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Abstract

Geoengineering, i.e. the use of artificial techniques aiming at cooling the planet, is increasingly considered as a realistic alternative to emission mitigation. Several methods are promising for their capacity to quickly halt global warming at a moderate cost. Such cheap technologies might be very beneficial to countries profoundly affected by global warming. In this paper, I propose a dynamic model in which geoengineering is introduced as an alternative to mitigation. Contrary to abatement, geoengineering is fast and cheap, but requires a large initial investment in research and development. Within this framework, I confirm the fear which is common among geoengineering opponents: abatement is reduced if geoengineering is expected to be available in the future. The long-run implications of the model are also alarming as geoengineering will not be undertaken progressively. The sudden implementation of geoengineering, together with the sharp jump in temperature induced, may disturb climate equilibrium and fragile ecosystems. Furthermore, the availability of geoengineering will exacerbate intergenerational issues: while current generations will anticipate the use of geoengineering by increasing their emissions, future generations will have to reduce their emissions, to bear the cost of sustaining geoengineering for centuries and to suffer from its negative side-effects.

Keywords: Geoengineering, Abatement, Climate change, Global warming, R&D, Intergenerational issues

JEL Classification: Q01, Q52, Q54, Q55, O44

1. Introduction

The Earth system is continuously heated by the short-wave light coming from the Sun. Before reaching the Earth surface, a fraction of this short-wave radiation, the albedo, is reflected by clouds and white surfaces. The rest, about two-thirds of the incident solar radiation, is absorbed by the Earth system and converted into heat. This heat is then re-emitted from the Earth surface as long-wave radiation. In equilibrium, the energy coming from the sun and absorbed by the Earth surface is exactly compensated by the heat that escapes the Earth system. This delicate energy balance determines Earth temperature: if the radiation stream is perturbed by 1%, the surface temperature would change by about $1.8°C$.

The increase in the atmospheric concentration of greenhouse gases (GHGs), principally carbon dioxide (CO_2), methane and water vapor, affects this fragile equilibrium. Indeed, while GHGs allow the passage of the short-wave radiation (the sunlight and the albedo), they absorb and re-emit a fraction of the long-wave radiation (heat) escaping from the Earth. Part of this energy is sent back in direction of the Earth surface and again converted into heat. This back-and-forth of long-wave radiation, commonly called "greenhouse effect", is seen as the main responsible for global warming.

Indeed, because of the industrial revolution, the atmospheric concentration of CO_2 increased over the past two centuries from 280 ppmv (parts per million by volume) in preindustrial time to 379 ppmv in 2005 (+40%)

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(IPCC Working Group I, 2007). Annual emission of carbon dioxide was increased by 80% between 1970 and 2004. With such a trend, atmospheric CO_2 concentration is projected to range from 540 to 970 ppmv by the end of the 21st century. Similarly, methane concentration is nowadays over 150% above its preindustrial level. Changes in atmospheric concentration of greenhouse gases have already risen the surface Earth's temperature of $0.8°C$. Even if the concentration of greenhouse gases remains stable, the average temperature is still expected to rise of one more degree (IPCC Working Group I, 2007). This is due to the time lag in global warming caused by the large heat capacity of the oceans. The IPCC anticipates a global warming ranging between 1.8 and $4°C$, leading to the collapse of the major ice sheets and a sea level rise of tens of meters (IPCC Working Group II, 2007). Even more frightening is the likelihood of unpredictable non-linearities in climate change, or "tipping points", at which temperature, or other factors, may rapidly generate irreversible and potentially very destructive changes (IPCC Working Group II, 2007; Swart and Marinova, 2010; Kousky et al., 2009).

In order to prevent such dangerous and irreversible consequences, the most popular approach, mitigation, seeks to reduce the emission of greenhouse gases in the atmosphere. Despite the last twenty years of proactive diplomatic talks, this strategy seems limited because subject to free-riding. The stabilization of CO_2 concentration would require a 60–80% worldwide reduction in current anthropogenic CO_2 emissions. Nevertheless, fossil fuels provide over 80% of the world's energy, and emissions of CO_2 are actually increasing by around 2% each year (Crutzen, 2006). Many governments are reluctant to engage in unpopular binding commitments whose cost is born in the short-run, while benefits mainly arise in the long-run.

