figure 2: Share of first-period abatement for different values of $p(=E\widetilde{\varphi})$ (CBA)

least over the relevant part of the domain of $\widetilde{\varphi}$.[13] In this case it follows immediately that an increase in risk in $\widetilde{\varphi}$ leads to a higher initial abatement level if $\widetilde{x}$ and $\widetilde{\varphi}$ are independent. This result can be contrasted with the case under certainty, where optimal abatement is always decreasing in φ. Moreover, it is convex in φ if and only if $\varphi > \sqrt{\frac{c_G(1+\beta)}{3c_A} + \frac{c_G}{3d}}$ or that for most of the domain of φ on the right, abatement under certainty is decreasing and convex leading to the strong difference to the uncertainty case.

If $\widetilde{x}$ and $\widetilde{\varphi}$ are not independent, the results become less clear. In particular, the share of geoengineering of future climate policy is now depending on $\widetilde{x}$ whereas it was constant in the CEA case. Since $\Gamma(\widetilde{x}, \widetilde{\varphi})$ is not separable in $\widetilde{x}$ and $\widetilde{\varphi}$, the overall effect of uncertainty is ambiguous. We therefore use the numerical calibration of the previous section adding a quadratic damage function with marginal damages twice as high as marginal abatement costs. Figure 2 shows the optimal first period abatement level the different correlation structures. Qualitatively, the result are similar to those in the CEA framework, and initial abatement decreases rather slowly in p here as well. Notably, the effect of the uncertainty about the damage function is very small compared to the effect of uncertain geoengineering while different correlation structures have a more moderate impact.

[13]As it is evident from Figure 2, this condition does not hold for $\widetilde{\varphi}$ very close to zero while it does hold for the most part of the domain of $\widetilde{\varphi}$ leading to the results discussed here.

4 Numerical results with an integrated assessment model

In this section we use the WITCH integrated assessment model (IAM) [5] to perform a numerical exercise to (a) see whether the theoretical results carry over to a much more detailed model and (b) assess the quantitative magnitude of the effect of uncertain geoengineering on the optimal abatement path. The integration of the geoengineering strategy into a numerical IAM has been carried out in some recent papers, but in all cases DICE a simplified, one region model was employed [3, 13, 14]. In this section we introduce geoengineering and uncertainty in a fully fledged integrated assessment model. WITCH has been used extensively in the literature of scenarios evaluating international climate policies. It is a multi regional (13 macro-regions), long term dynamic model based on a Ramsey optimal growth economic engine, and a hard linked energy system which provides a compact but exhaustive representation of the main mitigation options both in the energy and non energy sectors. The choice variables are investments and activities in the overall economy, in the abatement technologies, in the knowledge sector, and the objective is to optimize welfare measured by the logarithm of consumption, discounted with a social rate of time preference declining from 3% to 2% per year over the model time horizon (to 2150, with 5 years time steps). Technological change in both energy intensity and low carbon technologies is endogenous and is modeled via both innovation and diffusion processes. Emissions from fossil fuels accumulate in the atmosphere leading to temperature increase which generates a negative feedback on the economy. The model has a game theoretical set up which allows to portray different degrees of cooperation among regions, and to feature multiple externalities on both the environment and the innovation markets. For the sake of this analysis, we focus on the fully cooperative solution in which the joint regional welfare (measured as log of consumption) is maximized by the social planner. Negishi weights are used as social welfare aggregators. The model is solved numerically in GAMS/CONOPT. A description of the main model equations can be found at the model website www.witchmodel.org.

For the purpose of this paper, two main model extensions were carried out. In order to account for the uncertainty of geoengineering and the climate response, we use a stochastic programming version of WITCH (see Bosetti and Tavoni [4] for a previous application). Model variables are redefined on nodes belonging to a scenario tree with two branches[14]; at a given point in the future, geoengineering can either succeed (with some probability p), or fail (with probability $1 - p$). In the case of the uncertainty on both geoengineering and climate, we use a four branches scenario tree. Despite the simplified description of the state space, this reformulation of the model allows us capturing the implications of uncertainty on the abatement strategy before uncertainty is resolved, enabling us to devise an optimal hedging strategy[15]. Given that utility is defined as logarithm of consumption, this implies a degree of relative risk aversion of one in the stochastic version of the model. While the theoretical analysis is based on risk neutrality, higher values of risk aversion have been suggested in the literature. However, when we allowed for different degrees of risk aversion, the results remained almost unchanged, a fact in line with the findings of, e.g., Ackerman, Stanton, and Bueno [1].

