Regulating Geoengineering:
International Competition and Cooperation

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Abstract

We study international cooperation regarding climate policy when solar geoengineering is a policy option available to nations. Employing an analytical theoretical model, we show how the equilibrium levels of emissions abatement and geoengineering are affected by the level of cooperation between countries, with more cooperation leading to lower emissions and more geoengineering. To quantify these results, we modify a numerical integrated assessment model, DICE, to include solar geoengineering and cooperation among nations. The simulation results show that the effect of cooperation on policy depends crucially on whether damages from geoengineering are local or global. With local damages, more cooperation leads to more geoengineering, but the opposite is true for global damages.

1. Introduction

Solar geoengineering (SGE) consists of increasing the reflectivity of the Earth's atmosphere with the intention of reducing the impacts of climate change. Solar geoengineering offers a relatively inexpensive means to limit warming. In addition to its low cost, a main advantage of solar geoengineering is how quickly the climate system responds to it. Its biggest disadvantages are the possible side effects it can cause and the fact that the distribution of the benefits and damages will not be uniform across the globe.[1] These characteristics make solar geoengineering one of the most difficult climate approaches to regulate from an international perspective. First of all, the possibility of deployment of solar geoengineering options can decrease the incentives for countries to abate, thus creating a need to escalate the use of geoengineering. Alternatively, if perceived damages from solar geoengineering are too large, abatement can be used as a disincentive for the deployment of solar geoengineering. Second, because the approach is inexpensive, it can be implemented by a single country, or a small coalition of

[1] *See, e.g.,* John Latham et al., *Climate engineering: exploring nuances and consequences of deliberately altering the Earth's energy budget*, PHILOSOPHICAL TRANSACTIONS. SERIES A, MATHEMATICAL, PHYSICAL, AND ENGINEERING SCIENCES 372, 2031 (2014) and CLIMATE INTERVENTION: REFLECTING SUNLIGHT TO COOL EARTH (2015) for reviews of the science behind solar geoengineering, and see Gernot Klepper, and Wilfried Rickels, *Climate engineering: Economic considerations and research challenges*, 8(2) REVIEW OF ENVIRONMENTAL ECONOMICS AND POLICY 270, 289 (2014) and Garth Heutel, Juan B. Moreno-Cruz, and Katharine Ricke, *Climate engineering economics*, 8 ANNUAL REVIEW OF RESOURCE ECONOMICS 99, 118 (2016) for reviews of the economics of solar geoengineering.

countries. Thus, there is the threat that this country or coalition can impose its will on the rest of the planet.[2]

We study the issue of governance for solar geoengineering using both a static analytical model and a dynamic numerical model. In both models, we solve for abatement and solar geoengineering strategies under three different cooperation scenarios. First, we consider the centralized case, or the case of full cooperation, in which a single decision-making agent (the social planner) chooses all regions' outcomes to maximize net utility. Second, we consider the other extreme case of no cooperation whatsoever; each region acts independently, choosing only its own abatement and geoengineering level to maximize its own utility, taking other regions' actions as fixed. Third, we consider the case of limited cooperation, or coalitions, in which just a subset of regions act cooperatively and the rest act independently. The analytical model shows that total social welfare decreases as the extent of cooperation decreases, and the resulting abatement and geoengineering strategies becomes less stringent. These findings confirm the existence of the classic "free-rider" problem in this setting.

Next, we modify a well-known integrated assessment model (IAM) of climate change policy, the DICE model[3], in two ways. First, we include SGE as a policy tool alongside abatement. Second, we allow for two homogeneous players that can cooperate or not, depending on the simulation. One important difference between the analytical model and the numerical model is the inclusion of damages from SGE deployment in the numerical model. We model damages from SGE in the numerical model in two different ways - either local or global. The results depend on this assumption about SGE damages. When damages are local, there is a free-rider problem with both SGE and abatement, as predicted by the analytical model. Less coordination leads to less abatement and less SGE. However, when SGE damages are global, there is still a free-rider problem for abatement, but now there is a "free-driver" problem for SGE. Less coordination leads to less abatement but *more* SGE.

Our work is closely related to a recent study[4] that also uses an IAM with SGE to study the free-driving effect of geoengineering. While we use DICE, they use WITCH, a regional IAM with a detailed energy sector. In their theoretical model, the free-driving effect depends on the SGE implementation costs and impacts. They assume that SGE damages are the result of global SGE deployment. However, in our model, we have separated the damages of SGE deployment depending on its origin. Damages in each region can be a function of the local level of SGE deployed by that region or of the total level of SGE deployed by all regions.

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[2] *See, e.g.,* Juan B. Moreno-Cruz, *Mitigation and the geoengineering threat*, 41 RESOURCE AND ENERGY ECONOMICS} 248, 263 (2015) and Katharine L. Ricke, Juan B. Moreno-Cruz, and Ken Caldeira, *Strategic incentives for climate geoengineering coalitions to exclude broad participation*, 8(1) ENVIRONMENTAL RESEARCH LETTERS 014021 (2013) and Martin L. Weitzman, *A Voting Architecture for the Governance of Free-Driver Externalities, with Application to Geoengineering*, 117(4) *The Scandinavian Journal of Economics* 1049, 1068 (2015)
[3] William Nordhaus, *Estimates of the social cost of carbon: concepts and results from the DICE-2013R model and alternative approaches*, 1(1/2) JOURNAL OF THE ASSOCIATION OF ENVIRONMENTAL AND RESOURCE ECONOMISTS 273, 312 (2014)
[4] Johannes Emmerling, and Massimo Tavoni, *Quantifying non-cooperative climate engineering* (2017)

The incentives to over-provide SGE are also found in a theoretical model[5]. The free-driving effects come from the benefits that one country receives from unilateral deployment of SGE over other countries. Weitzman has shown that the combination of low SGE cost and private benefits from its deployment will result in over-provision of geoengineering or free driving[6].

In the following section, we present our base case analytical model. Section 3 refines the analytical model by adding damages from SGE. Section 4 presents the details of our numerical simulation model, and section 5 presents our simulation results.

2. Analytical model

Abatement policies are aimed at reducing the amount of emissions from economic activities. Solar geoengineering policies, on the other hand, are designed to reduce the impacts of greenhouse gas (GHG) emissions, namely, the rise in atmospheric temperature. In a simple climate model we present here, unabated emissions will add to the already existing amount of GHG in the atmosphere and will eventually raise the global mean temperature through an increase in radiative forcing. Solar geoengineering reduces radiative forcing directly reducing temperature. The temperature rise will reduce the economic output through sea level rise, extreme weather events, or disruptions in agricultural practices. The loss of economic output creates an incentive for present abatement efforts to reduce GHG emissions, and geoengineering efforts to directly reduce temperature. Both strategies are costly, and as a result, the optimal level of each can be found through balancing its short term costs against long term benefits.

