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Abstract

The potential of climate engineering to substitute or complement abatement of greenhouse gas emissions has been increasingly debated over the last years. The scientific assessment is driven to a large extent by assumptions regarding its effectiveness, costs, and impacts, all of which are profoundly uncertain. We investigate how this uncertainty about climate engineering affects the optimal abatement policy in the near term. Using a two period model of optimal climate policy under uncertainty, we show that although abatement decreases in the probability of success of climate engineering, this relationship is concave implying a rather ‘flat’ level of abatement as the probability of climate engineering becomes a viable policy option. Using a stochastic version of an integrated assessment model, the results are found to be robust to a wide range of specifications. Moreover, we numerically evaluate different correlation structures between climate engineering and the equilibrium climate sensitivity.

Keywords (separated by '-')	Climate engineering - Mitigation - Climate change - Uncertainty - Solar radiation management - Geoengineering
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Climate Engineering and Abatement: A ‘flat’ Relationship Under Uncertainty

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Abstract The potential of climate engineering to substitute or complement abatement of greenhouse gas emissions has been increasingly debated over the last years. The scientific assessment is driven to a large extent by assumptions regarding its effectiveness, costs, and impacts, all of which are profoundly uncertain. We investigate how this uncertainty about climate engineering affects the optimal abatement policy in the near term. Using a two period model of optimal climate policy under uncertainty, we show that although abatement decreases in the probability of success of climate engineering, this relationship is concave implying a rather ‘flat’ level of abatement as the probability of climate engineering becomes a viable policy option. Using a stochastic version of an integrated assessment model, the results are found to be robust to a wide range of specifications. Moreover, we numerically evaluate different correlation structures between climate engineering and the equilibrium climate sensitivity.

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1 Introduction

The slow progress in climate change abatement 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. Among these, climate engineering refers to the deliberate and large-scale intervention in the earth's climatic system with the aim of reducing global warming. Climate engineering options which counteract the temperature increase by managing incoming solar radiation (solar radiation management or SRM) have become increasingly debated in recent years.[1] Climate engineering has been argued to be a more cost-effective solution since it can reduce the effects of global warming relatively fast (Shepherd et al. 2009; Matthews and Caldeira 2007) and hence provides a potential game-changing option for climate policies (Swart and Marinova 2010; Victor et al. 2009). This has fueled a lively policy and scientific debate which is likely to further intensify in the coming years. Several institutions (US Congress, NASA, the Royal Society, National Academy of Sciences, the IPCC, and the UK Parliament) have started assessing and debating the potential of climate engineering. Fundamental opposed opinions are presented in this debate, often attributable to the fundamental uncertainties characterizing climate engineering approaches.

Historically, the reduction in solar radiation after volcanic eruptions has provided natural "experiments" as a basis for climate engineering via solar radiation management. For instance, in 1991, the eruption of Mount Pinatubo injected around 20 megatons of sulfur dioxide into the stratosphere, which led global temperatures to decrease by about 0.5 °C in the years following the eruption (Soden et al. 2002; Crutzen 2006). This illustrates the potential of quickly reducing global temperature through the periodic and continued injection of sulfate particles into the stratosphere. The extent to which this can compensate the radiative forcing of greenhouse gases and the associated climate damages is highly debated. The most recent literature suggests that while climate engineering cannot fully reverse climate change around the globe (Ricke et al. 2010), it still has the potential to partly compensate temperature and precipitation patterns even regionally (although not simultaneously) (Moreno-Cruz et al. 2012; Caldeira and Wood 2008). On the other hand, SRM technologies brings about substantial risks and potential side-effects such as ozone depletion, side effects of the implementation itself (Robock et al. 2009; Tilmes et al. 2008), as well as region-specific impacts such as increased droughts (Haywood et al. 2013). Moreover, SRM does not reduce the amount of carbon in the atmosphere. Therefore, damages from increased CO_2 concentration such as ocean acidification are not mitigated, and, moreover, a climate engineering policy cannot be suddenly discontinued as an abrupt temperature change would likely occur (Brovkin et al. 2008; Irvine et al. 2012). These and other potential side-effects of climate engineering are important to take into consideration, see Robock (2008) and Klepper and Rickels (2014) for a recent overview.

One common feature of most climate engineering options is that it tends to be speculative. First of all, no (large-scale) experiments have been conducted in order to assess its full potential to counteract global warming.[2] Second, the implementation is challenging in many respects. Even if climate engineering measures were effective in mitigating climate change

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[1] The broader term geoengineering in fact encompasses all engineering approaches to alter geophysical processes. While this term has been used extensively in recent years, "climate engineering" has been proposed to refer to methods altering the climate per se, notably the removal of carbon dioxide from the atmosphere and Solar Radiation Management (SRM). Throughout this article, we use the term climate engineering referring to SRM measures, as they have been frequently used interchangeably in the literature.

[2] The recent simulations in MacMartin et al. (2014) suggest that possibly even smaller scale implementations and experiments might be feasible, but on a theoretical level.

and were technically feasible to implement, very little is known about the size and scale of potential side effects discussed above. Still, climate engineering appears to be appealing, notably when facing potentially high costs of climate change mitigation through emission abatement and the political stall in climate policy negotiations. In particular, given the general uncertainties about the expected temperature change and the magnitude of impacts in the future, it has been argued that climate engineering 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, and moral issues regarding the manipulation of the climate, issues in international law regarding unilateral actions related to climate engineering create a strong barrier towards proceeding in research within this field.[3] It is therefore safe to say that if it were to be considered an option, it would take decades before a great deal of the surrounding uncertainties could be resolved (Robock et al. 2012).

Notwithstanding the challenge of modeling climate engineering, the literature examining it has been growing exponentially in recent years (Mercer et al. 2011). Economists have contributed to the debate regarding the risks and virtues of climate engineering, unsurprisingly finding mixed results (see Klepper and Rickels 2012 or Barrett 2008 for an overview). On the one hand, climate engineering can provide a viable strategy and might be the lesser of two evils, in particular if climate change is very harmful in the future (Bickel and Agrawal 2011). On the other hand, it comes with high uncertainty, potentially high costs in terms of potential damages, and an unknown effectiveness in the long run. Therefore, with our current knowledge, it may turn out to be costly to give up on emissions reductions and rely on climate engineering in the future (see e.g., the applications of Nordhaus' DICE model in Gramstad and Tjøtta 2010 or Goes et al. 2011). The fundamental driver of the divergence of opinions in this polarizing debate resides in the assumptions about relative costs, damages, and the uncertainty about these parameters (Sterck 2011). However, very few papers have provided an explicit modeling of the uncertainty of climate engineering, with the exception of Moreno-Cruz and Keith (2012). Their paper is similar to ours as they consider the dynamic decision problem using a simplified model and a numerical implementation based on DICE with convex abatement and linear SRM cost functions. Their numerical results suggest that the lower the side effects of climate engineering and the higher its effectiveness, the lower the abatement effort required in the first stage. Moreover, climate engineering is more likely to be used if the climate sensitivity turns out to be higher. This illustrates its potential "insurance" effect. Their results, however, are mainly numerical and based on a simple integrated assessment model. Furthermore, they do not investigate the impact of the correlation between general climate and climate engineering uncertainties.