The second model extension regards the development and inclusion of a geoengineering module. We model geoengineering as an option to reduce solar radiation through stratospheric aerosols. Specifically, we model million tons of sulfur (teragrams or TgS) injected into the stratosphere to lead –if successful– to a negative radiative forcing of $-1.75\frac{W}{m^2TgS}$, which is a best guess estimate [14] based on a range from -0.5 [9] to -2.5 [27]. Moreover, we assume a stratospheric residence time of two years which is in the range of a few years [28]. Finally, we assume a linear cost function at a cost of 10 billion \$/TgS within the range considered in the literature of between 5 [9] and 25 billion [32] USD per TgS. In line with the objectives of this paper, this specification of geoengineering is an optimistic one, in particular since we abstract from side-effects and damages associated with the deployment of geoengineering; when running a cost benefit analysis, we also assume that damages are only a function of temperature but are not linked to the CO_2 concentration, thus abstracting for the damages related to ocean acidification. These two effects could be integrated in our framework as increasing the costs of geoengineering and reducing the costs of abatement respectively and would increase the optimal first-period abatement level, further strengthening our results.

We run two different set up which mimics the two approaches considered in the analytical model. The cost effective analysis (CEA) is modeled by imposing a

[14]Instead of accounting explicitly for the non-anticipative constraints, non anticipativity is implicitly defined through characterization of predecessor/successor relationships among nodes in the scenario tree.

[15]The stochastic programming formulation of WITCH increases computational time substantially, by 3-4 times for a two branch scenario tree, and by 20 for a four branch scenario tree. The four branch scenario tree cooperative solution (for which we cannot take advantage of parallel computing) takes 180 hours to solve on a 2.6 GHz Intel Xeon processor.

target to be met by 2100, based on a radiative forcing of $2.8W/m^2$[16], which provides likely to very likely chances of maintaining temperature increase below 2C [17]. In this set up we don't consider the climate feedback on the economy, but rather prescribe the climate stabilization policy. The cost benefit analysis (CBA) is based on a global optimal policy which takes into account damages from increased global temperature due to climate change. Damages are modeled as a power function function of temperature, with an exponent of 2.2 and are expressed in relative terms of GDP with different coefficients across regions. In both cases, the social planner maximizes global welfare defined as expected discounted utility where the degree of risk aversion is equal to unity.

Figure 3 shows the main results of the CEA scenario with a probability $p = 0.5$ of geoengineering becoming available in the year 2050. For comparability, we also report a scenario without the geoengineering module as well as the no climate policy BAU. In the state of the world in which it is effective, geoengineering turns out to be a perfect substitute to mitigation; consequently, post 2050 abatement goes to zero and the containment of the forcing is achieved via solar radiation management, which is implemented just before 2100, given that it is assumed to be fast, costs are linear, and the forcing target can be overshot. These results are expected given the optimistic assumptions about the effectiveness and costs of geoengineering. What is interesting in this setting, though, is to understand to what extent the climate strategy before the uncertainty about geoengineering is resolved changes with respect to the certainty case. Figure 3 indicates quite clearly that before 2050, the differences are rather small. The optimal abatement path in the WITCH optimization under uncertainty is only slightly below the one without the geoengineering option. In both cases, significant abatement is carried out, both via energy efficiency measures as well as by deploying mitigation technologies such as CCS, renewables, nuclear power and low carbon fuels. The marginal cost of carbon in 2010 is 28.9 \$/tCO2 and 19.4 \$/tCO2 for the cases without geoengineering and with a 50% chance of geoengineering being effective respectively. Thus, as in the case of the analytical model, hedging against the risk of geoengineering not being effective provides a strong rationale for carrying out abatement prior to uncertainty being resolved. The hedging is significant since it has to allow avoiding to lock in fossil fuel capital

[16]The target is an 'overshoot' one, i.e. the 2100 target level can be exceeded prior to 2100. Its refers to the aggregate radiative forcing from Kyoto gases, Non-Kyoto gases, and aerosols. Direct forcing from nitrate aerosols, mineral dust and land surface albedo changes are not included in the list.

[17]Based on the MAGICC model.