We construct a simple model of economic output in order to capture the interactions between the climate system and the economic system. There are $\boldsymbol{N}$ players, which we will refer to as countries (alternatively, these could be regions), and which for now are assumed to be homogeneous. Each country $\boldsymbol{i}$ has two control variables: the level of emissions, $\boldsymbol{E_i}$, which indicates net emissions after abatement, and the level of geoengineering, $\boldsymbol{G_i}$. Both emissions and geoengineering affect radiative forcing in a linear relationship, and radiative forcing affects temperature through a linear function. Both assumptions will be relaxed later in the numerical model. Emissions and geoengineering are chosen at the country level, while radiative forcing and temperature are global. We denote by $\Delta\boldsymbol{R}$, the change in radiative forcing, which is a function of global emissions $\boldsymbol{E} = \sum_{i=1}^{N} \boldsymbol{E_i}$ and global geoengineering $\boldsymbol{G} = \sum_{i=1}^{N} \boldsymbol{G_i}$:

$$\Delta R = \alpha E - \beta G, \tag{1}$$

where $\boldsymbol{\alpha}$ is the scaling parameter and $\boldsymbol{\beta}$ is a parameter controlling the effectiveness of geoengineering.

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[5] *See, e.g.,* Juan B. Moreno-Cruz, *Mitigation and the geoengineering threat*, 41 RESOURCE AND ENERGY ECONOMICS} 248, 263 (2015) and Juan B. Moreno-Cruz, and Sjak Smulders *Revisiting the economics of climate change: the role of geoengineering* 71(2) RESEARCH IN ECONOMICS 212, 224 (2017)

[6] Martin L. Weitzman, *A Voting Architecture for the Governance of Free-Driver Externalities, with Application to Geoengineering*}, 117(4) THE SCANDINAVIAN JOURNAL OF ECONOMICS 1049, 1068 (2015)

In the extreme case when $\boldsymbol{\beta} = \mathbf{0}$ geoengineering is ineffective and therefore the only option to reduce climate damages will be through controlling the level of emissions.

Atmospheric temperature increase due to change in radiative forcing is:

$$\Delta T = \theta \Delta R \tag{2}$$

where $\boldsymbol{\theta}$ is a parameter representing climate sensitivity. Each country has a utility that is a function of its emissions, the amount of solar geoengineering, and global temperature:

$$U_i(E_i, G_i, \Delta T) = E_i - \frac{1}{2}\eta(E_i)^2 - \frac{1}{2}\gamma(G_i)^2 - \frac{1}{2}\delta \Delta T^2 \tag{3}$$

where $\boldsymbol{\eta}$, $\boldsymbol{\gamma}$, and $\boldsymbol{\delta}$ are the parameters of emissions cost function, solar geoengineering cost function, and climate change damage cost function, respectively. Both solar geoengineering and emissions reduction costs are local - accrued only by region $\boldsymbol{i}$. In Section 3 we will also consider the damages from SGE in local and global cases. We next consider three specifications for equilibrium behavior, depending on the level of coordination across countries.

2.1. Full Cooperation (First Best)

First, we consider the case of full international cooperation of all $\boldsymbol{N}$ countries. This is equivalent to a central planner choosing the optimal levels of emissions and solar geoengineering for each country taking into account all countries' actions simultaneously. This will yield the first-best outcome. The planner's problem is:

$$\max_{\substack{E_1,\cdots,E_N \\ G_i,\cdots,G_N}} \sum_{i=1}^{N} U_i(E_i, G_i, \Delta T) \tag{4}$$

Since we assume the $\boldsymbol{N}$ countries are identical, we can impose that the solutions are identical for each country and solve. Define the solutions to this first-best problem as $\boldsymbol{E_i^{fb}}$ and $\boldsymbol{G_i^{fb}}$. These solutions are:

$$\begin{aligned} E_i^{fb} &= \frac{\gamma + N^2\delta\theta^2\beta^2}{\eta\gamma + N^2\delta\theta^2(\eta\beta^2 + \gamma\alpha^2)} \\ G_i^{fb} &= \frac{N^2\delta\theta^2\alpha\beta}{\eta\gamma + N^2\delta\theta^2(\eta\beta^2 + \gamma\alpha^2)} \end{aligned} \tag{5}$$

These individual levels of emissions and geoengineering can be summed to the global levels of emissions $\boldsymbol{E^{fb}}$ and geoengineering $\boldsymbol{G^{fb}}$ by adding all $\boldsymbol{N}$ identical countries' actions:

$$E^{fb} = \frac{N\gamma + N^3\delta\theta^2\beta^2}{\eta\gamma + N^2\delta\theta^2(\eta\beta^2 + \gamma\alpha^2)} \tag{6}$$
$$G^{fb} = \frac{N^3\delta\theta^2\alpha\beta}{\eta\gamma + N^2\delta\theta^2(\eta\beta^2 + \gamma\alpha^2)}$$

Atmospheric temperature change can be calculated from plugging in these optimal values into Equation 1 and Equation 2:

$$\Delta T^{fb} = \theta(\alpha E^{fb} - \beta G^{fb}) = \frac{N\gamma\theta\alpha}{\eta\gamma + N^2\delta\theta^2(\eta\beta^2 + \gamma\alpha^2)} \tag{7}$$

When $\boldsymbol{\beta = 0}$ (i.e. geoengineering is ineffective) or when $\boldsymbol{\gamma} \to \infty$ (i.e. geoengineering is too costly), the optimal level of geoengineering is $\boldsymbol{G^{fb} = 0}$, and the optimal level of emissions is $E^{fb} = N(\eta + N^2\delta\theta^2\alpha^2)^{-1}$.