Our paper aims at advancing this literature by focusing explicitly on the uncertain features of climate engineering and most importantly how it would affect climate change policies today. Based on an analytical model similar to the one proposed by Lange and Treich (2008), we study the role of the uncertainties surrounding climate engineering and climate change as a whole to see whether it could or should be used in the future, under which conditions, and most importantly how it would affect climate change policies today. We analyze how much of the near-term optimal abatement should be carried out for different subjective success probabilities of a large-scale climate engineering program in the future and for different correlation structures with the uncertainty about the magnitude of climate change. Our paper uses a standard model of dynamic decision theory under uncertainty to analyze the interplay between climate engineering and abatement from an economic cost-minimizing perspective.

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[3] The cancellation of the Stratospheric Particle Injection for Climate Engineering (SPICE) project in 2012 provides an example of the difficulties that research faces in this field due to public opinion or the governance of such projects (Pidgeon et al. 2013).

We introduce a two-period model of abatement and climate engineering, where the latter is only available in the second stage since it is not available as a strategy as of today or the near future. We characterize the uncertainty about both climate engineering as well as the climate, and derive an analytical solution for the optimal policy under a global temperature target, that is, in a cost effectiveness (CEA) (and a CBA)[4] framework. Under fairly general conditions we show that although today's abatement effort is decreasing in the success probability of climate engineering, abatement remains strictly positive and the relation with the probability of success of SRM is strictly concave. As a result, it is optimal to significantly forego current abatement only under very optimistic assumptions regarding the feasibility of climate engineering. We also investigate the potential insurance effect of climate engineering by modeling the relationship between the uncertainty of both the climate sensitivity and climate engineering, and are able to confirm the results for reasonable correlation structures between both sources of uncertainty.

In order to quantify the effects of the analytical model, we use a stochastic version of a large-scale integrated assessment model with a rich description of the abatement options, integrating the possibility of climate engineering as an alternative policy option to abatement, which becomes available in the future with a certain probability. The numerical findings confirm the theoretical results: we find that the optimal path does not deviate too much from the standard optimal abatement path as long as the probability of climate engineering is not close to one. The results are found to be robust to different timings of uncertainty resolution, different climate stabilization targets, and different degrees of correlation of the climate and climate engineering 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 climate engineering options in the future, but it does not rule out the possibility of deploying climate engineering technologies in the future.

This paper is structured as follows. In Sect. 2, we present the general model considering the uncertain effectiveness of climate engineering in a framework with a given climate stabilization target. In Sect. 3, we allow for simultaneous uncertainty of both climate change and climate engineering. Using the an integrated assessment model, we provide a quantitative assessment of climate engineering in Sect. 4. Section 5 concludes.

2 Uncertain Effectiveness of Climate Engineering

We begin by sketching out a simple analytical framework which captures the interplay between climate engineering and abatement under uncertainty in sufficiently general terms. Our model can be thought of as an extension of the uncertainty framework in Lange and Treich (2008) where we add a second uncertain, but possibly very cheap mitigation technology. We model climate engineering as an uncertain process: as of today we do not know how effective it will be in substituting abatement to control global warming. While abatement measures can already be implemented, the limited evidence on the risks and impacts of climate engineering are such that a considerate amount of time will be needed to establish the scientific basis to implement climate engineering at a large scale. The question we try to answer in this section is how this uncertainty affects our decision today to mitigate climate change. Moreno-Cruz and Keith (2012) have highlighted the uncertainty and its importance for the optimal decisions regarding the implementation of climate engineering. They argue

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[4] We applied a similar model in a cost benefit analysis (CBA) framework. Overall, the results are qualitatively very similar. The results are available from the authors upon request.

that even if climate engineering is not potentially effective in offsetting global warming caused by CO_2 emissions, it might considerably shape climate change policies due to the implied quick response of the global temperature.

We use a simple model to analyze this question aiming to derive some general conclusions which economic theory can provide as guidance in this polarizing debate. Empirical calibration and specific assumptions will ultimately determine the best guess estimates of the potential crowding 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 can tell us something about the trade-off between climate engineering and abatement under uncertainty. This is a novel contribution to the literature. We use a simple two-period model where A_t denotes the level of abatement in period $t = 1, 2$, and G the level of climate engineering, which will be implemented only in the second period since it is not available as a large-scale alternative today.

To model the effect on the climate, we use a simple energy balance model, in which the change in the global mean temperature ΔT is approximated by a linear function of cumulative emissions as shown by Matthews et al. (2009).[5] The final temperature increase can then be written as a linear function of $S^{bau} - A_1 - A_2$, where S^{bau} denotes the business-as-usual CO_2 emissions and A_t the abatement in period t. In order to simplify notation, we measure climate engineering G also in terms of its potential to reduce global mean temperature through the radiative forcing and we take into account that its effectiveness is not perfect and moreover uncertain. Its effect on effective temperature change can be expressed by the random variable $\widetilde{\varphi}$ which can take on the values of 1 (with probability p) or 0 (with probability $1 - p$).[6] Overall, the increase of global mean temperature can then be written as:

$$\Delta T = \lambda(S^{bau} - A_1 - A_2 - \widetilde{\varphi} G) \tag{1}$$

where the factor λ denotes the carbon-climate response that takes into account the proportionality of temperature and radiative forcing as well as the equilibrium climate sensitivity.[7] Since the latter is far more uncertain and debated, we will refer to it simply as the climate sensitivity in the following.

The cost function $C_A(A)$ is the standard cost function of abatement and $C_G(G)$ for climate engineering and both A and G are non-negative. It is worth mentioning that we do not include potential damages from climate engineering. While we do not impose any functional form, we need to make some assumptions about the relative costs of abatement and climate engineering. Since we express all variables in their 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 climate engineering is effective, or that if $\widetilde{\varphi} = 1$, then it will be the only policy employed in the second stage. Formally, this can be ensured by assuming that marginal costs of climate engineering are never higher than the initial marginal abatement costs.

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[5] While the relationship between carbon *concentration* and temperature is concave, the authors find a linear response of temperature to cumulative *emissions* in trillion tons of carbon emitted of 1.0–2.1 °C/TtC.

[6] A way to interpret this binary random variable is on the one hand the effectiveness of SRM to tackle global warming, but could also be the social acceptability or political feasibility to implement such a strategy.