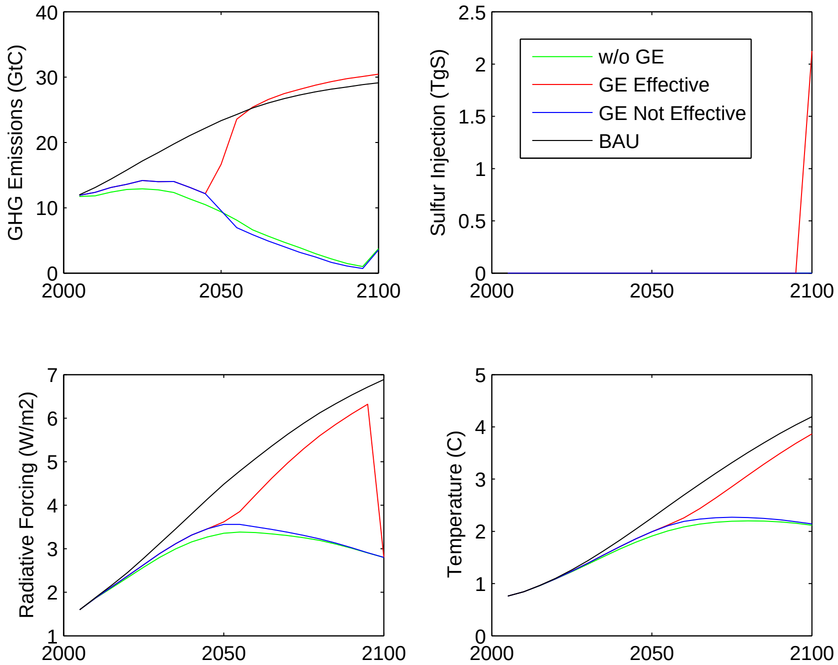

Figure 3: CEA results, $p = 0.5$.

which is long lived, and which would preclude the eventual attainment of the climate stabilization target, even when accounting for mitigation technologies which allow to sequester CO2 from the atmosphere.[18]

If instead of using a stabilization policy we consider climate change using the damage function in a cost benefit analysis, the results are found to be qualitatively similar, though not identical, as shown in Figure4. In a CBA, geoengineering -when effective- is deployed already at mid century and to a larger extent as way to decrease the damage feedback on the economy[19]. The additional flexibility due to the smooth damage function and the effect of discounting allows for more emissions until uncertainty is resolved in 2050 since the most expensive abatement options in the future can be avoided by accepting higher damages. However, even in this case, with relatively conservative assumptions about the extent of the temperature-damage function, the uncertain nature of geoengineering suggests that it is optimal

[18]This version of the WITCH model features as carbon dioxide removal options biomass burning and CCS, which allows negative emission and which plays a major role in the results of the integrated assessment modelsTavoni and Tol [39].

[19]Note that in the model we have put as lower bound for the temperature increase the warming of 0.7C which is observed today, given that the damage function used in the model (as in all IAMs) has been calibrated only for positive warming values.

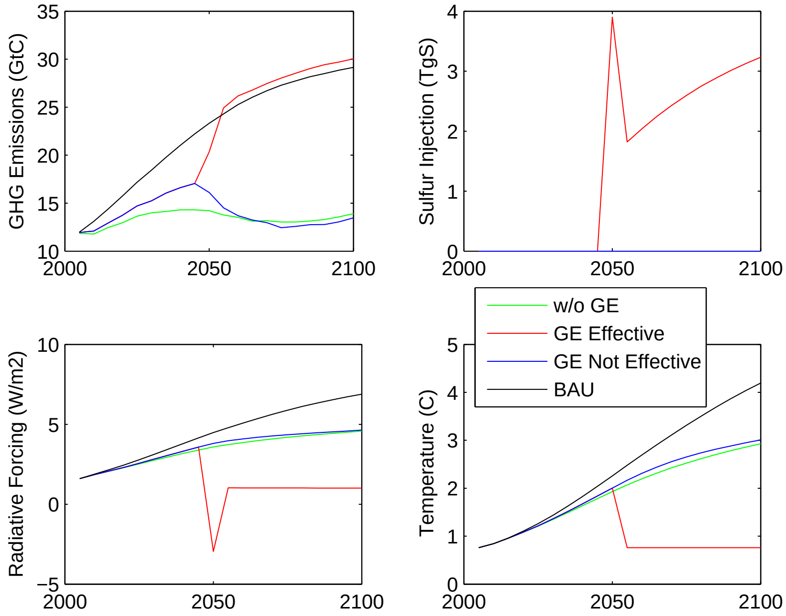

Figure 4: CBA results, $p = 0.5$.

to significantly abate emissions below Business as Usual. This is reflected by the impact on the social cost of carbon, which in 2010 in the CBA case decreases only slightly from 20.6\$/tCO2 to 15.6\$/tCO2 if the possibility of uncertain geoengineering is allowed.