2.2. Competition (Independent Action)

Now we assume that each of the $\boldsymbol{N}$ countries acts completely independently, choosing its privately optimal levels of abatement and geoengineering without cooperation with other countries and assuming that other countries' actions are fixed. Thus we solve for a (symmetric) Nash equilibrium. Country ‘s problem is:

$$\max_{E_i, G_i} U_i(E_i, G_i, \Delta T) \tag{8}$$

As in the previous subsection, we can solve for resulting levels of emissions $\boldsymbol{E_i^{comp}}$ and geoengineering $\boldsymbol{G_i^{comp}}$ using the first-order conditions, taking into account the homogeneity of the solutions.

$$E_i^{comp} = \frac{\gamma + N\delta\theta^2\beta^2}{\eta\gamma + N\delta\theta^2(\eta\beta^2 + \gamma\alpha^2)} \tag{9}$$
$$G_i^{comp} = \frac{N\delta\theta^2\alpha\beta}{\eta\gamma + N\delta\theta^2(\eta\beta^2 + \gamma\alpha^2)}$$

The total level of emissions $\boldsymbol{E_i^{comp}}$ and the total level of geoengineering $\boldsymbol{G_i^{comp}}$ are calculated as the sum of the all $\boldsymbol{N}$ countries' actions:

$$E^{comp} = \frac{N\gamma + N^2\delta\theta^2\beta^2}{\eta\gamma + N\delta\theta^2(\eta\beta^2 + \gamma\alpha^2)} \tag{10}$$
$$G^{comp} = \frac{N^2\delta\theta^2\alpha\beta}{\eta\gamma + N\delta\theta^2(\eta\beta^2 + \gamma\alpha^2)}$$

The change in atmospheric temperature is:

$$\Delta T^{comp} = \theta(\alpha E^{comp} - \beta G^{comp}) = \frac{N\gamma\theta\alpha}{\eta\gamma + N\delta\theta^2(\eta\beta^2 + \gamma\alpha^2)} \tag{11}$$

We can compare these results with those from the case of full cooperation. Equation 9 shows that the individual level of emissions is higher in the competition case compared to the full cooperation case (Equation 5), and that the individual level of geoengineering is lower in the competition case compared to the full cooperation case. In other words, both levels of abatement and geoengineering decrease in the competition case compared to the full cooperation case.

Consequently, comparing Equation 11 and Equation 7, the temperature change is larger in the competition case than in the full cooperation case. This confirms our hypothesis that in the competition case, due to the problem of free-riding countries have less incentive to lower their emissions or to use geoengineering. As the number of countries $\boldsymbol{N}$increases, both the level of emissions $\boldsymbol{E^{comp}}$ and the level of geoengineering $\boldsymbol{G^{comp}}$ increase.

$$\begin{aligned} \frac{\partial E^{comp}}{\partial N} &= \frac{\eta\gamma(\gamma + 2N\delta\theta^2\beta^2) + N^2\delta^2\theta^4\beta^2(\eta\beta^2 + \gamma\alpha^2)}{(\eta\gamma + N\delta\theta^2(\eta\beta^2 + \gamma\alpha^2))^2} > 0 \\ \frac{\partial G^{comp}}{\partial N} &= \frac{N\delta\theta^2\alpha\beta(2\eta\gamma + N\delta\theta^2(\eta\beta^2 + \gamma\alpha^2)}{(\eta\gamma + N\delta\theta^2(\eta\beta^2 + \gamma\alpha^2))^2} > 0. \end{aligned} \tag{12}$$

When $\boldsymbol{\beta = 0}$ (i.e. geoengineering is ineffective) or when $\boldsymbol{\gamma} \to \infty$ (i.e. geoengineering is too costly), the optimal level of geoengineering is $\boldsymbol{G^{comp} = 0}$ and the equilibrium level of emissions will be $E^{comp} = N(\eta + N\delta\theta^2\alpha^2)^{-1}$.

2.3. Coordination (Coalition/Partial Cooperation)

So far we have studied the two extreme cases of international climate policy regulations: full cooperation and competition. In reality, countries are standing somewhere in between these two cases. While there is a level of global coordination that tries to bring all countries together in achieving a global climate target, countries are, for the most part, acting independently. A recent example of such coordinating efforts was the development of nationally determined contributions (NDCs) as part of the Paris agreement. NDCs are a set of actions that each individual country is going to take in order to achieve a global goal (e.g. keeping the global mean temperature rise below 2°C). The key elements of this new approach are decision-making in the national level and setting climate targets at the global level.

We investigate this by modeling the case of coordination or partial cooperation. We model this by assuming that there is a set of $\boldsymbol{M}$ countries that are part of a coalition. This set is determined exogenously; we do not model the incentives behind coalition formation. Within the coalition, the $\boldsymbol{M}$ countries act fully cooperatively, as if there is a central planner choosing each country's $\boldsymbol{E_i}$ and $\boldsymbol{G_i}$ to maximize the total utility of all $\boldsymbol{M}$ coalition countries, taking the actions of the remaining $\boldsymbol{N - M}$

countries as exogenous. The non-coalition $\boldsymbol{N-M}$ countries each act completely independently, each choosing just its own $\boldsymbol{E_i}$and $\boldsymbol{G_i}$to maximize just its own utility $\boldsymbol{U_i}$**.** The result from these optimization problems is a set of $\boldsymbol{2M}$ first-order conditions, for emissions and geoengineering of the coalition countries, and $\boldsymbol{2(N-M)}$ first-order conditions for the non-coalition countries. We again assume that all countries are symmetric with respect to all features of their utility functions, but here there is asymmetry between the coalition and non-coalition countries. Thus, the set of first-order conditions is reduced to four equations for four unknowns: the emissions and geoengineering of each coalition country $\boldsymbol{E_i^{coal}}$ and $\boldsymbol{G_i^{coal}}$, and the emissions and geoengineering of each non-coalition country $\boldsymbol{E_i^{noncoal}}$and $\boldsymbol{G_i^{noncoal}}$.

The equilibrium solutions are:

$$\begin{aligned} E_i^{coal} &= \frac{\gamma + M\delta\theta^2(A\beta^2 - B\alpha^2\gamma)}{\eta\gamma + AM\delta\theta^2(\eta\beta^2+\gamma\alpha^2)} \\ G_i^{coal} &= \frac{MN\delta\theta^2\alpha\beta}{\eta\gamma + AM\delta\theta^2(\eta\beta^2+\gamma\alpha^2)} \\ E_i^{noncoal} &= \frac{\gamma + M\delta\theta^2(A\beta^2 + (\alpha^2\gamma/\eta)(M-1))}{\eta\gamma + AM\delta\theta^2(\eta\beta^2+\gamma\alpha^2)} \\ G_i^{noncoal} &= \frac{N\delta\theta^2\alpha\beta}{\eta\gamma + AM\delta\theta^2(\eta\beta^2+\gamma\alpha^2)} \end{aligned} \tag{13}$$

where $\boldsymbol{A \equiv M + \frac{N-M}{M}}$ and $\boldsymbol{B \equiv \frac{(M-1)(N-M)}{M\eta}}$.