In response to this coordination failure, geoengineering has been put forward in the scientific debate as a credible but controversial alternative to mitigation[2]. Geoengineering is defined by the National Academy of Sciences (1992) as the "options that would involve large-scale engineering of our environment in order to combat or counteract the effects of changes in atmospheric chemistry". Geoengineering techniques may be classified in two categories, depending on whether they aim at reducing the greenhouse effect, or at diminishing the share of sunlight that reaches and warms the Earth system. On the one hand, carbon dioxide removal (CDR) seek to remove CO_2 from the atmosphere in order to reduce the amount of long-wave radiation trapped in the Earth system through the greenhouse effect. For example, the literature proposes to extend the surface of the Earth covered by trees, to increase the oceanic uptake of CO_2 through enhanced algae and plankton growth, to accelerate artificially the mineral sequestration of CO_2, or to create "artificial trees" that capture CO_2 thanks to a chemical sorbent.

On the other hand, solar radiation management (SRM) aims at repelling short-wave sunlight before the radiation hits the Earth surface and turns into heat. Offsetting the warming caused by a doubling of the pre-industrial revolution atmospheric concentration of CO_2 would require shielding or reflecting approximately 1.8% of the incident solar radiation. The two most effective methods are the injection of reflective particles, principally sulfate aerosols, in the high-atmosphere (Crutzen, 2006), and the increase of the albedo of maritime areas by seeding and whitening stratocumulus clouds over the oceans (Salter et al., 2008; Latham et al., 2008). Recently, these two geoengineering techniques were evaluated using modified DICE models (Nordhaus, 2007; Bickel, 2009; Goes et al., 2009; Bickel and Agrawal, 2011). All but Goes et al. (2009) conclude that geoengineering is highly cost-effective. For example, Bickel (2009) estimates benefit-cost ratios of around 25 to 1 for aerosols injection in the stratosphere and around 5000 to 1 for cloud albedo enhancement. The study of Goes et al. (2009) is at odds with these conclusions. Rather, they argue that aerosol geoengineering is not cost-effective because too risky in case of failure to sustain aerosol injections. Another SRM method would be to launch space sunshields between the sun and the Earth to block incoming radiations. Proposals have also been made to increase Earth albedo by brightening land or ocean surfaces, for example by painting roofs or covering deserts with reflective sheets. These last two options appear to be less cost-effective than the injection of sulfate aerosols in the high-atmosphere or the enhancement of cloud albedo (see Shepherd (2009) for a detailed review of all geoengineering methods).

This paper aims at comparing mitigation (abatement) and geoengineering. More specifically, I will construct a theoretical model assessing under which conditions geoengineering may be used as cheap substitute for

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[2] A third approach, adaptation, proposes to render the society and the environment more robust to the changes in climate that are occurring. The evaluation of this third solution is beyond the scope of this paper.

abatement. As both mitigation and carbon management seek to reduce the quantity of CO_2 in the atmosphere, these two methods would be formalized in the same way. CDR can be regarded as special kind of mitigation method. Therefore, I focus only on SRM whose formalization and properties are sharply different from abatement. In what follows, I use the term geoengineering to refer to SRM.

I distinguish seven differences between geoengineering and abatement. First, while it would be technically feasible to drastically decrease emissions nowadays, geoengineering is not yet implementable and requires a sustained effort in research and development. Second, geoengineering is cheaper than abatement, but requires large investments in research and development. Third, geoengineering may act much faster than abatement. Indeed, abatement requires a sustained effort to mitigate emissions. Furthermore, because GHGs is a stock accumulating over time, and because the large heat capacity of the oceans induces a time lag in global warming, the positive impact of mitigating emissions is only expected in the long-run. Conversely, geoengineering is fast at decreasing the average temperature when it is implemented. Fourth, contrary to abatement, geoengineering does not fight the cause of global warming. Rather, it aims at artificially offsetting the greenhouse effect in order to prevent its detrimental consequences. Fifth, geoengineering is imperfect as it may have large side-effects on the environment. For example, stratospheric sulfate injection may have harmful consequences on stratospheric ozone and biological productivity. Cloud albedo enhancement may affect weather patterns and ocean currents. Both these methods have non-uniform effects, and induce significant regional climate changes (Jones et al., 2011). The sixth difference between geoengineering and abatement is related to their surrounding uncertainties. For geoengineering, the uncertainty is related to the cost, the effectiveness and the presence of possible side-effects. Conversely, for mitigation, the amount of abatement needed to avoid harmful consequences and “tipping points” is unknown. Finally, while countries implementing geoengineering may be clearly identified, it is much harder to assess which country has to mitigate its emissions, and by how much. Consequently, a country deciding unilaterally to use geoengineering may be punished by others. This is not the case for countries emitting more GHGs.