So far, we considered that the probability of geoengineering becoming a viable option was $p = 0.5$. If we allow this probability to vary, we are able to replicate the exercise of the previous sections. To this end, we have run the WITCH model with 10 different values of p and have determined the actual shape of abatement before the resolution of uncertainty in 2050 for increasing probabilities of success of geoengineering. Figure 5 shows this relationship for both CEA and CBA scenarios.

The results of Figure 5 confirm the theoretical findings of our analytical model. In both cases, the relation between optimal abatement prior to resolution of uncertainty and the probability of success of geoengineering appears to be concave. Moreover, the decrease of early abatement in p is slower in the CEA case of a stabilization goal while it becomes closer to linearity in the CBA case. With respect to the magnitude, in the CEA the level of abatement declines to almost zero only if the probability becomes very high: at a 80% probability of success of geoengineering, optimal abatement is approximately 60% of what would be carried in the absence of geoengineering. This result is particularly strong compared to the certainty case: if

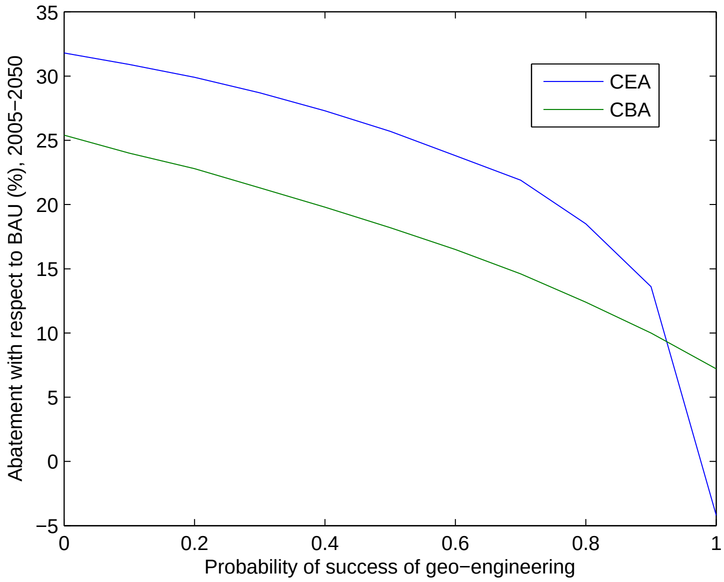

Figure 5: The relation between pre-2050 abatement and p for CEA and CBA.

it is known for sure that $\varphi = p$, no abatement would be implemented for any value of φ not too close to zero[20], since in this case geoengineering will be the only climate policy used in the future given its cost advantage. As outlined earlier, this shows that -due to the dynamic decision problem- uncertainty induces a very significant wedge in the optimal abatement strategy in the early periods, and provides a strong argument for maintaining mitigation policies even when taking a very optimistic viewpoint on the potential of geoengineering. .

4.1 Robustness Analysis

In this section we vary several parameters used in the previous analysis to investigate the robustness of the results presented so far. We investigate several dimensions. First, we consider a different timing of resolution of uncertainty: in addition to mid century, we also look at 2030, 2040, 2060 and 2070. The results shown in Figure 6 confirm the intuition that the further uncertainty is resolved into the future, the more abatement differs from the certainty case when measured in levels. In relative terms, though, the optimal share of abatement undertaken int the stochastic runs with respect to the certainty case slightly increases, from 57% with resolution in 2030 to 69% with resolution in 2070. These results confirm the main findings of our

[20]In our model simulations, no abatement was the optimal strategy for values of φ as small as 10^{-4}.

models: even if we were to learn the true state of geoengineering already in 2030, a significant abatement effort would nonetheless be optimal until then.[21]

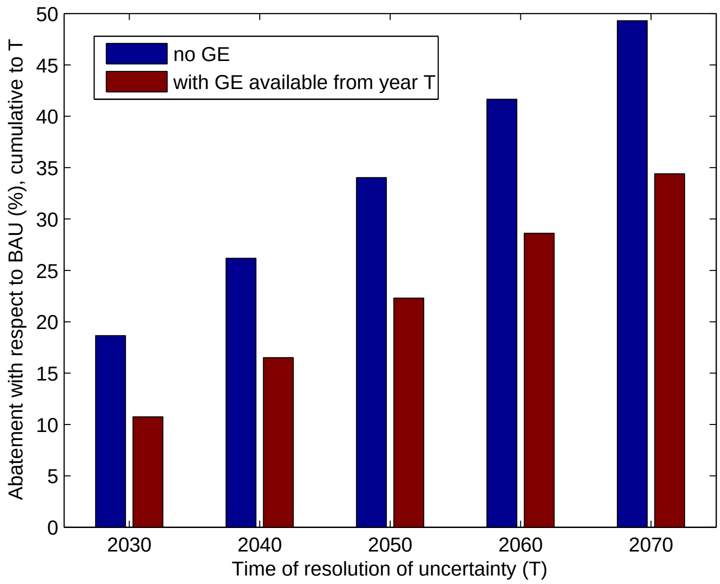

Figure 6: Different dates of resolution of uncertainty (CBA)