Total emissions and total geoengineering are $E^{coord} = ME_i^{coal} + (N-M)E_i^{noncoal}$ and $G^{coord} = MG_i^{coal} + (N-M)G_i^{noncoal}$, which can be simplified as:

$$\begin{aligned} E^{coord} &= \frac{N\gamma + AMN\delta\theta^2\beta^2}{\eta\gamma + MA\delta\theta^2(\eta\beta^2+\gamma\alpha^2)} \\ G^{coord} &= \frac{AMN\delta\theta^2\alpha\beta}{\eta\gamma + MA\delta\theta^2(\eta\beta^2+\gamma\alpha^2)} \end{aligned} \tag{14}$$

The resulting temperature increase is:

$$\Delta T^{coord} = \theta(\alpha E^{coord} - \beta G^{coord}) = \frac{N\gamma\theta\alpha}{\eta\gamma + MA\delta\theta^2(\eta\beta^2+\gamma\alpha^2)} \tag{15}$$

The coordination case is an intermediate case between the two previous cases modeled. When $\boldsymbol{M=N}$, the solutions here are identical to those in section 2.1. When $\boldsymbol{M=1}$, these solutions are identical to those in section 2.2.

We can conduct comparative statics on these solutions to see how policy is affected by the degree of coordination, measured by the size of the coalition $\boldsymbol{M}$.

$$\frac{\partial \Delta T^{coord}}{\partial M} = \frac{-N\gamma\theta\alpha(2M-1)(\delta\theta^2(\eta\beta^2+\gamma\alpha^2))}{(\eta\gamma+MA\delta\theta^2(\eta\beta^2+\gamma\alpha^2))^2} < 0 \tag{16}$$

Temperature is lower when there is more coordination, since the free rider problem becomes smaller and smaller as there are more coalition members.

$$\frac{\partial E^{coord}}{\partial M} = (2M-1)N\delta\theta^2\frac{\beta^2(1-\gamma\eta-\delta\theta^2AM(\eta\beta^2+\gamma\alpha^2))-\gamma^2\alpha^2}{(\eta\gamma+MA\delta\theta^2(\eta\beta^2+\gamma\alpha^2))^2} \tag{17}$$

Every term in equation 17 is negative except for the first $\mathbf{1}$ in the numerator, so the entire terms is negative unless the entire rest of the numerator is dominated by that $\mathbf{1}$. That is, with more coordination (higher $\boldsymbol{M}$), there is lower emissions.

$$\frac{\partial G^{coord}}{\partial M} = \frac{(2M-1)N\delta\theta^2\alpha\beta\eta\gamma}{(\eta\gamma+MA\delta\theta^2(\eta\beta^2+\gamma\alpha^2))^2} > 0 \tag{18}$$

With more coordination (higher $\boldsymbol{M}$), there is more geoengineering.

The analytical model provides intuitive results for how coordination affects policy outcomes and temperatures. But, it makes many crucial simplifications to arrive at these solutions. One crucial assumption that needs further investigation is to what extent the damages from deployment of SGE may affect optimal decisions. In the next section we theoretically investigate optimal policies under two different assumptions about SGE damages: one in which they are local and another where they are global. Following that, we consider a numerical simulation model that allows for either local or global SGE damages.

3. SGE damages

We modify our theoretical model to include a representation of SGE damages. We use a quadratic cost function similar to other costs in the model to account for SGE damages. We consider two cases with local and global SGE damages and investigate the optimal policies under each case.

3.1. Local SGE damages

First we consider the case with local SGE damages. In this case we an additional term to equation 3 to represent these damages:

$$U_i(E_i, G_i, \Delta T) = E_i - \frac{1}{2}\eta(E_i)^2 - \frac{1}{2}\gamma(G_i)^2 - \frac{1}{2}\delta\Delta T^2 - \frac{1}{2}\lambda(G_i)^2 \tag{19}$$

The last term captures the SGE damages, and $\boldsymbol{\lambda}$ is the parameter of these damages. Since only $\boldsymbol{G_i}$ enter's country $\boldsymbol{i}$'s damage function, these damages are local, not global. Following the calculations for the full cooperation case presented in Section 2.1 we derive $\boldsymbol{E_i^{fb-local}}$ and $\boldsymbol{G_i^{fb-local}}$, the optimal emission and SGE levels, as the solutions to this first-best (full cooperation) problem:

$$\begin{aligned} E_i^{fb-local} &= \frac{(\gamma+\lambda)+N^2\delta\theta^2\beta^2}{\eta(\gamma+\lambda)+N^2\delta\theta^2(\eta\beta^2+(\gamma+\lambda)\alpha^2)} \\ G_i^{fb-local} &= \frac{N^2\delta\theta^2\alpha\beta}{\eta(\gamma+\lambda)+N^2\delta\theta^2(\eta\beta^2+(\gamma+\lambda)\alpha^2)} \end{aligned} \tag{20}$$

As it is obvious from these equations, the local SGE damages appear in the optimal solution as an additional SGE cost.

We can derive similar solutions for the competition case following the calculations presented in Section 2.2. As in the previous subsection, we can solve for resulting levels of emissions $\boldsymbol{E_i^{comp-local}}$ and geoengineering $\boldsymbol{G_i^{comp-local}}$ using the first-order conditions, taking into account the homogeneity of the solutions.

$$\begin{aligned} E_i^{comp-local} &= \frac{(\gamma+\lambda)+N\delta\theta^2\beta^2}{\eta(\gamma+\lambda)+N\delta\theta^2(\eta\beta^2+(\gamma+\lambda)\alpha^2)} \\ G_i^{comp-local} &= \frac{N\delta\theta^2\alpha\beta}{\eta(\gamma+\lambda)+N\delta\theta^2(\eta\beta^2+(\gamma+\lambda)\alpha^2)} \end{aligned} \tag{21}$$

Comparing the levels of SGE in the equations above reveals that $\boldsymbol{G_i^{fb-local}} > \boldsymbol{G_i^{comp-local}}$, which means as we move from the full cooperation case to competition case, each region will take advantage of other regions' SGE deployment and will provide less SGE compared to the full cooperation case. This deviation from the first-best outcome is a standard free-riding problem. We will provide numerical evidence for this behavior in Section 4.