[7] In this simple relation we abstract from a non-linear forcing potential from climate engineering (Lenton and Vaughan 2009) and moreover the decay of the atmospheric carbon. While the former feature would limit the potential of climate engineering and thus strengthen our main result, the latter effect is included in the numerical application even though its role is minor, see Matthews et al. (2009).

Assumption 1

$$C'_G(x) \leq C'_A(0) \quad \forall x$$

This assumption in combination with our binary variable for the availability of climate engineering is sufficient to ensure that in the last period only one policy alternative will be used. This is motivated by the literature which portrays climate engineering as a climate strategy with 'incredible economics' (Barrett 2008). Based on estimates of abatement policies compared with cost estimates of climate engineering implementation such as McClellan et al. (2012), this assumption seems reasonable.

Throughout the paper, we deliberately take an optimistic view regarding the costs, potential side-effects, and overall potential of climate engineering vis à vis with abatement. This rather optimistic characterization of climate engineering allows us to explore a 'limiting' case that provides an important benchmark which is further extended in the numerical analysis outlined in the paper. This case can be thought of an upper bound of the role of SRM options in the climate policy portfolio. Most of the results we find here would only be strengthened by assuming a more pessimistic view. In reality, the risks and potential side-effects associated with climate engineering as well as the public opposition and the difficult governance process are likely to limit its potential to meet only a fraction of the climate solution space.

Assumption 1 ensures that if climate engineering turns out to be the most effective ($\widetilde{\varphi} = 1$), it will be adopted as the only policy. However, if $\widetilde{\varphi} = 0$, it will not be used at all. The effectiveness of climate engineering will be learned before the decision is made during the second period. While during implementation, learning about its effectiveness is plausible, our interpretation of availability is more about the political feasibility based on the assessment of effectiveness and potential side effects.

To determine the optimal climate policy, we consider the case of a climate stabilization policy, that is, we specify a ceiling in terms of maximum temperature increase over the pre-industrial level, ΔT^{max}, which can be directly converted into a goal in terms of maximum radiative forcing for a given value of climate sensitivity.[8] The Social Planner then minimizes the cost of attaining this stabilization goal of the induced change in world average temperature. The cost functions of mitigation and climate engineering are assumed to be increasing and convex. The total cost of achieving the target can be written as $V(A_1, A_2, G) = C_A(A_1) + \beta\,(C_A(A_2) + C_G(G))$ where β denotes the discount factor and hence the problem of a risk-neutral social planner can be stated as follows:

$$\min_{A_1, A_2, G} E\left[C_A(A_1) + \beta\,(C_A(A_2) + C_G(G))\right] \quad s.t. \quad \lambda(S^{bau} - A_1 - A_2 - \widetilde{\varphi}G) \leq \Delta T^{max} \tag{2}$$

In the following, we derive a general condition for the curvature of the optimal first-period decision variable $A_1(p)$ with respect to the probability p, which in our case captures the degree of uncertainty or subjective probability of the climate engineering option. Note that the result can however also be applied to other contexts of multiple policy instruments in a dynamic context under uncertainty. Regarding the total expected cost of attaining the stabilization goal, it is clear from (2) that an increase in the success probability of climate engineering reduces the expected costs. In this sense, climate engineering can be seen as an alternative option in the portfolio of actions against climate change, which has a strictly positive effect on the total expected policy costs in this stylized model.

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[8] See also Lemoine and Rudik (2014) who discuss the reasons for specifying temperature targets for climate policy.

Given that either abatement or climate engineering is chosen in the second period, we can obtain the first order condition of the program (2) as

$$C'_A(A_1^*) = \beta\left(pC'_G(S^{gap} - A_1^*) + (1-p)C'_A(S^{gap} - A_1^*)\right) \tag{3}$$

and the second order condition as

$$D \equiv C''_A(A_1^*) + \beta\left(pC''_G(S^{gap} - A_1^*) + (1-p)C''_A(S^{gap} - A_1^*)\right) > 0 \tag{4}$$

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

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 decreases in the success probability p of climate engineering or that $A_1^{*'}(p) < 0$ if Assumption 1 holds.[9] That is to say a more likely effective climate engineering program does reduce abatement today. This result is not surprising given the assumed substitutability between both policies, and confirms the results of Moreno-Cruz and Keith (2012). However, for the sake of this paper, it is more important to explore how effective climate engineering would need to be to reduce today's abatement efforts considerably. To this end, we need to understand the curvature of the function $A_1^*(p)$ and therefore we impose the following assumption discussed below:

Assumption 2 The marginal total cost increase 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 climate engineering costs in the second period $g(A_1) = C_A(S^{gap} - A_1) - C_G(S^{gap} - A_1)$, in the sense that $\frac{h''(x)}{h'(x)} > 2\frac{g''(x)}{g'(x)} \forall x \geq 0$.

The cost gap between climate engineering and abatement in the second period $g(A_1)$ continuously decreases 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 climate engineering, $(C'_G(x) \leq C'_A(x))$. The function $h(A_1)$ on the other hand continuously increases 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 $h(A_1^*) = 0$.

Thus, for all specifications that 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.[10] We are now able to state our first main result.

Proposition 1 *Under the assumptions 1 and 2, the optimal abatement in the first period decreases and is concave in the probability that climate engineering is effective, i.e.,* $A_1^{*'}(p) < 0$ *and* $A_1^{*''}(p) < 0$.

Proof Totally differentiating the first order condition (3) yields $\frac{dA_1^*}{dp} = \beta\frac{C'_G(S^{gap}-A_1^*)-C'_A(S^{gap}-A_1^*)}{D}$. The numerator is negative due to Assumption 1 while the

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

[10] Note that a sufficient condition for the Assumption 1 to hold is a unambiguous ordering of the higher order derivatives between climate engineering and abatement up to order three ($C''_G(x) \leq C''_A(x)$ and $C'''_G(x) \leq C'''_A(x)$) and moreover that $C''''_A \leq 0$.

second-order condition implies that the denominator is positive, hence $A_1^{*\prime}(p) < 0$. For the second part, we differentiate $\frac{dA_1^*}{dp}$ again with respect to p, which yields

$$A_1^{*\prime\prime}(p) = \frac{\beta}{D^2}\Bigg\{-\left(C_G''(S^{gap} - A_1^*) - C_A''(S^{gap} - A_1^*)\right)\frac{dA_1^*}{dp}D - \left(C_G'(S^{gap} - A_1^*) - C_A'(S^{gap} - A_1^*)\right)\left[\frac{dD}{dp} + \frac{dD}{dA_1^*}\frac{dA_1^*}{dp}\right]\Bigg\}.$$