Second, we study the role of the stringency of the climate stabilization objective in the CEA case, a central issue in the policy debate. As already visible from the theoretical results, in particular from equation (4), the stringency of the target affects abatement non-linearly. With a less stringent climate objective, more headroom in the carbon budget is allowed, providing additional flexibility in favor of a 'wait and see' strategy. Indeed, the numerical results indicate that a laxer policy target (here considered as limiting radiative forcing in 2100 to $3.5\frac{W}{m^2}$, which provides likely to very likely chances to maintain temperature increase below 3°C), while overall lowering mitigation effort, also leads to a somewhat less concave pattern in the probability of geoengineering, see Figure 7. The overall result, however, is preserved even in this case. In the same chart we also show an additional sensitivity case in which we limit the quantity of geoengineering to be deployed: this allows exploring the case in which both geoengineering and abatement would co-exist, generalizing some of the assumptions made in the theoretical model. It also represent the more realistic case of a geoengineering program which would be used to compensate only a limited fraction of warming.[22] As expected, the responsiveness of abatement to

[21]Here we only show the results for the CBA policy, since for the CEA policy target, no feasible solution could be found for some (late) dates considered.

[22]Specifically, we impose an upper limit on the quantity of sulfur injection at 1TgS/yr. Injections

the probability of success of geoengineering decreases when limiting its maximum deployment, since abatement is needed even if geoengineering will work for sure. The shape of the curve, though, remains close to general one shown in Figure 5.

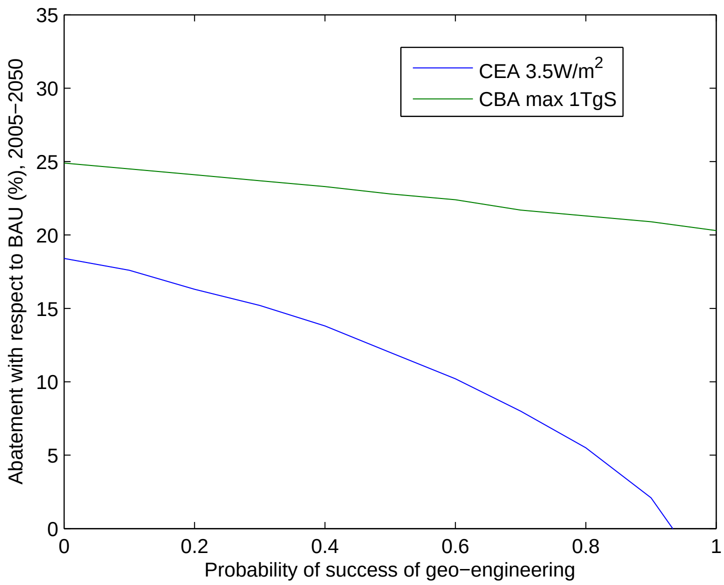

Figure 7: The relation between pre-2050 abatement and p : robustness to radiative forcing target (CEA: $3.5\frac{W}{m^2}$) and to the scale of Geo-engineering (CBA: max 1TgS).

Mimicking the theoretical part, we introduce uncertainty not only about the effectiveness of geoengineering, but also about climate change itself. In particular, we consider a binary distribution for value for the climate sensitivity (CS) which is calibrated at 3.2 in the standard version of WITCH. Now, instead, we consider that it can either take on a value of 2.7 or 3.7 with equal probability. This approach can be considered as rather conservative compared to estimates of the distribution of climate sensitivity (e.g, Murphy, Sexton, Barnett, Jones, Webb, Collins, and Stainforth [26]), but still captures the generally considered range of its values. We consider a CEA policy aiming at limiting temperature increase to at most 2.5°C by the end of the century. Given that now both geoengineering and climate are uncertain, we use a four-branches tree structure in WITCH. We assess the cases when different random variables are both uncorrelated and correlated[23].

above this value have been shown to significantly increase the extent of Arctic ozone depletion-Tilmes, Müller, and Salawitch [41]. The analysis has been done for the CBA case.

[23]In order to capture the effect of different climate sensitivity values, we have to define the stabilization target now in terms of temperature increase. We have chosen a value in line with previous runs.

