Reexamining the economics of aerosol geoengineering

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Abstract

In this paper, we extend the work of Goes, Tuana, and Keller (2011; GTK) by reexamining the economic benefit, of aerosol geoengineering. GTK found that a complete substitution of geoengineering for CO_2 abatement fails a cost-benefit test over a wide range of scenarios regarding (i) the probability that such a program would be aborted and (ii) the economic damages caused by geoengineering itself. In this paper, we reframe the conditions under which GTK assumed geoengineering would/could be used. In so doing, we demonstrate that geoengineering may pass a cost-benefit test over a wide range of scenarios originally considered by GTK.

Keywords: geoengineering, solar radiation management, economics

1. Introduction

The recent paper by Goes, Tuana, and Keller (2011, hereafter GTK) analyzed the economic benefit, “or lack thereof,” of aerosol geoengineering (GEO). Their paper and the model presented therein provide a useful framework for understanding and exploring the differing perspectives surrounding research into and possible deployment of geoengineering. GTK found that complete substitution of GEO for CO_2 abatement fails a cost-benefit test over a wide range of scenarios regarding (i) the probability that such a program would be aborted and (ii) the damages caused by its implementation (see their Fig. 7).

In this paper, we reconsider GTK’s analysis and extend their arguments. In so doing, we demonstrate that GTK’s conclusions were based on their framing of the GEO-use decision, rather than on the underlying concept itself. First, GTK assumed that a decision to use GEO is a decision to pursue a policy of no emissions controls. Since a policy of no controls is, by definition, economically worse than optimal controls, especially so given GTK’s assumptions, burdening a decision to use GEO with the decision to pursue no controls conflates the costs of these two distinct decisions. Second, they compared their policy of GEO use along with no emissions controls to a policy of “optimal” and strong emissions controls (e.g., GTK’s abatement strategy called for a 25% reduction in global CO_2 emissions by 2015 and 40% by 2025). As we show below, the breakeven probabilities provided by GTK are very sensitive to assumptions of what will occur if GEO is not used. Third, GTK assumed that society cannot react to an aborted GEO program by implementing emissions controls, for example. This increases the potential risk of pursuing GEO. Finally, while they allowed for discontinuities in the deployment of GEO, GTK assumed that emissions controls would continue in perpetuity.

This paper does not argue either for or against geoengineering deployment. Rather, our intent is to show that reframing GTK’s positioning of GEO results in GEO passing a cost-benefit test over the wide range of scenarios, related to the chance a GEO program would be aborted and the damages caused by its implementation, that GTK considered. This does not imply that GEO would pass cost-benefit test under other assumptions. Indeed, future research may identify significant drawbacks to any GEO implementation.

This paper is organized as follows. In the next section, we summarize GTK's methods, results, and analysis. In §3, we reframe the use of GEO and extend GTK's analysis. Finally, we conclude in §4.

2. GTK Methods, Results, and Analysis

GTK used the Dynamic Integrated model of Climate and the Economy (DICE-07) (Nordhaus, 2008) but made four changes to this model. First, they included a term in DICE's radiative forcing equation to account for the quantity of SRM deployed, measured in W m^{-2} (see their Equation 14). This technique was also employed by Bickel and Lane (2010). Second, they altered the term structure of discount rates (see their Fig. 1) by using the framework presented by Newell and Pizer (2004), which is based on Weitzman (1998). Third, they replaced DICE's climate model with an implementation of DOECLIM (Kriegler, 2005), which they argued is better able to capture the fast response of atmospheric temperatures to the presence of aerosols (see discussion in their §2.3). Finally, GTK replaced DICE's damage function (see their Equation 15), which is a function of temperature change, with a damage function developed by Lempert et al. (2000). This new damage equation is a function of both the temperature change since pre-industrial times and the rate of temperature change. In addition, they added a component to this function that accounts for the economic damages caused by the use of GEO. Specifically, they assumed that damages due to GEO increase linearly, from zero, with usage intensity, and defined a parameter θ, which is the damage caused by GEO, as a percent of gross world product (GWP), when GEO offsets radiative forcing equal to a doubling of CO_2 concentrations (again, see their Equation 15).

In this paper, we too use DICE-07 and implement all of the modifications detailed above. As we show below, our results, given the same assumptions and framing, closely match those of GTK. We then analyze other GEO-usage scenarios and test the sensitivity of GTK's results to assumptions regarding discounting.[1]

[1] GTK used the discounting framework detailed in Newell and Pizer (2004). As Gollier and Weitzman (2010) have recently shown, this framework assumes there is an immediate and permanent dislocation in

GTK focused the majority of their attention on two policy alternatives: optimal abatement of CO_2 emissions beginning in 2015 (Abate) and business-as-usual (BAU), the latter's being a policy of no controls. They allowed for the use of GEO in the BAU case, also beginning in 2015, and assumed that this program either will be aborted 50 years later (intermittent GEO) or will continue indefinitely (continuous GEO).

GTK considered the uncertainty in three important model parameters: climate sensitivity, abatement costs, and climate damages. Their paper further discussed and supported these assessments (see their §2.4). Following GTK, we discretize these uncertainties, yielding 6300 States of the World (SOW): 50 possible outcomes for climate sensitivity, 7 for abatement costs, and 18 for damages.