Taking into account that A_1^* itself depends on p as computed before, and noting that $\frac{dD}{dp} = \beta\left(C_G''(S^{gap} - A_1^*) - C_A''(S^{gap} - A_1^*)\right)$ and hence the first and second additive terms in the numerator of the last expression are exactly the same, we get that

$$A_1^{*\prime\prime}(p) = -\frac{\beta^2}{D^2}\left(C_G'(S^{gap} - A_1^*) - C_A'(S^{gap} - A_1^*)\right)\cdot \left[-2\left(C_G''(S^{gap} - A_1^*) - C_A''(S^{gap} - A_1^*)\right) + \frac{dD}{dA_1^*}\frac{C_G'(S^{gap} - A_1^*) - C_A'(S^{gap} - A_1^*)}{D}\right].$$

Now based on Assumption 1, the first term is negative and thus we have that

$$A_1^{*\prime\prime}(p) < 0 \iff \left[\frac{\frac{dD}{dA_1^*}}{D}\left(C_G'(S^{gap} - A_1^*) - C_A'(S^{gap} - A_1^*)\right) - 2\left(C_G''(S^{gap} - A_1^*) - C_A''(S^{gap} - A_1^*)\right)\right] > 0.$$

Noting that in Assumption 2, $h'(A_1) \equiv D(A_1)$ and $g(A_1)$ is the difference between abatement and climate engineering costs in the second period, this condition is equivalent to $\frac{h''(x)}{h'(x)} > 2\frac{g''(x)}{g'(x)}$ for $A_1^{*\prime\prime}(p)$ to be negative □

While the condition in Assumption 2 might seem difficult 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 climate engineering costs 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 climate engineering, this seems to be a justifiable assumption. Considering some frequently used specifications, we find that condition 2 holds for the most widely discussed parameters.

First, let us consider quadratic cost functions (or equivalently, damage functions if climate engineering damages and CO_2 concentrations 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 climate engineering is sufficient to ensure that $A_1^*(p)$ will be concave. This means that abatement will be reduced slower than linearly and optimal first-period abatement only slowly decreases. Similarly, a linear (as in Moreno-Cruz and Keith (2012)) or even quadratic cost function of climate engineering 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 effectiveness probability of the climate engineering option. A linear climate engineering cost function, which is an exponent of the abatement cost function between two and three (implying $C_A'''(A) \geq 0 \geq C_A''''(A)$) also satisfies Proposition 1.This case covers widely used abatement cost functions such as the one used in RICE with an exponent of 2.8 or estimates for EU countries in Eyckmans and Cornillie (2000) with an exponent between 2.1 and 2.9. In multi-model ensembles, which have used a large suite of integrated assessment models (Clarke et al. 2009; Kriegler et al. 2013), marginal abatement costs (as measured by carbon prices) have been shown to be convex with respect to cumulative emission reductions, which are linearly related to radiative forcing, see also Matthews et al. (2009).

These results suggest that for a fairly general specification of the costs of achieving a stabilization goal of global warming, the assumptions of the outlined model hold and that short-term abatement is decreasing but strictly concave in the probability of success of climate engineering. Since optimal abatement is zero only for $p = 1$, this implies a rather gradual (i.e., less than linear) decrease in abatement as the probability of successful climate engineering increases. The intuition for this result comes from the fact that abatement costs are relatively high and convex, moreover climate engineering is only available in the future, and this option might fail to work in the future altogether. That is, climate engineering does provide an alternative to abatement in the model, but the uncertainty of its effectiveness makes abatement today respond slowly to an increase of the the success probability of climate engineering, suggesting a rather *‘flat relation’* between the two climate control strategies.

3 Uncertain Climate Engineering and Climate

Since uncertainties are pervasive in the climate system itself, it seems reasonable to take into account much of this uncertainty and to see how the results with respect to climate engineering might change. Indeed, the strongest argument in favor of climate engineering is that it might provide a hedge against climate change, should this turn out to be more severe than expected. In this section we tackle this issue and model uncertainty also around key parameters of climate change or its impacts. In particular. the climate sensitivity has been found to be highly uncertain in this context, see e.g., Millner et al. (2013). The decision problem becomes now deciding on optimal abatement today and abatement and climate engineering in the future after learning the state of the world. Conceptually, this framework could be related to the theory of endogenous risks (Kane and Shogren 2000) 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 abatement and climate engineering renders this problem much more complex. We therefore concentrate our attention on a fully quadratic model; although 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

$$\underset{A_1}{min} C_A(A_1) + \beta E\left[\underset{A_2,G}{min} V_2(A_1, A_2, G, \widetilde{\varphi}, \widetilde{x})\right] \tag{5}$$

where the objective function in the second period represents the cost of achieving the specified stabilization target in period two. We now consider two sources of uncertainty, the effectiveness of climate engineering ($\widetilde{\varphi}$) and the magnitude of damages or the stringency of the stabilization goal ($\widetilde{x}$). Without loss of generality, we restrict the random variables, namely that $0 \leq \widetilde{\varphi} \leq 1$ and moreover assume that, in expectation, $\widetilde{x}$ equals one so we can easily compare the results to the certainty case. As before, uncertainty is fully resolved before period two so that the decision made during the second period is deterministic. Moreover, we now use a a continuous distribution for $\widetilde{\varphi}$ due to the additional uncertainty on the climate. Note that this implies that even under Assumption 1, we now can have simultaneous abatement and climate engineering implementations in the future, since the effect on radiative forcing is potentially different.

Due to the stabilization target, now in the second period climate engineering and abatement must be such that that the stabilization target in terms of the allowed temperature change is met. This target is now considered to be uncertain: if the climate sensitivity turns out to be high due to positive feedbacks 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 climate engineering and abatement) must be greater or equal to $S^{bau} - \frac{\Delta T^{max}}{\widetilde{x}\lambda}$ where the climate sensitivity $\widetilde{x}\lambda$ is now uncertain. The term $\frac{\Delta T^{max}}{\widetilde{x}\lambda}$ can be interpreted as the cumulative emissions (taking into account climate engineering as effective negative emissions) that 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 implying a more stringent effective emission target. The social planner's decision program in the second period case can be written as:

$$\underset{A_2,G}{min} C_A(A_2) + C_G(G)\ \text{s.t.}\ \widetilde{x}\lambda(S^{bau} - A_1 - A_2 - \widetilde{\varphi}G) \leq \Delta T^{max} \tag{6}$$

We specify the cost functions to be quadratic with marginal abatement costs c_A and marginal costs of climate engineering c_G. The quadratic cost assumptions allow us to keep our optimistic assumption about the costs and potential impacts from climate engineering. Moreover, since this assumption excludes effects from prudence or the third derivatives of cost functions, it does not give rise to a precautionary savings motive in abatement due to the timing of the model. We solve the model backwards starting in the second period. Given that the climate sensitivity $\widetilde{x}\lambda$ and hence the effective emission target $S^{bau} - \frac{\Delta T^{max}}{\widetilde{x}\lambda}$ and the effectiveness of climate engineering are learned before making the decisions on abatement and climate engineering, we know that marginal costs are equalized between them. Solving for the amount of abatement in the second period, one gets that

$$A_2(A_1^*) = \frac{c_G/\widetilde{\varphi}^2}{c_G/\widetilde{\varphi}^2 + c_A}\left(S^{bau} - \frac{\Delta T^{max}}{\widetilde{x}\lambda} - A_1^*\right).$$