3.2. Global SGE damages

In the case with global SGE damages, equation 3 is modified to:

$$U_i(E_i, G_i, \Delta T, G) = E_i - \frac{1}{2}\eta(E_i)^2 - \frac{1}{2}\gamma(G_i)^2 - \frac{1}{2}\delta\Delta T^2 - \frac{1}{2}\lambda(G)^2 \tag{22}$$

where $\boldsymbol{G}$ is the sum of SGE from all $\boldsymbol{N}$ regions and represents the global damages from SGE, with $\boldsymbol{\lambda}$ still capturing the magnitude of these damages. Similar to the case with local damages, we derive $\boldsymbol{E_i^{fb-global}}$ and $\boldsymbol{G_i^{fb-global}}$, the optimal emission and SGE levels, as the solutions to the first-best (full cooperation) problem:

$$E_i^{fb-global} = \frac{(\gamma + N^2\lambda) + N^2\delta\theta^2\beta^2}{\eta(\gamma + N^2\lambda) + N^2\delta\theta^2(\eta\beta^2 + (\gamma + N^2\lambda)\alpha^2)} \tag{23}$$
$$G_i^{fb-global} = \frac{N^2\delta\theta^2\alpha\beta}{\eta(\gamma + N^2\lambda) + N^2\delta\theta^2(\eta\beta^2 + (\gamma + N^2\lambda)\alpha^2)}$$

The levels of emissions $\boldsymbol{E_i^{comp-global}}$ and geoengineering $\boldsymbol{G_i^{comp-global}}$ in the competition case are:

$$E_i^{comp-global} = \frac{(\gamma + N\lambda) + N\delta\theta^2\beta^2}{\eta(\gamma + N\lambda) + N\delta\theta^2(\eta\beta^2 + (\gamma + N\lambda)\alpha^2)} \tag{24}$$
$$G_i^{comp-global} = \frac{N\delta\theta^2\alpha\beta}{\eta(\gamma + N\lambda) + N\delta\theta^2(\eta\beta^2 + (\gamma + N\lambda)\alpha^2)}$$

Comparing the SGE levels under the full cooperation case to the competition case, it is ambiguous which is larger. In fact, we find a condition under which the solution switches from free-riding behavior (i.e. providing less SGE in the competition case compared to the full cooperation case) to free-driving behavior (i.e. providing more SGE in the competition case compared to the full cooperation case). If the SGE damage parameter $\boldsymbol{\lambda}$ is greater than $\frac{\boldsymbol{\gamma\eta}}{\boldsymbol{N^3\delta\theta^2\alpha^2}}$, then the SGE level in the competition case is greater than the optimal SGE level in the full cooperation case: $\boldsymbol{G_i^{comp-global}} > \boldsymbol{G_i^{fb-global}}$ (free-driving). On the other hand, if the SGE damage parameter $\boldsymbol{\lambda}$ is less than $\frac{\boldsymbol{\gamma\eta}}{\boldsymbol{N^3\delta\theta^2\alpha^2}}$, the SGE level in the competition case is less than the optimal SGE level in the full cooperation case: $\boldsymbol{G_i^{comp-global}} < \boldsymbol{G_i^{fb-global}}$ (free-riding). In other words, when global SGE damages are relatively high, then competition results in a free-driving effect where countries actually conduct too much SGE, because they only account for its effect on their own utility and not on the damages that their SGE cause to other countries. This only occurs when global SGE damages $\boldsymbol{\lambda}$ are high enough so that its free-driving effect dominates the free-riding effect from the benefits of SGE (which are always global).

Next, we move on to our numerical model, where $\boldsymbol{N = 2}$ and the SGE damages are assumed comparable with other costs and therefore the first condition (free-driving) holds.

4. Numerical model

We base our numerical simulation on a well-known integrated assessment model that is widely used in academic research and policy making to find the optimal emission levels in the face of imminent damages from temperature change. The Dynamic Integrated Climate-Economy (DICE) model is designed and developed by William Nordhaus at Yale University. It is a centralized decision making tool with a representative-agent economic model. There is an endogenous capital stock and an exogenous technological and population growth dynamic inside the model. Carbon emissions are directly linked to economic production, but they can be reduced through two processes: first, the carbon intensity of output is decreasing over time through an exogenous procedure, and second, abatement action can reduce the emissions. The carbon cycle in the model consists of a three-layer model of the atmosphere and upper and lower oceans. The atmospheric carbon concentration affects the atmosphere's radiative forcing and the atmospheric temperature consequently. Finally, the climate and economy sections of the model are linked together through a damage function that indicates the loss in total economic output due to a change in atmospheric temperature. The objective of the model is to maximize the net present value of total social welfare by finding the optimal carbon abatement trajectories. The model has a 5-year time period and runs for 60 periods.

Details of the DICE model are available publicly and also at William Nordhaus's website[7]. We are using the version DICE-2013R, the most recently published version.

4.1. Modifications to DICE

We modify the DICE model in the same way as in our previous study[8]. In this section, we present only a brief summary of how the DICE model has been modified. More details of the modifications that we make are available in our other papers[9]. Those papers and their appendices contain the full list of model equations and the calibration methodology. Here, we merely summarize our modifications to DICE.

There are five ways in which we modify DICE to incorporate solar geoengineering.

- In addition to a policy choice variable $\boldsymbol{a_t}$ for the intensity of emissions abatement, we add a second policy choice variable, $\boldsymbol{g_t}$, representing the intensity of solar geoengineering.
- There is a direct cost of geoengineering implementation, modeled analogously to the way that abatement cost is modeled in DICE. Based on prior literature, this cost is quite small, reflecting the fact that solar geoengineering is cheap relative to abatement. To completely offset the radiative forcing caused by greenhouse gases costs about 0.27% of global GDP.
- In addition to its implementation costs, we model damages from solar geoengineering. These damages are modeled analogously to the way that climate change damages are modeled in DICE. These damages are highly uncertain, and so in our parameterization we are very conservative about the value. That is, we assume these damages are very high. The amount of geoengineering needed to offset the warming effects of $\boldsymbol{CO_2}$ leads to damages of 3% of gross global GDP, which is about equal to damages from climate change itself under moderate warming. As in Section 3 above, we model SGE damages in two ways: local and global. We numerically verify that that this modeling choice has a direct impact on the incentives for the regions and results in either a free-rider or a free-driver effect.

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[7] William Nordhaus, *Estimates of the social cost of carbon: concepts and results from the DICE-2013R model and alternative approaches*, 1(1/2) JOURNAL OF THE ASSOCIATION OF ENVIRONMENTAL AND RESOURCE ECONOMISTS 273, 312 (2014) and also available at https://sites.google.com/site/williamdnordhaus/dice-rice

[8] Garth Heutel, and Juan Moreno-Cruz, and Soheil Shayegh, *Solar geoengineering, uncertainty, and the price of carbon*, 87 JOURNAL OF ENVIRONMENTAL ECONOMICS AND MANAGEMENT 24, 41 (2018)

[9] Garth Heutel, and Juan Moreno-Cruz, and Soheil Shayegh, *Solar geoengineering, uncertainty, and the price of carbon*, 87 JOURNAL OF ENVIRONMENTAL ECONOMICS AND MANAGEMENT 24, 41 (2018) and Garth Heutel, and Juan Moreno-Cruz, and Soheil Shayegh, *Climate tipping points and solar geoengineering*, 132 JOURNAL OF ECONOMIC BEHAVIOR & ORGANIZATION 19, 45 (2016). These papers model epistemic uncertainty over certain parameter values, though here we restrict analysis to the deterministic case.