2.1 GTK's Base-Case Results

We begin by verifying GTK's base-case results (see discussion in their §4), which were based on best-guess estimates for each of the three uncertainties described above and an assumption that deployment of GEO does not cause any economic damages (i.e., $\theta = 0$). Given our use of the same models and assumptions, our results are similar to GTK's. For example, Fig. 1 presents the radiative forcing (panel a) and temperature changes (panel b) for BAU, optimal abatement, continuous GEO, and intermittent GEO (compare to GTK's Fig. 3a and 3c). As highlighted by GTK, we see that once GEO is aborted, atmospheric temperature increases rapidly, returning after about 40 years to the level that would have been obtained under BAU. This issue has been raised by several authors including Wigley (2006) and Matthews and Caldeira (2007). Fig. 1 also presents the economic damages (climate damage and abatement costs, panel c) and abatement rate (panel d) for our implementation of the GTK model (compare to GTK's Fig. 4b and 4c). BAU damages exceed 2% of GWP in 2075, and total damages under abatement surpass 2% of GWP around 2055. Damages increase above the BAU scenario when GEO is aborted, slightly exceeding 6% of GWP, but quickly return to the BAU and remain there for the duration. While our base-case damage estimates are broadly similar to GTK, they not identical. For example, our

the return to capital. Gollier (2009) proved that if uncertainty in returns is transitory, for example, if it follows Geometric Brownian Motion, as assumed by Newell and Pizer (2004), then the term-structure of interest rates should be flat.

peak damage estimates, in the year 2075 are slightly higher than those reported by GTK, while our 2065 and 2085 damages are lower (compare our Fig. 2a to their Fig. 4b). Exactly matching GTK's results is difficult because the damage estimates are highly sensitive to the damage equation parameters and differences in the rate of temperature changes. These differences, however, do not alter (i) our ability to closely match GTK's overall results or (ii) our conclusions. This occurs for two reasons. First, neither ours nor GTK's results or conclusions are based on this base-case analysis. Rather, these figures are meant to help the reader understand the structure of the model. As described above and elaborated on below, both we and GTK determine our results by computing averages across 6300 SOW, none of which are the best-guess values. GTK do not present their best-guess estimates and therefore our estimates may not match theirs. Second, as can be seen in Fig. 2a, the damages attributable to aborting GEO, are a relatively small addition to the total damages under this scenario, as compared to BAU (compare the area under the Interm. GEO curve to the BAU curve).

We have included in Fig. 1 DICE-07's estimates of the optimal radiative forcing, temperature change, total costs, and abatement (i.e., these values under a policy of optimal abatement). GTK's modification of DICE-07 significantly increased climate damages and therefore the optimal level of abatement. For example, under DICE-07 the maximum temperature change reaches 3.5K, whereas GTK's model implements a level of abatement sufficient to hold temperature changes below 2K.

As a point of reference, Fig. 2 explores the effect of GTK's modeling changes on the optimal level of emissions controls. The line labeled GTK is the emissions-control profile used by GTK and in this paper. DICE-07 is the best-guess optimal emissions profile obtained from the base-case DICE-07 model (i.e., all input uncertainties set at their mean or "best-guess" values), as reported by Nordhaus (2008). DICE-07+LEM is the best-guess optimal emissions profile when DICE's damage function is replaced with the one used by GTK, which is based on Lempert et al. (2000). DICE-07+LEM+DOE is the best-guess optimal emissions profile when DICE's damage function is replaced by the one used by GTK and DICE's climate model is replaced by DOECLIM. Finally, DICE-07+LEM+DOE+NP is the best-guess optimal emissions profile when one makes the previous two changes and also replaces DICE-07's discounting with the Newell and Pizer (2004) methodology used by GTK. The difference between DICE-07+LEM+DOE+NP and GTK is that the former is the best-guess emissions control profile whereas the latter has been optimized under uncertainty. While there is some difference between these two strategies, they are rather close. For example, the GTK strategy, optimized under uncertainty, phases out CO_2 emissions by 2085, whereas the best-guess policy phases out CO_2 by 2105. GTK's emissions control profile, which we, again, use in this paper, is more aggressive because it takes into account the possibility that particular uncertainties (e.g., the climate sensitivity) might obtain values that would result in increased warming. However, the primary difference between DICE-07 and GTK's strategy is the change to the discounting framework.

In the online supplement to this paper, we present the cumulative discounted total costs under each of GTK's scenarios (Fig. S1). This analysis demonstrates that the cumulative costs of GTK's aborted GEO program are less than the costs of BAU, assuming GEO causes no additional damage. This suggests that adding GEO to a BAU policy could be better than BAU even if the GEO program is later aborted. We also note that the total costs of an aborted GEO program are lower than optimal abatement through 2150—almost 100 years after the GEO termination date. We explore these issues further in §3, including consideration of cases where GEO itself causes damages.

2.2 Probabilistic Results

As mentioned above, GTK considered 6300 equally likely SOW (50 possible outcomes for climate sensitivity, 7 for abatement costs, and 18 for damages). The online supplement to this paper displays a simplified decision tree representing GTK's framing of the GEO decision (Fig. S2). Specifically, GTK assumed that society can choose either Optimal Abatement (Abate) or BAU with GEO (BAU_GEO). The expected utility of the Abate alternative is

$$EU[Abate] = \sum_{i=1}^{6300} \frac{1}{6300} U(SOW_i, Abate), \tag{1}$$

where SOW_i is the i-th SOW and $U(SOW_i, Abate)$ is the utility assigned to the i-th SOW given that the Abate strategy is in place. In other words, both we and GTK compute the expected utility of each alternative, where the expectation is taken with respect to GTK's 6300 SOW. Again, the emissions profile associated with Abate is shown in Fig. 1d and Fig. 2. GTK found this optimal policy using a global optimization method described in McInerney and Keller (2008). We do not repeat GTK's analysis here since the optimal policy is provided in their Fig. 4c.