The first term can thus be interpreted as the share of abatement of total climate policy in the second period. Based on the optimal second period's decisions, this allows us to use an envelope theorem argument to simplify the first-period decision based on (5). We obtain the optimal first-period abatement level expressed as the share of total abatement without climate engineering option as:

$$A_1^* = \frac{S^{bau} - \frac{\Delta T^{max}}{\lambda}\left(\frac{E[\Omega(\widetilde{\varphi})/\widetilde{x}]}{E\Omega(\widetilde{\varphi})}\right)}{1 + \frac{1}{\beta E\Omega(\widetilde{\varphi})}} \quad \text{where} \quad \Omega(\widetilde{\varphi}) = \frac{c_G/\widetilde{\varphi}^2}{c_G/\widetilde{\varphi}^2 + c_A}. \tag{7}$$

Note that due to the quadratic cost specification without fixed costs, the solution will always be interior.[11] From this condition it can be seen that the quadratic specification implies among others that rather than assuming the uncertain effectiveness of climate engineering, we can specify its costs as uncertain since the tuples $(\widetilde{\varphi}, \widetilde{x}, c_G)$ and $\left(1, \widetilde{x}, c_G/\widetilde{\varphi}^2\right)$ are equivalent in

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[11] Note that in general we don't restrict the level of abatement, even though one could consider the case where, in particular for a high value of the climate sensitivity, traditional abatement measures can be not sufficient to meet a given climate target, see also Neubersch et al. (2014).

this model.[12] The share of abatement of the total climate policy in the second period denoted as $\Omega(\widetilde{\varphi})$and decreases in the effectiveness of climate engineering. It is also 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 climate engineering costs ensure that the following condition holds:

$$\widetilde{\varphi} \geq \sqrt{\frac{c_G}{3c_A}} \tag{8}$$

This condition states that the share of climate engineering in the climate policy during the second period is concave in $\widetilde{\varphi}$ provided that abatement is more expensive. This 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 take the estimate of McClellan et al. (2012) who suggest that climate engineering costs are only around one per cent of the equivalent CO_2 abatement costs, this condition is easily met. Basically, this condition states that climate engineering must be cost-effective enough in order to dominate abatement in the future, which seems reasonable. Based on the analytical formula of first-period abatement and the curvature of $\Omega(\widetilde{\varphi})$ we can derive the following results for the quadratic model specification under consideration:

Proposition 2 *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* (8) *holds, while an increase in risk in* $\widetilde{x}$ *leads to a decrease of* A_1^*. *If* $(\widetilde{x}, \widetilde{\varphi})$ *are not independent and the distribution* $F(\widetilde{x}, \widetilde{\varphi})$ *undergoes a marginal preserving increase in concordance,*[13] *optimal first-period abatement* A_1^* *decreases.*

Proof The first part for independence follows since the numerator of (7) simplifies in this case to $S^{bau} - E\left[\frac{\Delta T^{max}}{\widetilde{x}\lambda}\right]$. Since the term in the expectation is convex in $\widetilde{x}$ and subtracted from S^{bau}, the Jensen inequality immediately implies that an increase in risk in $\widetilde{x}$ leads to a lower level of A_1^*.[14] Considering the denominator of (7), and due to the convexity of $\Omega(\widetilde{\varphi})$ ensured by the condition in (8), by its definition, an increase in risk in $\widetilde{\varphi}$ leads to an increase of $E\Omega(\widetilde{\varphi})$ and hence to a higher level of A_1^*. For the second part, first note that the denominator of (7) is not affected by the marginal preserving increase in concordance. However, an increase in concordance implies that $Cov(\Omega(\widetilde{\varphi}), \frac{1}{\widetilde{x}})$ decreases (see Epstein and Tanny 1980 or Egozcue et al. 2009) since $\Omega(\widetilde{\varphi})$ is monotonically decreasing. Rewriting the fraction in the numerator of (7) as $\frac{Cov(\Omega(\widetilde{\varphi}), \frac{1}{\widetilde{x}}) + E\Omega(\widetilde{\varphi})E\frac{1}{\widetilde{x}}}{E\Omega(\widetilde{\varphi})}$ thus shows that initial abatement decreases since the univariate expectations are unchanged. □

More uncertainty about climate engineering implies a higher level of initial abatement since the probability of having to rely on expensive abatement also in the future is higher. A higher degree of uncertainty about the climate sensitivity on the other hand lowers optimal abatement in the first period. Intuitively, it affects the target in both cases with and without climate engineering, and the possibility of a lower target reduces to first-period abatement

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

[13] Concordance describes the degree of association between two random variables in a more generalized way than correlation.

[14] This effect is due to the fact that the target in terms of emission reduction depends on the reciprocal of the climate sensitivity. Since $E[\widetilde{x}] = 1$, the convexity around this point is comparably small as the hyperbola in this region can be approximated by a linear function and thus the effect of uncertainty of $\widetilde{x}$ alone is expected to be rather low.

to avoid potentially unnecessary, "irreversible" abatement costs. In this model, due to the quadratic specification, no precautionary motive arises, which explains this effect besides the lock-in effect of initial abatement.

If the effectiveness of climate engineering and the uncertain stabilization target are not independent, this introduces another effect depending on the sign of the correlation. It affects the numerator of (7) which can be understood as the perceived stringency of the stabilization target from an ex-ante perspective. To separate both effects, we use the concept of concordance as in Tchen (1980). 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 $\frac{\Delta T^{max}}{\lambda}\left(\frac{E[\Omega(\widetilde{\varphi})/\widetilde{x}]}{E\Omega(\widetilde{\varphi})}\right)$ becomes less stringent than if it were known with certainty $(\frac{\Delta T^{max}}{\lambda})$ if $(\widetilde{x}, \widetilde{\varphi})$ become less concordant. That is, we obtain an "insurance" effect of climate engineering: initial abatement can be lower if climate engineering is more likely to be effective when $\widetilde{x}$ is high. Note that this "insurance" effect might be counteracted by the direct interaction between effectiveness of climate engineering and the climate sensitivity, see also Ricke et al. (2012).