- The radiative forcing equation is modified to include the effect of geoengineering. The radiative forcing is a sum of the original specification of radiative forcing from DICE and the radiative forcing caused by solar geoengineering g_t.
- Finally, we modify the climate change damage function to reflect the fact that damages are not only a function of temperature, but are also a function of atmospheric and ocean carbon concentrations. This is crucial when modeling solar geoengineering policy, because solar geoengineering reduces temperature but does not reduce atmospheric or ocean carbon. We set 80% of climate change damages from temperature increase, 10% from atmospheric carbon concentrations, and 10% from ocean carbon concentrations.

Furthermore, to study coordination among countries or regions, we must extend the model beyond a global, representative agent model. While DICE has been regionally disaggregated via the RICE model[10], here we take a much simpler approach. We assume that there are two homogeneous countries indexed by i and j, and we calibrate each country simply by dividing all of the relevant stock variables by half. Costs of abatement and geoengineering are borne just by the individual country, but the damages from climate change and geoengineering and the radiative forcing effect of geoengineering are global and depend on the total amount from both countries.

4.2. International Coordination

As with the analytical model in section 2, we consider three different frameworks for international governance of climate policy, including geoengineering deployment.

- **Cooperation** First is the case of full cooperation, analogous to the treatment in section 2.1. Both countries are working together as one to maximize the sum of the two countries' utilities. This is equivalent to a social planner choosing abatement and geoengineering in all periods for both countries:

$$\max_{\{a_{i,t},g_{i,t},a_{j,t},g_{j,t}\}_{t=1}^{T}} U_i(\{a_{i,t}, g_{i,t}, a_{j,t}, g_{j,t}\}_{t=1}^{T}) + U_j(\{a_{i,t}, g_{i,t}, a_{j,t}, g_{j,t}\}_{t=1}^{T}) \qquad (25)$$

where U_i and U_j represent the net present value of utility for each country over the entire T periods and are a function of all choice variables over each period from both countries.

- **Competition** Next is the case of competition, or independent action, as in section 2.2. Each country is trying to maximize its welfare independently, holding constant the action of the other country:

[10] William D. Nordhaus, and Zili Yang, *A regional dynamic general-equilibrium model of alternative climate-change strategies*, 1996 THE AMERICAN ECONOMIC REVIEW 741, 765

$$\max_{\{a_{i,t},g_{i,t}\}_{t=1}^{T}} \quad U_i(\{a_{i,t}, g_{i,t}, a^*_{j,t}, g^*_{j,t}\}_{t=1}^{T}) \tag{26}$$

$$\max_{\{a_{j,t},g_{j,t}\}_{t=1}^{T}} \quad U_i(\{a^*_{i,t}, g^*_{i,t}, a_{j,t}, g_{j,t}\}_{t=1}^{T})$$

In country $\boldsymbol{i}$'s maximization problem, the actions of country $\boldsymbol{j}$ are taken as fixed - $\boldsymbol{a^*_{j,t}}$ and $\boldsymbol{g^*_{j,t}}$, and likewise for country $\boldsymbol{j}$.

- **Coordination** Last is the case of coordination, or partial cooperation. This is analogous to the treatment in section 2.3, but here in the numerical model coordination is modeled somewhat differently than it was in the analytical model. The analytical model had a subset of $\boldsymbol{M}$ of the $\boldsymbol{N}$ total countries forming a coalition. Here, with just $\boldsymbol{N = 2}$ countries, any strict subset is just 1 and identical to the competition case. Therefore, we assume that each country is acting independently, choosing just its own abatement and geoengineering levels, but is maximizing the sum of its own welfare and a portion of the other country's welfare. We call this portion $\boldsymbol{\omega}$ the *coordination factor*, and it measures the degree of coordination, similar to how $\boldsymbol{M}$, the size of the coalition, does in the analytical model. The coordination factor $\boldsymbol{\omega}$ can be between $\boldsymbol{0}$ (corresponding to the competition case) and $\boldsymbol{1}$ (corresponding to the cooperation case). In a more formal way it means simultaneously solving the welfare maximization problem of each agent by applying the coordination factor, $\boldsymbol{\omega}$, to obtain the partial sum of the two agents' welfare and then solving the first order conditions for both agents simultaneously:

$$\max_{\{a_{i,t},g_{i,t}\}_{t=1}^{T}} \quad U_i(\{a_{i,t}, g_{i,t}, a^*_{j,t}, g^*_{j,t}\}_{t=1}^{T}) + \omega U_j(\{a_{i,t}, g_{i,t}, a^*_{j,t}, g^*_{j,t}\}_{t=1}^{T}) \tag{27}$$

$$\max_{\{a_{j,t},g_{j,t}\}_{t=1}^{T}} \quad \omega U_i(\{a^*_{i,t}, g^*_{i,t}, a_{j,t}, g_{j,t}\}_{t=1}^{T}) + U_j(\{a^*_{i,t}, g^*_{i,t}, a_{j,t}, g_{j,t}\}_{t=1}^{T})$$

When the coordination factor $\boldsymbol{\omega = 0}$, this case becomes identical to the competition case. When $\boldsymbol{\omega = 1}$, the solution is identical to the solution in the cooperation case. In the simulations, we consider two different values for $\boldsymbol{\omega}$: a low coordination value $\boldsymbol{\omega = 1/3}$ and a high coordination value $\boldsymbol{\omega = 2/3}$.

5. Results

We perform two sets of simulations, corresponding to the two assumptions about SGE damages described above. In the first set, we assume that the damages from deploying SGE in each region are only a function of the local deployment of SGE. In this case, each region is only affected by the SGE cost and SGE damage that are incurred due to the deployment of SGE in that region. In the second set of simulations, however, we assume that the SGE damages are global, meaning that each region's SGE damages are a function of the total amount of SGE deployed by all regions.

5.1. Local SGE Damages

The results under this assumption are shown in Figure 1. Panel $\boldsymbol{A}$ shows optimal SGE under different levels of coordination. It verifies our analytical result on the free-riding problem in the case of non-cooperative strategies. As we move from a cooperative world to the world with less coordination and more competition, the level of SGE decreases. In all cases, the SGE level starts out with a jump and gradually increases as the damages from climate change increase. It eventually peaks in around year 2110 and reaches its maximum value between $2.2\ W/m^2$ in the full cooperation case and $1.8\ W/m^2$ in the competition case. Since the results shown here are only for one of the two identical regions, this translates into $3.6 - 4.4\ W/m^2$ reduction in solar radiative forcing in the next 100 years.