The literature on the economics of geoengineering is scarce. Barrett (2007) was the first economist to discuss governance challenges brought about by geoengineering. He argues that any countries for which implementation costs are lower than benefits will be willing to try it. As Barrett (2007) does not propose a formal model, he can not predict which country or group of countries will bear the cost. Only four papers introduced geoengineering in economic models as a cheap alternative to abatement. First, using a one-country model with climate damages, Moreno-Cruz and Smulders (2010) conclude that geoengineering is an imperfect substitute for abatement as it generates negative side-effects (fourth and fifth differences). Second, by using numerical estimations, Moreno-Cruz and Keith (2009) expand this framework to allow for uncertainty on the effectiveness and the consequences of geoengineering (sixth difference). They show that geoengineering is an effective means to approach the uncertainty on climate damages as it can be implemented quickly if the bad outcome of the uncertainty is revealed. Finally, Moreno-Cruz (2009) and Millard-Ball (2011) show that countries act strategically when geoengineering is made available in a multi-country framework (Seventh difference). For example, Moreno-Cruz (2009) shows that a country may substitute away from abatement to induce higher levels of geoengineering in other countries. Conversely, if a country fears the side-effects of geoengineering, it may increase its level of abatement to deter the use of geoengineering by other countries. Similarly, Millard-Ball (2011) shows that countries not much affected by climate change may nevertheless strengthen their level of abatement to avoid the threat of unilateral geoengineering use coming from a country highly affected by global warming.

For now, the theoretical literature on geoengineering disregarded the three first differences between abatement and geoengineering. Introducing these in a theoretical framework is the main objective of the paper. I will construct a dynamic model that takes into account both the fastness and the specific cost structure of geoengineering. More specifically, geoengineering will be introduced besides abatement in a two-period model with climate damages. Geoengineering will be characterized by a fixed cost which includes both research and development investments as well as indirect costs related to governance issues or conflict mitigation. While geoengineering may quickly reduce temperature and climate damages, abatement is much slower as emissions accumulate as a stock. Within this framework, I will study the short- and the long-run implications of geoengineering availability, with a special focus on intergenerational issues. Some crucial differences with Moreno-Cruz and Smulders (2010) will be highlighted along the way.

In the next section, I introduce the two-period model, in which both abatement and geoengineering may be undertaken to prevent climate change damages. In section 3, I assess the long-run implications of the model and I discuss the main findings of the paper. Section 4 concludes.

2. A model of climate change and geoengineering

2.1. Set-up

We consider the maximization problem of a unique country that seeks to maximize consumption over two periods. In order to produce one unique good, the country uses energy e_t. One unit of energy costs π, and generates one unit of GHG emission (later, e_t will refer for energy use as well as emissions at time t).

The accumulation of GHG emissions in the atmosphere damages the environment through global warming. In order to avoid dramatic loss of production due to the temperature increase, the country may choose to reduce its emissions (mitigation or abatement) or to implement geoengineering. Both strategies are costly. On the one hand, by limiting emissions, abatement constrains production. On the other hand, implementing geoengineering requires a large initial investment in the research and the development of the cooling technology as well as a sustained effort for maintaining temperature at the desired level.

At each period, the consumption is equal to the production $f(e_t)$, minus the energy cost πe_t, the damages due to global warming $\Omega(T_t)$, and the geoengineering cost $\Gamma(G_t)$.

$$c_t = f(e_t) - \pi e_t - \Omega(T_t) - \Gamma(G_t).$$

Formally, we assume that the production function of the country is quadratic and given by:

$$f(e_t) = e_t(\alpha - \beta e_t).$$

We assume that $\alpha > \pi$ to ensure the existence of a positive solution for e_t in the "no damage case" ($f' > 0$, $f'' < 0$, $f(0) = 0$).

The evolution of the stock of GHG in the atmosphere, P_{t+1}, is determined by the sum of current emissions and the remaining stock of pollution:

$$P_{t+1} = P_t(1 - \delta) + e_t. \tag{1}$$

The factor δ is constant and represents the length of life of CO_2 in the atmosphere ($0 \leq \delta < 1$). Current emissions only have an impact in the next period. This specification reflects the time lag in global warming.

The world temperature T_t at time t is positively related to the stock of greenhouse gases in the atmosphere P_t and negatively related to the total quantity of geoengineering used G_t. We assume a linear specification:

$$T_t = \Phi(P_t, G_t) = P_t - \kappa G_t. \tag{2}$$

It is worth noting that pollution P_t is a stock. Hence, emissions have a long-lasting impact on temperature. Conversely, the quantity of geoengineering G_t is a flow. At each period, geoengineering has to be re-implemented if it is optimal to cool the planet.