But how strong are these effects? In order to assess the relative magnitude, we turn to a simple calibration of the model. In particular, we specify the climate engineering effectiveness as a binary Bernoulli random variable: $\widetilde{\varphi} \sim \{1 : p; 0 : (1 - p)\}$. The potential of climate engineering is thus either zero or as effective as abatement in order to reduce global temperature. We assume, as argued in McClellan et al. (2012), that the cost of climate engineering is around one per cent of abatement , i.e., $c_A/c_G = 100$, and use a discount factor for a fifty-year time span (the first period in our model) based on a yearly one percent discount rate. Finally, we assume a degree of uncertainty about the climate sensitivity typically found in the literature (Meinshausen et al. 2009)in that we consider a uniform distribution $\widetilde{x} \sim U[0.5, 1.5]$ resulting in a range of 2–4.5 °C which is considered most likely according to the IPCC fourth assessment report.

Figure 1 shows the optimal first-period abatement relative to the total abatement level without the climate engineering option (denoted CE) for varying probabilities of climate engineering becoming a viable climate policy option. Considering uncertainty as specified and assuming that both random variables are independent, the curve is concave in p–as shown in the previous section—and initial abatement A_1^* is substantially higher than under certainty (dashed line), showing a rather "flat" behavior in the value of p.[15]

Let us now consider different degrees of the relatedness between the effectiveness of climate engineering and the climate sensitivity. To date, little is known about the correlation between how possible climate engineering strategies work and the fundamental parameters of climate change, in particular, the reaction of the climate to greenhouse gas emissions. Matthews and Caldeira (2007) argue that a priori there is no reason to assume any relationship between both parameters. On the other hand, the potential difficulty of climate engineering to compensate for the regional differences of climate change might give rise to a negative correlation (Ricke et al. 2012). Moreover, if aerosols are more effective at cooling the climate, the historically observed warming and thus estimates for the climate sensitivity could have been too low, which would imply a positive correlation.[16]

To quantify how the correlation between climate engineering effectiveness and climate sensitivity would affect our results, we use a copula approach to model the joint distribution

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[15] As stated in Proposition 2, the situation where only the climate sensitivity is uncertain (depicted in light blue) implies a lower level of initial abatement. However, as argued before, this effect is much smaller than the effect of uncertain climate engineering.

[16] We thank an anonymous referee for pointing out this interesting point to us.

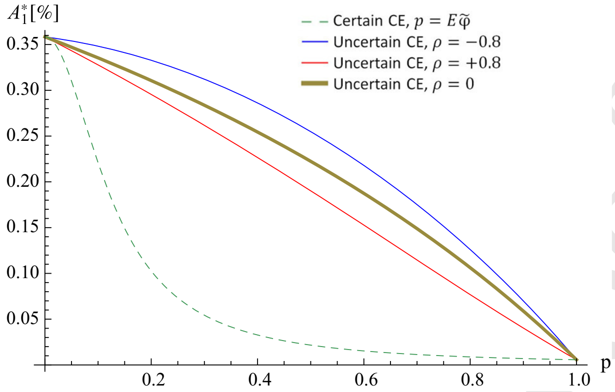

Fig. 1 Share of first-period abatement of total abatement without climate engineering for different values of p

$F(\widetilde{x}, \widetilde{\varphi})$ 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 a positive as well as a negative relationship, since it is symmetric, and allows including very extreme degrees of relatedness, see, e.g., Trivedi and Zimmer (2006). This approach allows the quantitative impact on the optimal abatement policy to be assessed. In Fig. 1, we also show the optimal first-period abatement for the extreme positive and negative correlation admissible. We take rather extreme values for the parametrization of the copula such that for $p = 0.5$ it implies a rank correlation between $\widetilde{x}$ and $\widetilde{\varphi}$ of -0.8, zero, and $+0.8$. 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 $A_1^*(p)$ becomes almost linear. In this case, climate engineering has a strong insurance character and therefore the least abatement is optimal. But even in this case of positive hedging of climate engineering against severe climate outcomes, first-period abatement remains substantially higher compared to the certainty case for all chances that climate engineering is effective.[17]

4 Numerical Results with an Integrated Assessment Model

In this section we use the integrated assessment model (IAM) WITCH (Bosetti et al. 2009) 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 climate engineering on the optimal abatement path and a series of key variables of climate mitigation effort. The integration of the climate engineering strategy into a numerical IAM has been carried out in some recent papers using DICE, a simplified, one region model Bickel and Agrawal (2011); Goes et al. (2011); Gramstad and Tjøtta (2010). In this section we introduce climate engineering and uncertainty in a fully fledged integrated assessment model. First, we consider the case of only uncertainty about climate engineering and then we take into account also uncertainty about the climate sensitivity.

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[17] 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.

WITCH has been used extensively in the literature of scenarios evaluating international climate policies. It is a 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 abatement options both in the energy and non-energy sectors. The choice variables are investments and activities in the overall economy, in the abatement technologies, and in the knowledge sector. 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-year 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 portraying different degrees of cooperation among regions as well as 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 global social planner. The model is solved numerically in GAMS/CONOPT. A description of the main model equations can be found on the model website at www.witchmodel.org.

For the purpose of this paper, two main model extensions have been carried out. The first extension is using a stochastic version of the model. Stochasticity has been introduced in IAMs in several recent contributions, in the most cases using a version of DICE, see Keller et al. (2004), Lontzek et al. (2015), or Lemoine and Traeger (2016). In order to account for the uncertainty of climate engineering and the climate response, we use a stochastic programming version of WITCH (see Bosetti and Tavoni (2009) for a previous application). Model variables are redefined on nodes belonging to a scenario tree with two branches;[18] at a given point in the future, climate engineering can either succeed (with some probability p), or fail (with probability $1 - p$). In the case of the uncertainty on both climate engineering and climate, we use a four-branch scenario tree. Despite the simplified description of the state space, this reformulation of the model allows us to capture the implications of uncertainty on the abatement strategy before uncertainty is resolved, enabling us to devise an optimal hedging strategy.[19] Given that utility is defined as a 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 et al. (2013).

The second model extension regards the development and inclusion of a climate engineering module. We model climate engineering as an option to reduce solar radiation through stratospheric aerosols. Specifically, we model million tons of sulfur (teragrams or TgS) injected into the stratosphere at the global scale to lead—if successful—to a negative radiative forcing of $-1.75 \frac{W}{m^2 TgS}$, which is a best guess estimate as in Gramstad and Tjøtta (2010), based on a range from -0.5 (Crutzen 2006) to -2.5 (Rasch et al. 2008a). We also assume a stratospheric residence time of two years, which is in the range of a few years (Rasch et al.

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

[19] 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.

2008b). Finally, we assume a linear cost function at a cost of 10 billion \$/TgS within the range considered in the literature, between 5 (Crutzen 2006) and 25 billion (Robock et al. 2009) USD per TgS. In line with the objectives of this paper, this specification of climate engineering is an optimistic one, in particular since we abstract from side-effects and damages associated with the deployment of climate engineering; 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 since increasing the costs of climate engineering and reducing the costs of abatement respectively would increase the optimal first-period abatement level, further strengthening our results.