If, on the other hand, society chooses BAU_GEO, then GEO is used to completely offset all energy imbalances created by greenhouse gas emissions (and land use changes). Under this alternative, GEO will be aborted after 50 years (in 2065) with probability p or continued indefinitely with probability 1-p. If GEO is aborted, the expected utility is EU[BAU_GEO_INT, θ], where we have included θ to emphasize that the value of this outcome depends upon the damages caused by GEO. If GEO is continued indefinitely, the expected utility is EU[BAU_GEO_CONT, θ], where, again, the expectations are take with respect to GTK's 6300 SOW, as in Equation (1). The expected utility of BAU_GEO is then

$$EU\left[\text{BAU\_GEO},\theta\right] = pEU\left[\text{BAU\_GEO\_INT},\theta\right] + \left(1 - p\right)EU\left[\text{BAU\_GEO\_CONT},\theta\right]. \quad (2)$$

GTK solved for the breakeven probability, p^*, that would make society indifferent between Abate and BAU_GEO, or when EU[Abate] = EU[BAU_GEO, θ], which is given by

$$p^*(\theta) = \frac{EU[\text{BAU\_GEO\_CONT},\theta] - EU[\text{Abate}]}{EU[\text{BAU\_GEO\_CONT},\theta] - EU[\text{BAU\_GEO\_INT},\theta]}. \quad (3)$$

This probability is a function of θ, the damage caused by the use of GEO. The numerator of p^* measures how much better off society is under a continuous GEO program than it would have been otherwise, where GTK assume that "otherwise" is optimal abatement. The denominator measures how much worse off society would be under an aborted GEO program compared to a continuous GEO program. There are many reasons that GEO could fail such a test. For example, if one assumes, as GTK did in many cases, that the damages caused by a continuous GEO program are larger than the damages caused by climate change (climate damages and abatement costs), then GEO would be an uneconomic choice.

It is important to emphasize that p^* is not the breakeven probability of "geoengineering." Rather, it is the breakeven probability between *BAU-with-GEO* and optimal abatement. These are different and, as Equation (3) makes clear, the baseline to which one compares the use of GEO will significantly affect these breakeven probabilities. This includes assumptions regarding the efficiency of the abatement strategy. The abatement strategy used by GTK was optimal and therefore *EU*[*Abate*] was maximal. As can be seen in Equation (3), this will result in lower breakeven probabilities than a non-optimal abatement program. Likewise, GTK assumed that GEO can perfectly balance all energy imbalances. The impact of this assumption is harder to sign since it alters the numerator and denominator of Equation (3).

Fig. 3 presents a scenario map for the breakeven probability and the level of economic damages, θ, caused by GEO, using GTK discounting. The line dividing the GEO Passes and GEO Fails regions is the set of breakeven probabilities. If $p^* = 0$ (GEO will not be aborted), then any level of GEO damages above about 0.74% of GWP would result in optimal abatement being preferred to BAU-with-GEO. Increasing the probability that GEO will be aborted decreases the level of tolerable damages. GEO is not preferred for any level of damages if the probability that GEO is aborted is greater than about 0.15. These results are very close, but not identical to those of GTK (see their Fig. 7). For example, when $p^* = 0$, GTK found any level of GEO damages below about 0.60% would result in BAU-with-GEO being preferred. Again, the damage estimates are very sensitive to changes in the damage equation parameters. Based on the very small region where GEO passes the cost-benefit test, GTK concluded that substituting GEO for abatement fails a cost-benefit test "rather close to the most optimistic assumptions, and…for most of the explored parameter combinations."

We add to Fig. 3 a line (triangles) that identifies the breakeven line under DICE discounting. The emissions control strategy for this case was obtained using best-guess parameters and is the policy labeled "DICE-07+LEM+DOE" in Fig. 2. The region in which GEO may pass a cost-benefit test is considerably enlarged under DICE discounting. For example, a continuous GEO program passes as long as θ is less than about 1.4%. An aborted GEO program passes as long as θ is less than about 0.5%. In other words, if the damages related to GEO are less than 0.5% of GWP then GEO may pass a cost-benefit test even if society knew the program would be aborted, but could do nothing, either now or in the future, to deal with that scenario. Again, this result may not hold under a different set of assumptions.

Several questions naturally arise regarding this analysis:

1. Do we face a choice between optimal abatement *or* complete substitution of geoengineering for emissions controls? This will affect the results, as Equation (3) makes clear; the breakeven probability strongly depends on the baseline to which GEO is compared.
2. Should we assume that society cannot respond when the GEO program is aborted? If society can choose abatement now, why can't it choose abatement 50 years from now after it has learned that its GEO program has ended?
3. Could the same factors that GTK posited would interrupt a GEO program (e.g., a war or a breakdown in an international agreement) also result in the abandonment of emissions controls?

3. Reframing the Use of Geoengineering

In this section, we reframe the use of GEO by considering several deployment scenarios. The cases we consider are not the only possible uses of GEO. Rather, we consider canonical usage scenarios by relaxing GTK's assumptions that GEO is used only under BAU, that abatement cannot be interrupted, and that society is unable to respond in the event of an aborted GEO program. Reality is certainly more complex than the stylized examples presented below.