Scenario	Abatement 2005-2050	
$\rho = 0$	21.8%	
$\rho = +0.8$	13.9%	
$\rho = -0.8$	25.6%	
certainty, w/o SRM	23.0%	
uncertain CS, w/o SRM	27.4%	

Table 1: Sensitivity of abatement to uncertainty about climate and geoengineering.

Independent of the value of climate sensitivity, the level of geoengineering will be such to offset all global warming due to its very low cost. If geoengineering becomes not an option, a higher mitigation effort after 2050 is needed if CS turns out to be higher. The interesting question thus is how abatement prior to the time of learning will be affected by the two sources of uncertainty, and, henceforth, by considering different correlation structures. In particular, we consider two rather extreme correlation structures where the probability of geoengineering becoming a viable option is 0.9 in case of a high (low) climate sensitivity and 0.1 in case the CS is low (high) and symmetrically for the no-geoengineering case. This results in a bivariate distribution with unchanged marginal distributions but a correlation coefficient of $\rho = +0.8(-0.8)$, which can be considered as a very extreme correlation structure. Table 1 summarizes the abatement effort prior to the resolution of uncertainty in all scenarios.

Firstly, the uncertainty around climate sensitivity leads to higher initial abatement (27.4% vs. 23.0%). With the most unfavorable correlation structure in which geo-engineering is likely to be effective when CS is low ($\rho = +0.8$), this abatement level is almost kept constant. In the uncorrelated and favorable cases, initial abatement is lowered to around 22% and 14% of BAU emissions respectively. Still, even with this very optimistic correlation structure in which geoengineering is most effective exactly when the climate warms mostly, a significant share of abatement appears as socially optimal to be implemented in the near future. This result provides further support of the thesis presented in the preceding analysis: even when considering the insurance value of geoengineering, abatement is only partially crowded out and remains the dominant strategy in the medium term.

As a final remark, it is noteworthy that throughout the analysis we considered the optimal climate policy from a global perspective. It is interesting to compare the results with a case where regions act unilaterally, which can give rise to a sort of "Tuvalu Syndrome" [23] in which the most vulnerable countries decide to independently implement geoengineering. Therefore, we run WITCH in a CBA framework now solving for the fully non-cooperative Nash-equilibrium. In this setup, each region chooses the optimal level of geoengineering taking all other regions decisions as given. Given the extremely low costs of geoengineering, implementing it is even optimal for individual countries that do not take into account damages to other countries or regions. Due to the fact that in the non-cooperative case almost no abatement will be implemented, the amount of SO_2 injected starting as of 2050 is slightly higher in the non-cooperative case ($4.5TgS$) compared to the $3.9TgS$ of the cooperative solution depicted in Figure 4. This underlines the importance of the global governance of a potential geoengineering scheme as discussed in [33, 43, 44].

5 Conclusions

This paper has assessed the interplay between geoengineering and abatement in the presence of uncertainty. We have deliberately taken an optimistic view about the costs and efficacy of geoengineering, and asked ourselves to what extent the uncertainty about geoengineering provides a rationale for undertaking more or less abatement. In order to address this question, we have used an analytical economic model as well as numerical integrated assessment model and explored the optimal economic decisions both in a cost effective and cost benefit framework. Our results consistently show that considering the possibility of geoengineering as a comparably cheap and effective alternative to traditional mitigation climate policies has an impact on optimal climate change policies. However, we demonstrate that even disregarding potential side effects and secondary costs, the fact that it will only be a viable option in the future with some given probability gives rise to a strong case of traditional mitigation as optimal near-term climate policy. In particular, the uncertainty surrounding the effectiveness[24] of geoengineering implies that the social planner should optimally rely on a significant mitigation effort for the coming decades. The response of abatement to the probability of success of geoengineering is shown to be non linear and concave under a reasonably broad set of formulations, both in CEA and CBA, though more markedly in the former. Previous studies such as Bickel and Agrawal [3], Gramstad and Tjøtta [14], Goes, Tuana, and Keller [13], and Sterck [36] did not take into account this dynamic decision problem but rather rely on Monte Carlo exercises which do not capture the dynamic learning and de-

[24] which could also be interpreted as its public acceptance or prohibitively high costs or side-effects.

cision making process. We also showed that our results hold true to a significant degree even when we allow for different relations between the uncertainty about geoengineering and the climate, as a way to assess the insurance value of geoengineering. Our results are also confirmed by means of extensive robustness analysis on several key parameters.