We run scenarios to mimic the theoretical approach outlined before. In particular, we implement the stabilization policy by imposing a target[20] to be met by 2100 in terms of "very likely" maintaining the temperature increase below 2 °C, which we implement through a target based on a radiative forcing of $2.8\,\mathrm{W/m^2}$. In this set up we do not consider the climate feedback on the economy, but rather prescribe the climate stabilization policy. The social planner maximizes global welfare defined as expected discounted utility based on a logarithmic utility function.

Figure 2 shows the main results with a probability $p = 0.5$ of climate engineering becoming available in the year 2050. For comparability, we also report a scenario without the climate engineering module (green dotted line) as well as the no climate business as usual (BAU) policy (black dash-dotted line). In the state of the world in which it is effective (red line), climate engineering turns out to be a perfect substitute for abatement; consequently, post 2050 abatement becomes zero and the the forcing target is achieved entirely via climate engineering, which is implemented just before 2100, given the assumptions that it is fast, costs are linear, and the forcing target can be overshot. These results are expected given the optimistic assumptions regarding the effectiveness and costs of climate engineering. In the case were CE is no effective (blue dotted line), emissions have to be reduced even below the case without CE due to the reduced mitigation prior to 2050. Now for the short and medium term policy implications, it is interesting to understand to what extent the climate strategy changes with respect to the certainty case before the uncertainty about climate engineering is resolved. Figure 2 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 climate engineering option. In both cases, significant abatement is carried out, both by energy efficiency measures as well as by deploying abatement technologies such as carbon capture and storage (CCS), renewable energy, nuclear power and low-carbon fuels. The marginal social cost of carbon in 2010 is 28.9 \$/tCO2 and 19.4 \$/tCO2 for the cases without climate engineering, with a 50% chance that climate engineering is effective respectively. Thus, as in the case of the analytical model, hedging against the risk that climate engineering is not 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 which is long lived. It would also preclude the eventual attainment of the climate stabilization target, even when accounting for abatement technologies, which allow sequestering CO_2 from the atmosphere.[21]

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[20] The target is an 'overshoot' one, i.e., the 2100 target level can be exceeded prior to 2100. It 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.

[21] 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 (2010).

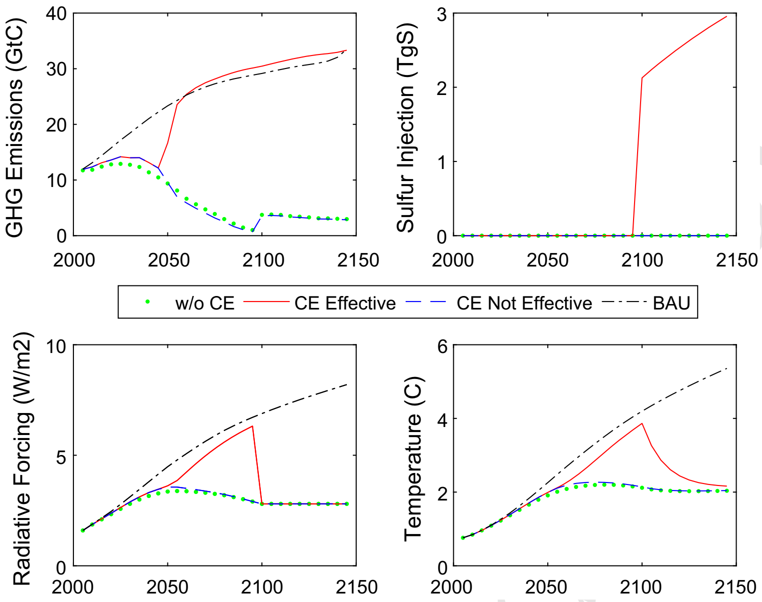

Fig. 2 Climate and emission trajectories ($p = 0.5$)

So far, we have considered that the probability of climate engineering becoming a viable option is $p = 0.5$. 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 ten different values of p (from 0 to 1) and have determined the actual shape of abatement before the resolution of uncertainty in 2050 for increasing the success probabilities of climate engineering. Figure 3 shows this relationship for the climate stabilization target and alternatively a cost-benefit approach based on a damage function (analytical and numerical results are available upon request from the authors).

The results of Fig. 3 clearly confirm the theoretical findings of our analytical model. The relation between optimal abatement prior to the resolution of uncertainty and the success probability of climate engineering appears to be concave and moreover quite “flat” when we increase p. Moreover, the decrease of early abatement in p is slower in the CEA case of a stabilization target while it becomes closer to linearity in the CBA case.[22] With respect to the magnitude, the level of abatement declines to almost zero only if the probability is very high: at an 80% success probability of climate engineering, optimal abatement is approximately 60% of what would be carried out in the absence of climate engineering. This result is particularly strong compared to the certainty case: if it is known that $\varphi = p$, no abatement would be implemented for any value of φ not too close to zero[23], since in this case climate engineering 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 abatement policies even when taking a very optimistic viewpoint on the potential of climate engineering. Given the non linear relation between

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[22] We performed a similar analysis using a CBA approach with a damage function rather than a fixed climate target. These results are available upon request from the authors.

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

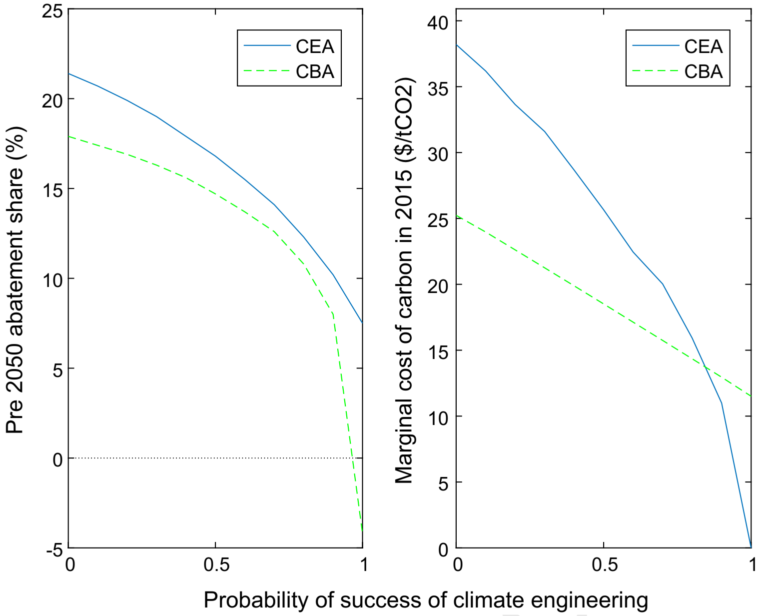

Fig. 3 The share of pre-2050 abatement and the marginal cost of carbon

abatement and marginal costs, the marginal abatement cost—shown in the right panel of Fig. 3—is more sensitive to the probability of success of climate engineering.