3.1 Slight Modifications to GEO-Use Framing

We begin by making minor modifications to the framing of GEO use. We still assume that the choice is between BAU-with-GEO or optimal abatement. However, in this section we first allow society to respond to an aborted GEO program. Next, we relax the assumption that emissions controls, once started, are certain to continue indefinitely and that only GEO is subject to being abandoned.

3.1.1 Responding to an Aborted Geoengineering Program

GTK assumed that if society chooses to pursue BAU along with GEO, it has no ability to respond in the event that GEO is aborted. In this section we explore how allowing for some response capability alters the region in which GEO passes a cost-benefit test.

The online supplement (Fig. S3) presents a simple decision tree for the case we analyze here. Specifically, the initial choice is still between Abate and BAU_GEO, but we now allow for the option to respond to an aborted GEO program. To facilitate our analysis, we simply assume that society can choose GTK's abatement policy (shown in Fig. 1b and Fig. 2), but shift its start date to 2065 (e.g., 25% emissions reductions in 2065, 40% emissions reductions in 2075, etc.). We do not claim that this response is optimal. Rather, we are simply investigating the sensitivity of GTK's results to the assumption of no response.

Our scenario map, with GTK's discounting, appears in Fig. 4. The point of indifference when $p^* = 0$ is the same as in Fig. 3, since GEO is continued indefinitely in this case and society does not need to respond. Again, we also display GTK's original breakeven range. This change expands the region in which GEO passes a cost-benefit test: instead of GEO failing for any probability of abortment greater than 0.15, the new threshold is 0.89. As before, we show the breakeven line under DICE discounting (triangles), which expands the acceptable region yet further. In this case, GEO may pass a cost-benefit test for any probability of abortment as long as θ is less than 0.9%.

Optimizing the level of emissions reductions in this scenario would only serve to enlarge the region in which GEO passes a cost-benefit test, strengthening our argument. This can be seen by referring to Equation (3). Finding the optimal level of emissions controls would strictly increase EU[BAU_GEO_INT,θ], which would increase the breakeven probabilities.

3.1.2 Aborting Emissions Controls

Although GTK allowed GEO to be aborted because of "a war, a breakdown of an international agreement, or the discovery of sizable negative side effects due to the aerosol forcing," they assumed that abatement was not subject to this risk. We do not claim to know the likelihood of this event, but it seems possible that an international agreement regarding emissions targets or carbon pricing may not be sustained following a major war or, perhaps even, a global depression. In this section, we investigate the sensitivity of GTK's results to this possibility.

Let p_A and p_G be the probabilities that abatement and geoengineering, respectively, are aborted. One could create a three-dimensional scenario map that would display the breakeven surface for θ, p_A, and p_G. However, to facilitate communication, we assume there is some exogenous uncertainty (e.g., a war) that would end a program of emissions controls or a geoengineering. Thus, we assume that $p_A = p_G = p$. In this case, the breakeven probability formula becomes

$$p^*(\theta) = \frac{EU[\text{BAU\_GEO\_CONT},\theta] - EU[\text{Abate}]}{\Delta EU[\text{BAU\_GEO},\theta] - \Delta EU[\text{Abate}]}, \tag{4}$$

where $\Delta EU[\text{BAU\_GEO},\theta]$ is the difference in expected utility between a continuous GEO program and an intermittent GEO program, and $\Delta EU[\text{Abate}]$ is the difference in expected utility between a continuous abatement program and an intermittent abatement program. GTK implicitly assumed that $\Delta EU[\text{Abate}] = 0$, which will strictly decrease the size of the acceptable region.

Specifying how an aborted emissions control program would unfold is a challenge. Would existing capital stocks of carbon-free energy sources be destroyed during the precipitating event? How quickly would countries transition back to traditional energy sources? For example, would carbon capture and storage activities end immediately, given its performance penalties? As a point of reference, again to test the implications of this possibility, we assume that emissions controls are phased out as installed capital stock is retired. As an illustrative example, we assume that emissions reductions decrease linearly from their 2055 level to 0% over 40 years.

Fig. 5 presents the scenario map for this case. Again, the acceptable region is increased relative to that presented by GTK. In fact, as long as θ is less than about 0.11%, GEO may pass a cost-benefit test for all values of p. The use of a higher discount rate (triangles) enlarges this area still further.

3.2 The Addition of Geoengineering to BAU or Emissions Controls

Geoengineering does not present an either/or choice; geoengineering and emissions controls are not mutually exclusive. Rather, GEO could be added to many strategies. Thus, the proper test of

GEO's cost-benefit is an *incremental* one. The economic question is whether the addition of GEO to a particular strategy results in a Pareto-optimal improvement. In the next two sections, we consider the addition of GEO to either a policy of BAU or a policy of optimal controls.

3.2.1 GEO under BAU

We now assume that society faces a choice between BAU or BAU_GEO. The schematic decision tree is omitted, since its structure is identical to that of §2.2, except that Abate is replaced with BAU. In this case, society does not respond to an aborted GEO program with emissions controls, nor have we assumed that emissions controls could be aborted. This is not meant to convey that we think such cases are impossible. Rather, we are investigating only the incremental addition of GEO to BAU.