While further research is a prerequisite to assess whether there will be a viable geoengineering option at some point in the future, the results suggest that for the time being, geoengineering does not warrant to be taken as a reason to significantly delay abatement effort from an economic point of view, even under optimistic scenarios about its feasibility and acceptability. These results are derived disregarding any ethical or governance issues which have been shown to raise further concerns about the potential of geoengineering.

References

[1] Ackerman, F., E. A. Stanton, and R. Bueno (2013): "Epstein–Zin Utility in DICE: Is Risk Aversion Irrelevant to Climate Policy?," *Environmental and Resource Economics*, pp. 1–12.

[2] Barrett, S. (2008): "The Incredible Economics of Geoengineering," *Environmental and Resource Economics*, 39(1), 45–54.

[3] Bickel, J., and S. Agrawal (2011): "Reexamining the economics of aerosol geoengineering," .

[4] Bosetti, V., and M. Tavoni (2009): "Uncertain R&D, backstop technology and GHGs stabilization," *Energy Economics*, 31, S18–S26.

[5] Bosetti, V., M. Tavoni, E. D. Cian, and A. Sgobbi (2009): "The 2008 WITCH Model: New Model Features and Baseline," Working Paper 2009.85, Fondazione Eni Enrico Mattei.

[6] Brovkin, V., V. Petoukhov, M. Claussen, E. Bauer, D. Archer, and C. Jaeger (2008): "Geoengineering climate by stratospheric sulfur injections: Earth system vulnerability to technological failure," *Climatic Change*, 92(3-4), 243–259.

[7] Caldeira, K., and L. Wood (2008): "Global and Arctic climate engineering: numerical model studies," *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 366(1882), 4039 –4056.

[8] Clarke, L., J. Edmonds, V. Krey, R. Richels, S. Rose, and M. Tavoni (2009): "International climate policy architectures: Overview of the EMF 22 International Scenarios," *Energy Economics*, 31, Supplement 2(0), S64–S81.

[9] Crutzen, P. (2006): "Albedo Enhancement by Stratospheric Sulfur Injections: A Contribution to Resolve a Policy Dilemma?," *Climatic Change*, 77(3-4), 211–220.

[10] Egozcue, M., L. Fuentes Garcia, and W. Wing-Keung (2009): "On some covariance inequalities for monotonic and non-monotonic functions," *Journal of Inequalities and Applications*, 10(3), 1–7.

[11] Epstein, L. G., and S. M. Tanny (1980): "Increasing Generalized Correlation: A Definition and Some Economic Consequences," *The Canadian Journal of Economics / Revue canadienne d'Economique*, 13(1), 16–34, ArticleType: primary_article / Full publication date: Feb., 1980 / Copyright © 1980 Canadian Economics Association.

[12] Eyckmans, J., and J. Cornillie (2000): "Efficiency and Equity of the EU Burden Sharing Agreement," Energy, Transport and Environment Working Papers Series 2000-02, Katholieke Universiteit Leuven.

[13] Goes, M., N. Tuana, and K. Keller (2011): "The economics (or lack thereof) of aerosol geoengineering," *Climatic Change*, 109(3-4), 719–744.

[14] Gramstad, K., and S. Tjøtta (2010): "Geoengineering - a part of climate change policies," Discussion paper.

[15] Haywood, J. M., A. Jones, N. Bellouin, and D. Stephenson (2013): "Asymmetric forcing from stratospheric aerosols impacts Sahelian rainfall," *Nature Climate Change*, advance online publication.

[16] Kane, S., and J. F. Shogren (2000): "Linking Adaptation and Mitigation in Climate Change Policy," *Climatic Change*, 45(1), 75–102.

[17] Klepper, G., and W. Rickels (2012): "The Real Economics of Climate Engineering," *Economics Research International*, 2012, 1–20.

[18] Kriegler, E., J. Weyant, G. Blanford, L. Clarke, J. Edmonds, A. Fawcett, V. Krey, G. Luderer, K. Riahi, R. Richels, S. Rose, M. Tavoni, and D. v. Vuuren (????): "The Role of Technology for Climate Stabilization: Overview of the EMF 27 Study on Energy System Transition Pathways Under Alternative Climate Policy Regimes.," *Climatic Change*.

[19] Matthews, H. D., and K. Caldeira (2007): "Transient climate-carbon simulations of planetary geoengineering," *Proceedings of the National Academy of Sciences*, 104(24), 9949–9954.

[20] Matthews, H. D., N. P. Gillett, P. A. Stott, and K. Zickfeld (2009): "The proportionality of global warming to cumulative carbon emissions," *Nature*, 459(7248), 829–832.

[21] McClellan, J., D. W. Keith, and J. Apt (2012): "Cost analysis of stratospheric albedo modification delivery systems," *Environmental Research Letters*, 7(3), 034019.