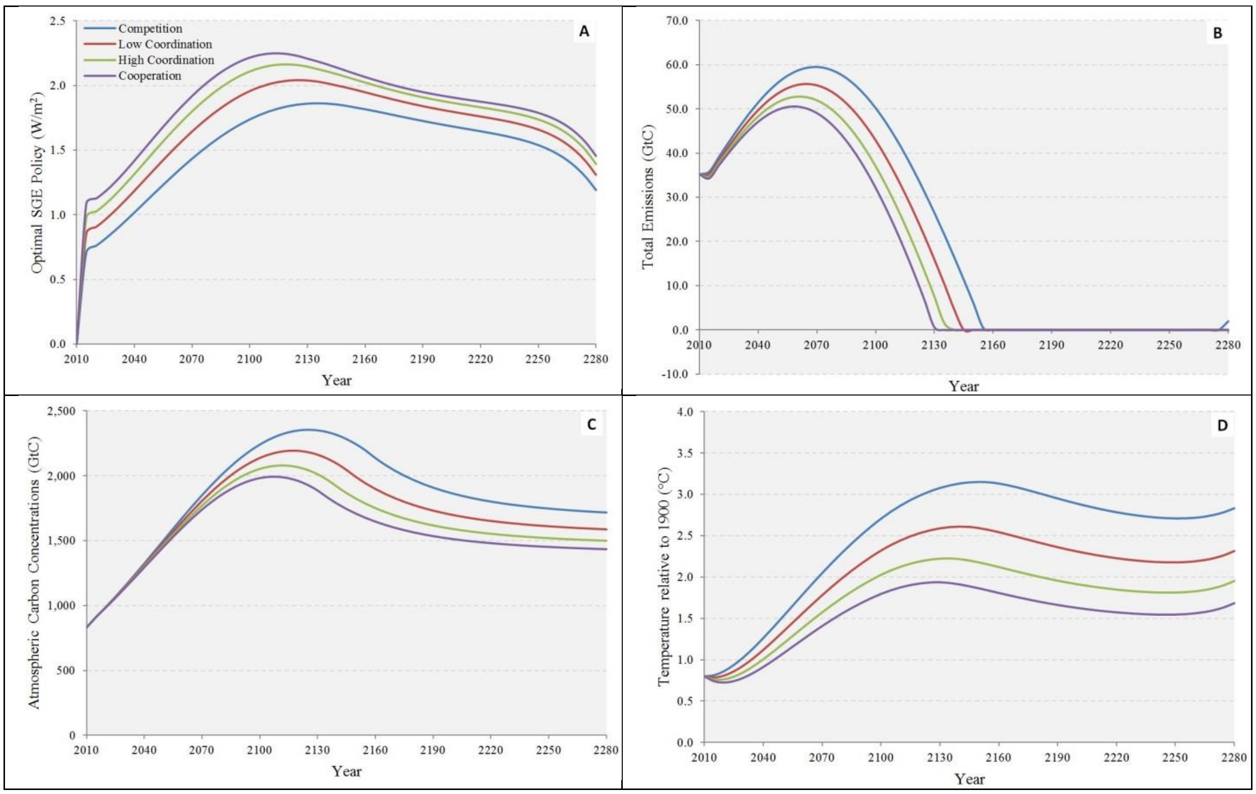

Figure 1: Climate policies and outcomes for the model with local SGE damages. Each panel shows four scenarios: cooperation, high coordination, low coordination, and competition.

Similar free riding can be observed for abatement. Panel $\boldsymbol{B}$ shows the level of emissions under the four different coordination assumptions. Cooperation yields the highest abatement and therefore the lowest level of emissions, while the emissions are highest under competition. Emissions over the next 100 years increase to up to $60\ GtC$ in the competition case and $50\ GtC$ in the full cooperation case. By 2130, all emissions are abated in the full cooperation case. In contrast, the competition case delays reaching the 100% abatement point to year 2160. When the 100% abatement point is reached, there will be less need for reducing the temperature through SGE and therefore the level of SGE gradually decreases.

The results from these two panels are in line with our theoretical model from section 2, which assumes local SGE damages. Comparing Equations 5 and 9, it can be shown that for $\boldsymbol{N > 1}$:

$$
\begin{aligned}
E_i^{fb} &< E_i^{comp} \\
G_i^{fb} &> G_i^{comp}
\end{aligned}
\tag{28}
$$

These equations show the free-riding effect in the context of climate change policy. For both abatement and SGE actions, moving away from a cooperation regime to a competitive regime reduces the regional incentives for adopting a more stringent climate policy. While the cost and damages of climate actions (abatement and SGE) are locally incurred, the benefit of these actions in the form of reduction in the global mean temperature is felt globally by all regions. Therefore, each individual region has no incentive to commit to the optimal (cooperative case) policy.

As a result of the free-riding effect in abatement, atmospheric concentration increases as the level cooperation between the two region decreases (panel $\boldsymbol{C}$). While in the cooperation case, carbon concentration reaches only up to about $2000\ GtC$ by 2110, it peaks 20 years later at about $2300\ GtC$ in the competition case. After abatement efforts in each case reach the 100% abatement rate, the atmospheric concentration starts declining and stabilizes around $1450\ GtC$ in the cooperation case and $1700\ GtC$ in the competition case. Meanwhile, as shown in panel $\boldsymbol{D}$, temperature gradually increases to just under 2.0°C above pre-industrial in the cooperation case while it reaches 3.0°C in the competition case.

The middle two lines in all panels of Figure 1 show the two intermediate cases with high and low degrees of coordination between the two regions. The high coordination case is closer to the cooperation case, while the low coordination case is closer to the competition case.

5.2. Global SGE Damages

The results for simulations under this assumption are shown in Figure 2. Panel $\boldsymbol{A}$ shows SGE under different coordination levels. In contrast to the results under the assumption that SGE damages are local, we now observe a free-driving effect rather than a free-riding effect from non-cooperative cases. As we move from the cooperative case to the competition case, the level of SGE increases. In all cases, the SGE level starts out with a jump and gradually increases as the damages from climate change increase. It eventually peaks in around year 2120 and reaches its maximum value between $1.0\ W/m^2$ in the full cooperation case and $1.2\ W/m^2$ in the competition case. Given that the results shown here are only for one of the two identical regions, this translates into $2.0 - 2.4\ W/m^2$ reduction in solar radiative forcing in the next 100 years.