Fig. 6 presents the scenario map for this case. Here, GEO may pass a cost-benefit test over almost the entire range of values investigated by GTK. This result is not surprising since, as discussed in §2.1, the cumulative discounted costs of an aborted BAU_GEO program are lower than the costs of BAU, based on GTK's assumptions and modeling changes. In this case, use of DICE discounting reduces the acceptable region (triangles). This is because high values of θ (greater than the climate damages under BAU) impose a cost in the near term for the possibility of a future benefit (if GEO is not aborted). These future benefits are not valued as highly under DICE discounting. Thus, changing the discount rate can make GEO more or less attractive.

3.2.2 GEO under Emissions Controls

Several authors (Wigley, 2006; Bickel and Lane, 2010) have suggested that the use of geoengineering in conjunction with emissions controls may present an economical and less risky strategy than pursuing emissions reductions alone. For example, GEO might be used to stabilize temperatures while emissions controls are used to reduce CO_2 concentrations. GTK briefly examined the combined use of abatement and GEO as well. In particular, they solved for the degree to which GEO should substitute for abatement as a function of GEO damages. They found that higher GEO damages result in less GEO use and that no GEO should be deployed if its damages exceed 5% of GWP, at a forcing equal to a doubling of CO_2 concentrations. They did not allow for the possibility that a GEO program would be ended.

In this section, we consider the combined use of GEO and emissions controls, but allow for the possibility that GEO could be abandoned. Specifically, we assume that society faces a choice between Abate or GEO. In order to test this strategy, we assume that society agrees to adopt a GEO strategy where 1 W m^{-2} of negative forcing is provided via aerosol injection, for example, which we refer to as GEO1. We note, by referring to Fig. 1a, that GEO1 offsets approximately half of the radiative forcing under GTK's abatement policy.

In the interest of space, we do not consider other levels of GEO use. In particular, we do not attempt to solve for the "optimal" level of GEO use because this requires estimates of the economic damage caused by GEO, which we take to be a variable to which we will test sensitivity, how this damage scales with use (e.g., we do not know that damages will scale linearly with usage intensity), and the probability that GEO would be aborted, which we also take to be a variable.

Based on the knowledge that GEO1 will be implemented, society chooses an emissions trajectory that will be lower than the one that would be selected under a policy of emissions controls without GEO (i.e., Abate). We further assume that society chooses this emissions control strategy under the belief, perhaps mistaken, that its GEO1 program will be in place indefinitely. In Fig. 7, we compare the GEO1 emissions profile to GTK's emissions control profile. We found this level of emissions reductions by assuming mean values for the parametric uncertainties. We assume that if GEO1 is aborted, then society cannot increase its abatement. Relaxing this assumption would only strengthen our results, which are presented in Fig. 8. Again, GEO may pass a cost-benefit test over a wide range of scenarios considered by GTK. For example, as long as the economic damages caused by GEO are less than 0.7% of GWP, adding GEO1 to an emissions control strategy could pass a cost-benefit test even if society knew that its GEO1 program would be aborted ($p^* = 1$) and could do nothing to prepare for or react to that eventuality. DICE discounting enlarges the acceptable region (triangles).

3.3 The Ethics of Geoengineering

Due to space limitations, we cannot address the ethics of geoengineering here. However, some of the conclusions on which GTK based their ethical analysis are overturned by a reframing of the

GEO use decision. An aborted GEO program could indeed harm future generations, possibly resulting in more damage at the termination date, but perhaps lower overall, than BAU or optimal abatement. In this sense, choosing to use GEO is a risk-based decision to transfer some risk into the future. At the same time, a decision *not* to use GEO is a decision to accept the risk of crossing a tipping point, for example, which could be very near (Lenton et al., 2008); this also passes a risk to future generations.

4. Conclusion

As stated at the outset, this paper has made no attempt to argue for the deployment of geoengineering. Instead, we have demonstrated that framing the use of geoengineering is critical to determining its cost-benefit. All of our changes to GTK's analysis have resulted in a much larger region in which GEO may pass a cost-benefit test, because of the way GEO was positioned: Society can either (i) implement an optimally designed abatement policy (beginning with 25% reductions four years from now) that will proceed uninterrupted for the next several hundred years, or (ii) implement geoengineering that completely substitutes for emissions reductions and if things go badly (50 years from now), society must suffer the consequences and is not permitted to choose emissions reductions later. Given this choice, it is not surprising that the range in which GEO would be economic is quite small. Differing and we believe more reasonable framings of geoengineering use result in nearly the opposite conclusion: GEO may pass a cost-benefit test over a wide range of scenarios regarding (i) the probability it would be abandoned, and (ii) the economic damage caused by its use. This conclusion, however, is not invariant to changes in the underlying assumptions or model structure upon which it is based. For example, future research may determine that GEO damages increase non-linearly with usage intensity or are more damaging than GTK assumed.