[22] Mercer, A. M., D. W. Keith, and J. D. Sharp (2011): "Public understanding of solar radiation management," *Environmental Research Letters*, 6(4), 044006.

[23] Millard-Ball, A. (2012): "The Tuvalu Syndrome," *Climatic Change*, 110(3), 1047–1066.

[24] Moreno-Cruz, J. B., and D. W. Keith (2012): "Climate policy under uncertainty: a case for solar geoengineering," *Climatic Change*.

[25] Moreno-Cruz, J. B., K. L. Ricke, and D. W. Keith (2012): "A simple model to account for regional inequalities in the effectiveness of solar radiation management," *Climatic change*, 110(3), 649–668.

[26] Murphy, J. M., D. M. H. Sexton, D. N. Barnett, G. S. Jones, M. J. Webb, M. Collins, and D. A. Stainforth (2004): "Quantification of modelling uncertainties in a large ensemble of climate change simulations," *Nature*, 430(7001), 768–772.

[27] Rasch, P., P. Crutzen, and D. Coleman (2008): "Exploring the geoengineering of climate using stratospheric sulfate aerosols: The role of particle size," *Geophysical Research Letters*, 35(2), L02809.

[28] Rasch, P., S. Tilmes, R. Turco, A. Robock, L. Oman, C. Chen, G. Stenchikov, and R. Garcia (2008): "An overview of geoengineering of climate using stratospheric sulphate aerosols," *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 366(1882), 4007.

[29] Ricke, K. L., M. G. Morgan, and M. R. Allen (2010): "Regional climate response to solar-radiation management," *Nature Geoscience*, 3(8), 537–541.

[30] Ricke, K. L., D. J. Rowlands, W. J. Ingram, D. W. Keith, and M. G. Morgan (2012): "Effectiveness of stratospheric solar-radiation management as a function of climate sensitivity," *Nature Climate Change*, 2(2), 92–96.

[31] Robock, A., D. G. MacMartin, R. Duren, and M. W. Christensen (2012): "Studying Geoengineering with Natural and Anthropogenic Analogs," mimeo.

[32] Robock, A., A. Marquardt, B. Kravitz, and G. Stenchikov (2009): "Benefits, risks, and costs of stratospheric geoengineering," *Geophysical Research Letters*, 36(19).

[33] Schelling, T. (1996): "The economic diplomacy of geoengineering," *Climatic Change*, 33(3), 303–307.

[34] Shepherd, J., K. Caldeira, J. Haigh, D. Keith, B. Launder, G. Mace, G. MacKerron, J. Pyle, S. Rayner, and C. Redgwell (2009): "Geoengineering the climate: science," *Governance and Uncertainty, The Royal Academy.*

[35] Soden, B. J., R. T. Wetherald, G. L. Stenchikov, and A. Robock (2002): "Global Cooling After the Eruption of Mount Pinatubo: A Test of Climate Feedback by Water Vapor," *Science*, 296(5568), 727–730.

[36] Sterck, O. (2011): "Geoengineering as an alternative to mitigation: specification and dynamic implications," Discussion paper.

[37] Swart, R., and N. Marinova (2010): "Policy options in a worst case climate change world," *Mitigation and Adaptation Strategies for Global Change*, 15(6), 531–549.

[38] Tavoni, M., and R. Socolow (2013): "Modeling meets science: Modeling meets science and technology: An introduction to a Special Issue on Negative Emissions," *Climatic Change, forthcoming.*

[39] Tavoni, M., and R. Tol (2010): "Counting only the hits? The risk of underestimating the costs of stringent climate policy," *Climatic change*, 100(3), 769–778.

[40] Tchen, A. H. (1980): "Inequalities for Distributions with Given Marginals," *The Annals of Probability*, 8(4), 814–827.

[41] Tilmes, S., R. Müller, and R. Salawitch (2008): "The sensitivity of polar ozone depletion to proposed geoengineering schemes," *Science*, 320(5880), 1201–1204.

[42] Trivedi, P. K., and D. M. Zimmer (2006): "Copula Modeling: An Introduction for Practitioners," *Foundations and Trends® in Econometrics*, 1(1), 1–111.

[43] Victor, D. G., M. G. Morgan, F. Apt, and J. Steinbruner (2009): "Geoengineering Option-A Last Resort against Global Warming, The," *Foreign Affairs*, 88, 64.

[44] Virgoe, J. (2008): "International governance of a possible geoengineering intervention to combat climate change," *Climatic Change*, 95, 103–119.