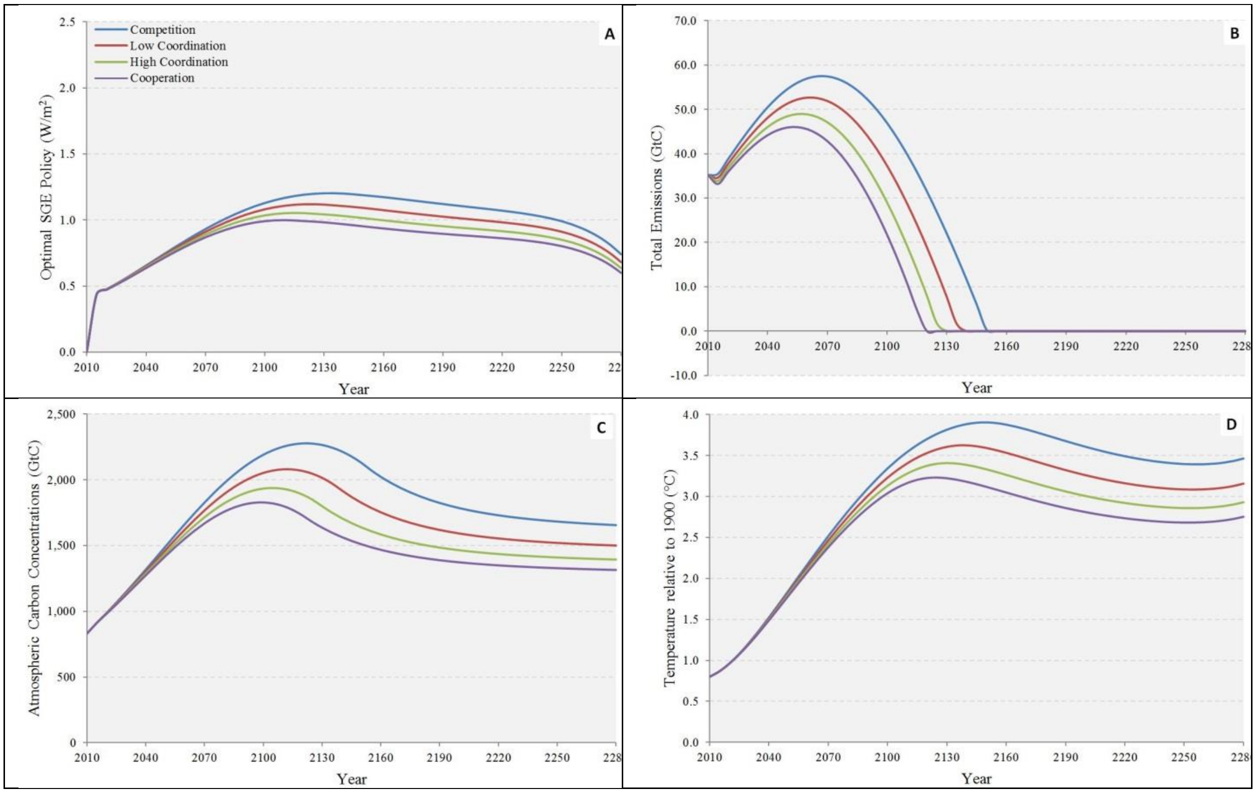

Figure 2: Climate policies and outcomes for the model with damages from global SGE deployment. Each panel shows four scenarios of cooperation, high coordination, low coordination, and competition.}\label{fig:2}

The free-riding effect, however, still can be observed for abatement. Panel $\boldsymbol{B}$ shows the level of emissions under different strategies. In contrast to SGE, the cooperation case has the highest abatement and therefore the lowest emissions, while the competition case has the lowest abatement and highest emissions. Emissions over the next 100 years increase to 57 GtC in the competition case and 46 GtC in the full cooperation case. By 2120, all emissions are abated in the full cooperation case. In contrast, competition delays reaching the 100% abatement point to 2150. As in Figure 1, when the 100% abatement point is reached, the level of SGE gradually decreases.

The results from panel $\boldsymbol{A}$ and panel $\boldsymbol{B}$ of Figure 2 show the free-driving and free-riding effects in the context of climate change policy, respectively. For abatement action, moving away from a cooperative regime to a competitive regime reduces the regional incentives for adopting a more stringent climate policy. This is because all of the costs of abatement are local, while the benefits are global, leading to the classic free-rider problem. In contrast, individual regions in the competitive regime find it more attractive to act unilaterally and increase their contribution of SGE deployment compared to the cooperative regime. This is because, unlike for abatement and unlike for SGE under the previous assumption of local damages, here the damages from SGE are global rather than local. Therefore, individual regions have an incentive to increase their SGE level above what is optimal (under the cooperative regime). This is the free-driver problem[11].

As a result of free riding in abatement, atmospheric concentration is higher in the competition case (panel $\boldsymbol{C}$). While in the cooperation case, carbon concentration reaches only about $1800\ GtC$ by 2100, it peaks at about $2200\ GtC$ in the competition case. After each case reaches the 100% abatement rate, atmospheric concentration starts declining and it stabilizes around $1300\ GtC$ in the cooperation case and $1650\ GtC$ in the competition case. Free-riding in abatement and free-driving in SGE have offsetting effects on temperature: lower abatement from free-riding raises temperature while higher SGE from free-driving lowers temperature. Panel $\boldsymbol{D}$ shows that the free-riding effect of abatement dominates the free-driving effect of SGE; temperature is higher in the competition case than in the cooperation case, despite the higher SGE use in that case. Temperature starts out with a gradual increase to about 3.2℃ in the cooperation case, while it reaches just under 4.0℃ in the competition case.

As in Figure 1, the middle two lines in all panels of Figure 2 show two intermediate cases with high and low degrees of coordination between the two regions.

6. Conclusion

We investigate the potential use of solar geoengineering as a policy tool to achieve a lower global temperature under different levels of international coordination. Our theoretical and numerical models suggest that (1) geoengineering, if deployed, can play an important role in the climate policy portfolio, (2) low cooperative regimes with local SGE damages result in a under-provision of abatement and SGE actions (free riding), and finally (3) low cooperative regimes with global SGE damages result in a under-provision of abatement (free riding) but over-provision of SGE (free driving).

These results are important in that they highlight the need for careful examination of costs and impacts of SGE options before committing to any international accord to regulate their deployment. In setting international regulations over the future deployment of SGE, decision makers should take into account the possibility of free-riding and free-driving effects that may emerge in any level of cooperation among individual regions.

[11] Martin L. Weitzman, *A Voting Architecture for the Governance of Free-Driver Externalities, with Application to Geoengineering*, 117(4) THE SCANDINAVIAN JOURNAL OF ECONOMICS 1049, 1068 (2015)