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Figures

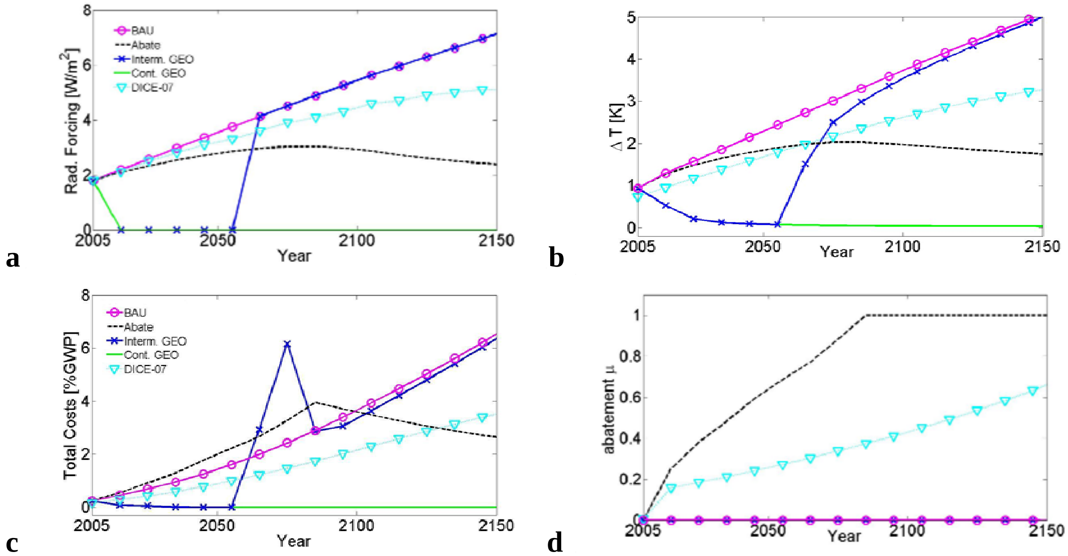


Fig. 1 Radiative forcing (panel **a**), global mean surface temperature change (panel **b**), total costs of climate change, abatement costs plus climate damages, (panel **c**), and fraction of CO_2 abatement (panel **d**), for BAU (circles), optimal abatement (dashed line), continuous geoengineering (solid line), and intermittent geoengineering (crosses). DICE-07 results (triangles) are added as a reference. These results are based on mean inputs (not averaged over all 6300 SOW) and neglect potential economic damages due to aerosol geoengineering forcing.

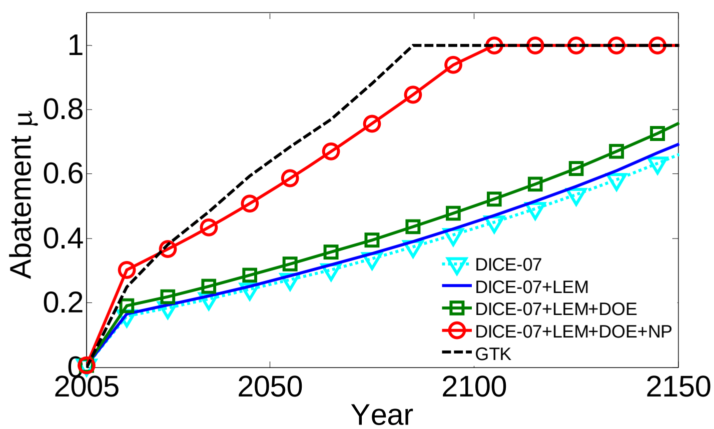
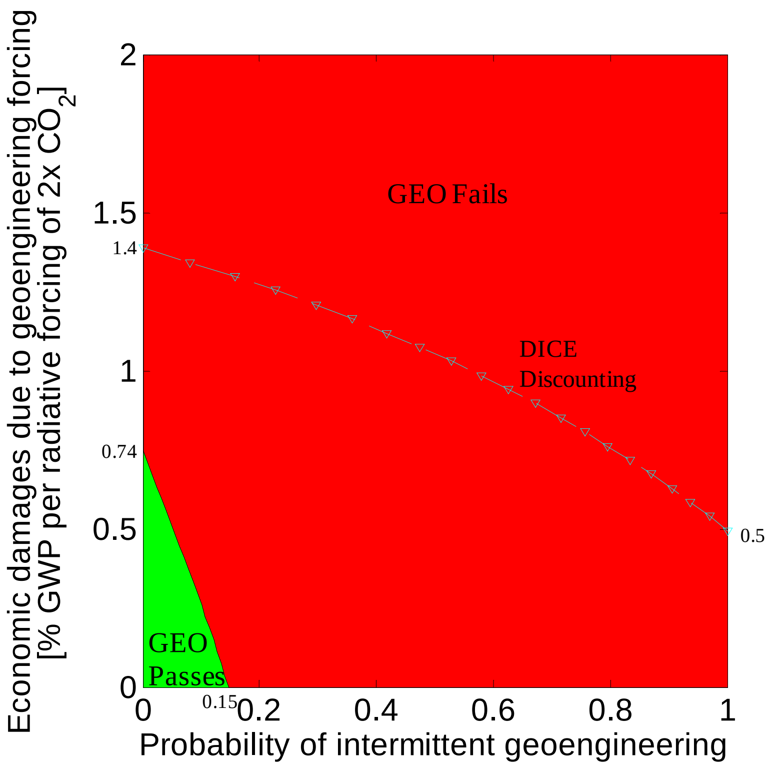


Fig. 2 Effect of GTK modeling changes on the optimal level of emissions controls. The difference between GTK's and DICE-07's abatement strategies is dominated by GTK's change to DICE-07's discounting.



a

Fig. 3 Scenario map for the cost-benefit test to substitute geoengineering for CO_2 abatement as a function of the probability of aborted geoengineering and the estimated damages due to geoengineering radiative forcing under GTK discounting or DICE discounting (triangles). The change in discounting greatly increases the region in which GEO may pass a cost-benefit test.