As in Sect. 3, we now introduce uncertainty about not only the effectiveness of climate engineering, but also climate change itself. In particular, we consider a binary distribution for the value of the equilibrium climate sensitivity (CS) which is calibrated at 3.2 in the standard version of WITCH. We assume that it can either take on a value of 2.7 or 3.7 with equal probability. Although this approach can be considered as rather conservative compared to estimates of the distribution of climate sensitivity (e.g, Murphy et al. (2004)), it still captures the generally considered range of its values. We consider again a policy aiming at limiting the temperature increase to at most 2.5 °C by the end of the century. Given that now both climate engineering and climate are uncertain, we use a four-branch stochastic tree structure in WITCH. We assess the cases when different random variables are both uncorrelated and correlated.[24] In particular, we consider two rather extreme correlation structures where the probability of climate engineering 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). This results in a bivariate distribution with unchanged marginal distributions but a correlation coefficient of $\rho = +0.8(-0.8)$, which can be considered a very extreme correlation structure. In particular, a very high correlation could rationalized if the probability of climate engineering were to be interpreted as its public acceptability, which could be higher if climate change impacts are more severe. Table 1 summarizes the abatement effort prior to the resolution of uncertainty in all scenarios compared to the abatement over the whole century in the certainty case without climate engineering. That is, the values can be interpreted as how strong the short—to medium term optimal abatement levels are across scenarios.

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[24] 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.

Table 1 Abatement relative to total abatement in the 21st century in the certainty case without climate engineering for different correlation structures

Scenario	SRM	Abatement 2005–2050 (%)
$\rho = 0$	yes	16.2
$\rho = +0.8$	yes	10.4
$\rho = -0.8$	yes	19.1
certainty	no	17.1
uncertain CS	no	20.3

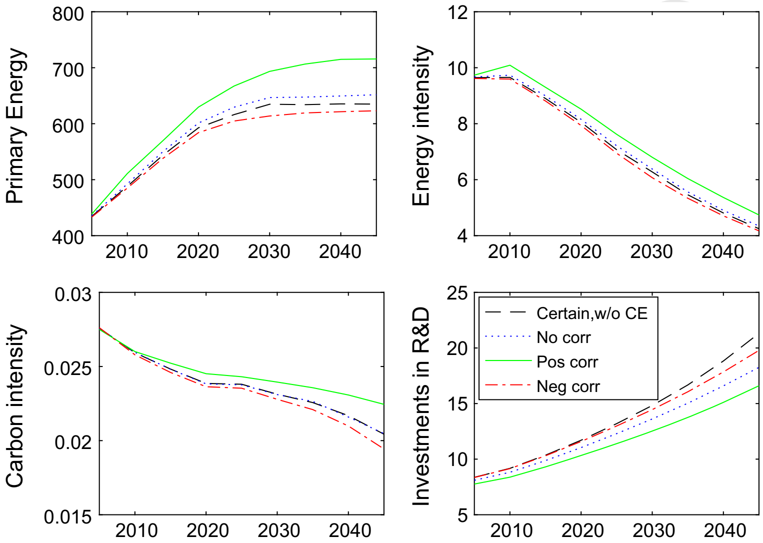

Fig. 4 Emission and energy related variables 2005–2045, for different correlation structures between CS and SRM

The table shows that climate sensitivity uncertainty alone leads to higher initial abatement (20.3 vs. 17.1%). With the most unfavorable correlation structure in which climate engineering is likely to be effective when CS is low ($\rho = -0.8$), the abatement level is only slightly reduced to 19.1%. In the uncorrelated and positive correlation cases, initial abatement is lowered to around 16 and 10% of total 21st century abatement, respectively. Even with a very optimistic correlation structure in which climate engineering is most effective when the climate warms mostly and thus has a strong insurance characteristic, roughly half of the abatement remains socially optimal .

Figure 4 provides an additional comparison of the scenarios with different correlation structures, by providing a series of key indicators of transformation of the energy system.[25] The chart shows that the extent of the transformation of the energy system towards an efficient and low carbon one is indeed negatively driven by the correlation between climate engineering effectiveness and climate sensitivity: in particular when the correlation is positive (green solid line), there is significant less effort to promote energy efficiency, reduce carbon intensity, and invest in energy saving research and development. However, all the scenarios entail significant efforts to promote a more efficient and clean energy system. Moreover, if the correlation is

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[25] Primary energy is measured in exajoules, energy intensity in MJ per US-\$, carbon intensity in kgC/MJ and investment in bln. US-\$.

negative (red dash-dotted line), energy and carbon intensity improvements are even higher than under certainty without CE (black dashed line).

Overall, the WITCH numerical results provide further support of the thesis presented in the preceding sections: even when considering the insurance value of climate engineering, the traditional strategy to mitigate emissions by restructuring the energy sector is only partially crowded out and remains the most important climate policy option in the short and medium term.

5 Conclusion

This paper has assessed the interplay between climate engineering and abatement in the presence of uncertainty. We have deliberately taken an optimistic view regarding the costs and effectiveness of climate engineering, and have studied to what extent the uncertainty about climate engineering provides a rationale for undertaking more or less abatement. To address this question, we have used a rather general analytical economic model as well as a numerical integrated assessment model and have explored the optimal economic decisions both in a cost effectiveness framework.

Our results consistently show that considering the possibility of climate engineering through solar radiation management as a comparably cheap and effective alternative to traditional abatement climate policies has an impact on optimal climate change policies. However, we demonstrate that even when disregarding potential side effects and secondary costs, the uncertainty surrounding the large scale implementability of climate engineering[26] gives rise to a strong case of traditional abatement as an optimal near-term climate policy. In particular, our paper shows that the response of abatement to the success probability of climate engineering is nonlinear and strictly concave, thus implying a rather constant or “flat” reaction of abatement to the introduction of climate engineering. Previous studies such as Bickel and Agrawal (2011), Gramstad and Tjøtta (2010), Goes et al. (2011), and Sterck (2011) do not take into account this dynamic decision problem but rather rely on Monte Carlo exercises which do not capture the dynamic learning and decision making process. We also show that our results hold true to a significant degree even when we allow for different relations between the uncertainty about climate engineering and the climate, as a way to assess the insurance value of climate engineering. Our results are also confirmed by means of extensive robustness analysis on several key parameters.

Further research is a prerequisite to assess whether there will be a viable climate engineering option at some point in the future and how or whether it could alleviate global warming (MacMartin et al. 2014). Our results however suggest that, for the time being, climate engineering does not warrant to be taken as a reason to significantly delay the abatement effort from an economic point of view, even under optimistic scenarios related to its feasibility and acceptability. These results are derived disregarding any ethical or governance issues which have been shown to raise further concerns regarding the potential of climate engineering.

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[26] Uncertainty can also be interpreted in terms of public acceptance or prohibitively high costs or side-effects.

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