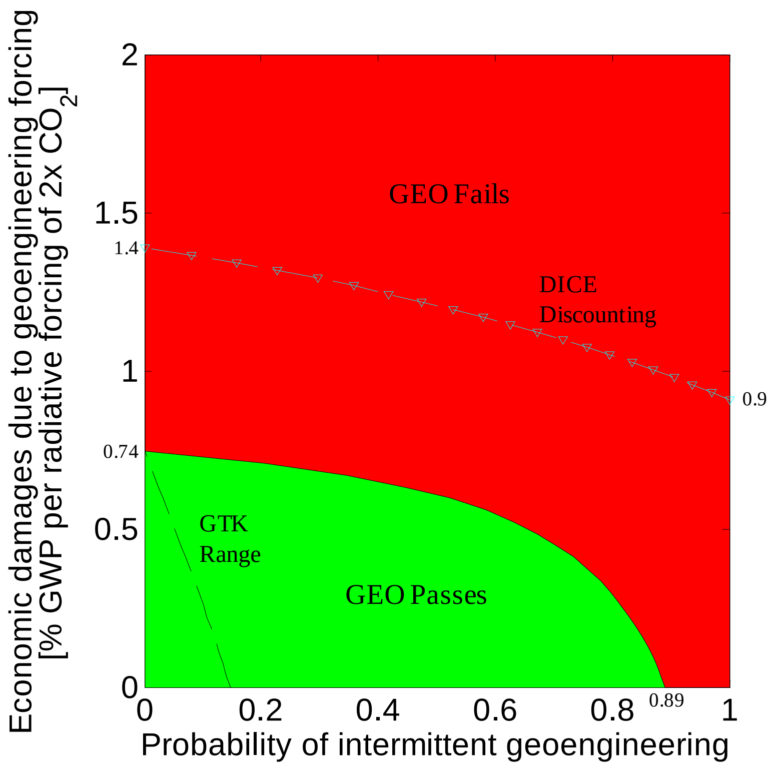


Fig. 4 Scenario map for the cost-benefit test to substitute geoengineering for CO_2 abatement, including the option to implement emissions reductions if the geoengineering program is aborted, as a function of the probability of aborted geoengineering and the estimated damages due to geoengineering radiative forcing under GTK discounting or DICE discounting (triangles). Allowing society to respond to an aborted GEO program greatly increases the region in which GEO may pass a cost-benefit test.

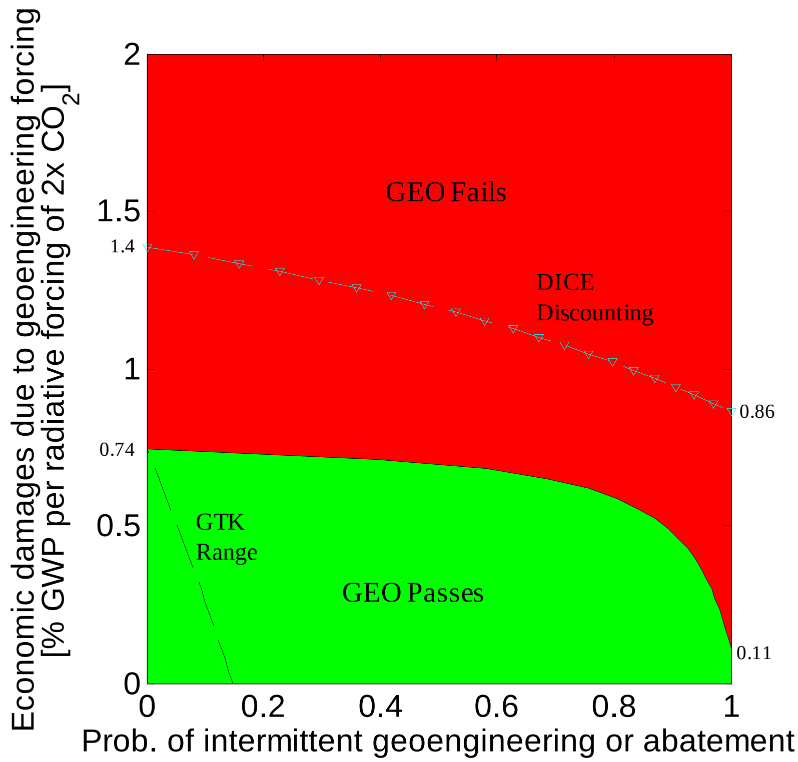


Fig. 5 Scenario map for the cost-benefit test to substitute geoengineering for CO_2 abatement, assuming that both geoengineering and emissions controls could be aborted under GTK discounting or DICE discounting (triangles). Allowing for the possibility that abatement may not continue indefinitely increases the region in which GEO may pass a cost-benefit test.

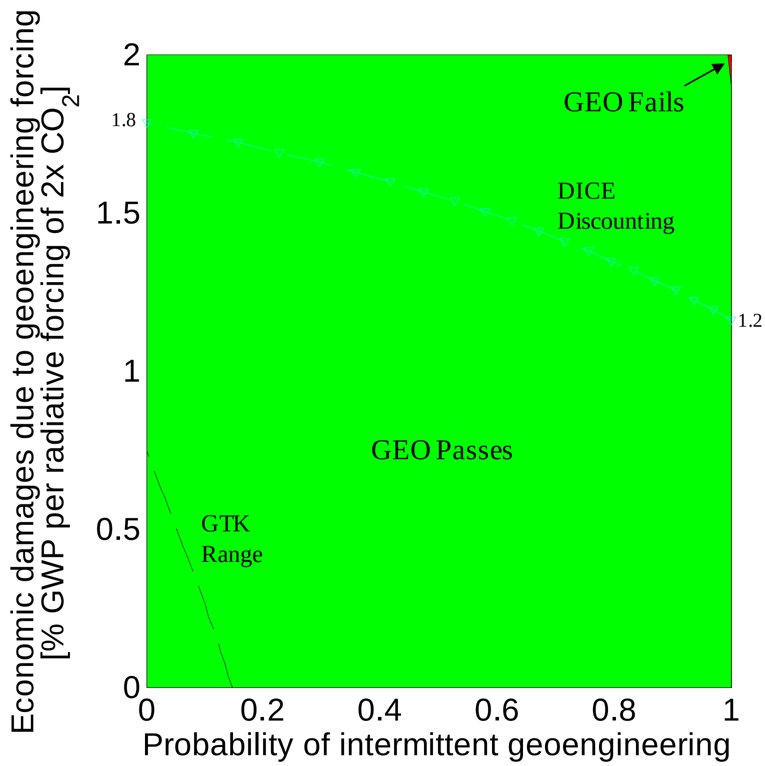


Fig. 6 Scenario map for the cost-benefit test to add geoengineering to a BAU policy under GTK discounting or DICE discounting (triangles). Geoengineering now may pass a cost-benefit test over almost the entire range of values tested by GTK. Viewing GEO as an incremental policy change greatly enlarges the region in which it may pass a cost-benefit test, compared to GTK's conclusions.

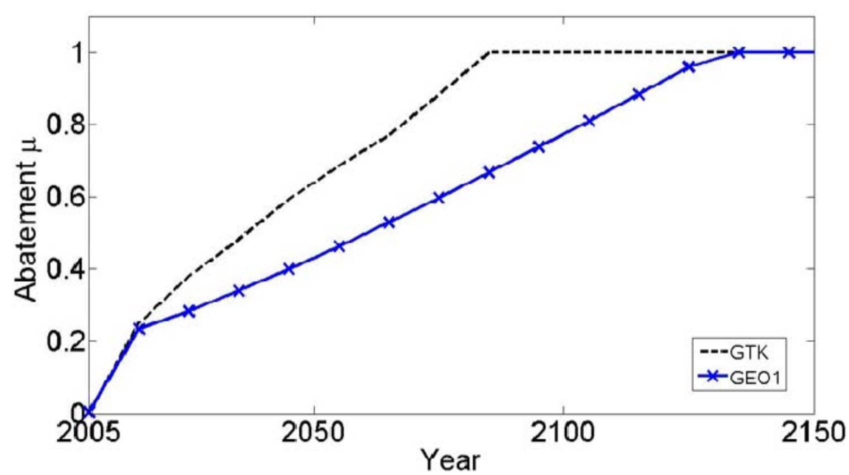


Fig. 7 Comparison of emissions control trajectories under GTK's optimal control case and under GEO1. GEO1 assumes that society deploys 1 W m^{-2} of geoengineering and alters its emissions reductions accordingly.

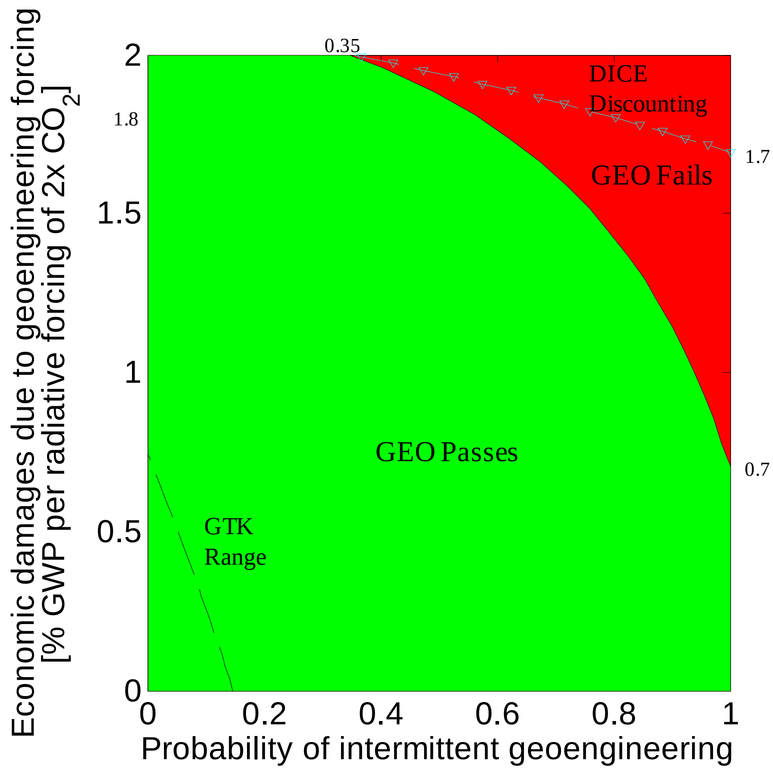


Fig. 8 Scenario map for the cost-benefit test to add geoengineering to a policy emissions reductions under GTK discounting or DICE discounting (triangles). Geoengineering may now pass a cost-benefit test over a wide range of scenarios tested by GTK.