The global temperature T_t affects the economy through the damage function $\Omega(T_t)$. We assume a quadratic form for the damage function:

$$\Omega(T_t) = (T_t - \gamma)^2.$$

The damage function is positive, strictly convex and U-shaped with a minimum in γ. This minimum is called the optimal temperature.

Geoengineering is costly. Contrary to the existing literature, we assume that the geoengineering cost function $\Gamma(G_t)$ is not continuous near $\Gamma(0) = 0$ because of the existence of a fixed cost p. This fixed cost represents the large investment in R&D and infrastructure needed to put geoengineering technologies into service. For $G_t > 0$, we assume that the cost function of geoengineering is linear:

$$\Gamma(G_t) = \begin{cases} 0 & \text{if } G_t = 0 \\ mG_t + p & \text{if } G_t > 0 \end{cases}$$

In summary, the objective of the country is to maximize the discounted sum of consumption flows:

$$\max_{e_1,e_2,G_1,G_2} V(e_1, e_2, G_1, G_2) = c_1(e_1, G_1) + \rho c_2(e_1, e_2, G_2)$$
$$= \sum_{t=1,2} \rho^{t-1}[e_t(\alpha - \beta e_t) - \pi e_t - (P_t - \kappa G_t - \gamma)^2 - \Gamma(G_t)].$$

The decision variables are the energy consumed and the geoengineering levels at each period of time (e_1, e_2, G_1, G_2). The stock of greenhouse gases in the atmosphere at time $t = 1$, $P_1 \geq 0$ is given.

2.2. *Solution without climate damages*

In order to define abatement, we consider the benchmark case of an economy which does not suffer from global warming ($\Omega(T_t) = 0$). The problem is then static. The consumption of energy is chosen such that the marginal benefit of energy equals its marginal cost:

$$f'(e_t) = \alpha - 2\beta e_t = \pi \Leftrightarrow e^* = \frac{\alpha - \pi}{2\beta}. \tag{3}$$

The solution, denoted e^*, is constant, unique and positive as $\alpha > \pi$. Figure 1 shows the graphical solution of the maximization. In the lower-part of the figure, the green line represents the production function, and the red line the energy cost. The marginal counterparts of these functions are drawn in the upper-part. The optimal use of energy is defined by the equality between the marginal productivity of energy (the green line) and its marginal cost (the red line).

Contrary to the existing literature (Moreno-Cruz and Keith, 2009; Moreno-Cruz, 2009; Moreno-Cruz and Smulders, 2010), emissions are explictly considered in this model, and abatement is only an indirect decision variable. This difference makes possible the dynamic analysis of geoengineering and climate change. We define abatement A_t, as the optimal level of emission without climate damages, e^*, minus the emission level at time t, e_t: $A_t = e^* - e_t$.

2.3. *With geoengineering*

The problem is dynamic as present emissions have an impact on both present production and future damages. In order to prevent damages from climate change, the country may mitigate its emissions or invest in geoengineering. The country chooses e_1, e_2, G_1 and G_2 to maximize the discounted sum of consumption flows:

$$\max_{e_1,e_2,G_1,G_2} V(e_1,e_2) = f(e_1) - \Omega(T_1) - \pi e_1 - \Gamma(G_1)$$
$$+\rho[f(e_2) - \Omega(T_2) - \pi e_2 - \Gamma(G_2)],$$

Subject to:

$$\begin{cases} T_t = \Phi(P_t, G_t) \\ P_2 = P_1(1-\delta) + e_1 \\ G_1, G_2 \geq 0 \\ P_1 > 0 \text{ given.} \end{cases}$$

Because of the fixed cost, the objective function is not continuous. Therefore, we cannot apply the Mangasarian Lemma: the first-order conditions are not sufficient to have a maximum. Because of the discontinuity near $G_t = 0$, we will compare the solution given by the resolution of the first-order conditions with the solution for $G_1 = 0$ and/or $G_2 = 0$ (section 2.4). As both G_1 and G_2 should be positive, we form the Generalized Lagrangean:

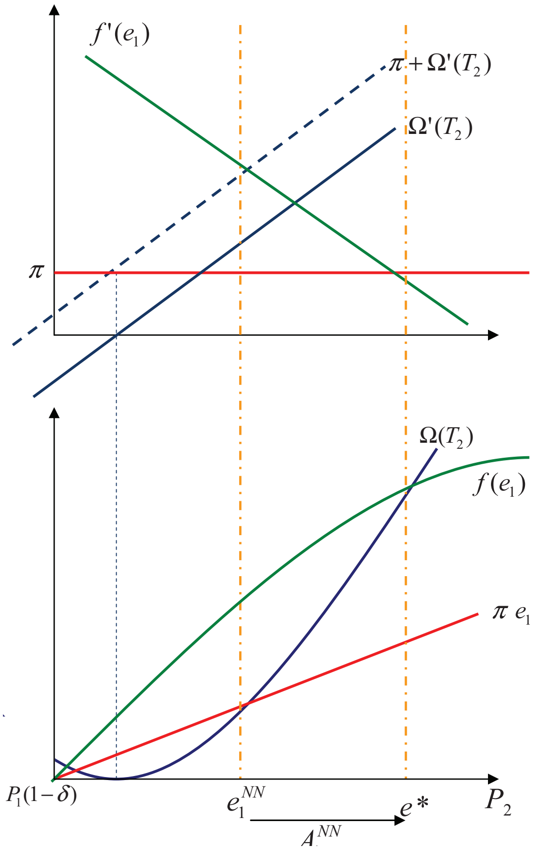

Figure 1: Emissions are lower with the damage function

$$\max_{e_1,e_2} L(e_1,e_2,G_1,G_2) =$$
$$\sum_{t=1,2} \rho^{t-1}[f(e_t) - \Omega(T_t) - \pi e_t - \Gamma(G_t)]$$
$$+ \lambda[P_2 - P_1(1-\delta) - e_1] + \mu_1 G_1 + \mu_2 G_2.$$

Because of the inequality constraints $G_1 \geq 0$ and $G_2 \geq 0$, two complementary slackness conditions should hold simultaneously:

$$\mu_i \geq 0 \text{ , } G_i \geq 0 \text{ and } \mu_i G_i = 0 \text{ , } i = 1, 2. \tag{4}$$

The two slackness conditions imply four cases.

CASE NN: $G_1 = G_2 = 0$. Geoengineering is never used to counteract global warming, either because it is too expensive or because the pollution stock is low. The first-order conditions of the maximization program give the optimal levels of emission and geoengineering:

$$\Leftrightarrow \begin{cases} e_{NN} = \dfrac{\alpha - \pi - 2\rho[P_1(1-\delta) - \gamma]}{2(\beta + \rho)} \\ \quad\;\; = e^* - \rho \dfrac{e^* + P_1(1-\delta) - \gamma}{\beta + \rho} & (5) \\ e_{NN} = \dfrac{\alpha - \pi}{2\beta} = e^*. & (6) \end{cases}$$

The marginal return of emissions at time $t = 1$ equals its marginal cost π plus the discounted value of the marginal damage due to these emissions. Emissions in $t = 1$ are positively related to the discount rate ρ, the dissipation of CO_2 δ and the optimal temperature γ. They are negatively related to the energy price π and the initial pollution stock P_1. Abatement in the first period is positive if emitting e^* would induce a temperature in $t = 2$ which is above the optimal temperature level γ, that is, if emitting more than e^* would increase climate damages. As our framework is limited to two periods, emissions at time $t = 2$ will always be equal to e^* as they do not induce damage in the future.

Slackness conditions imply that both μ_1^{NN} and μ_2^{NN} are strictly positive:

$$\begin{cases} \mu_1^{NN} = m - 2\kappa(P_1 - \gamma) > 0 \\ \mu_2^{NN} = \dfrac{2\beta\kappa\rho}{\beta + \rho}\left[\dfrac{m}{2\kappa} - [P_1(1-\delta) - \gamma + e^* - \dfrac{m\rho}{2\beta\kappa}]\right] > 0. \end{cases}$$

The complementary slackness conditions are sufficient conditions for geoengineering to be suboptimal. However, these conditions are not necessary: if the fixed cost of geoengineering is high, geoengineering may not be implemented even if slackness conditions hold. For sufficient conditions, we will need to compare the discounted sum of consumption flows for the four cases (section 2.4). By reversing the sign of the slackness conditions, we obtain necessary conditions for geoengineering to be optimal.

Graphically, the damage function and its marginal counterpart are represented by the blue lines in figures 1 and 2. The optimal level of emission is determined by the intersection between the marginal productivity of energy (the green line in the upper-part) and the sum of its marginal cost plus the marginal damages at time $t = 2$ due to emissions at time $t = 1$ (the dotted blue line in the upper-part). In figure 1, abatement is positive as increasing emissions would increase climate damages. In figure 2 abatement is negative: increasing emissions would reduce climate damages.

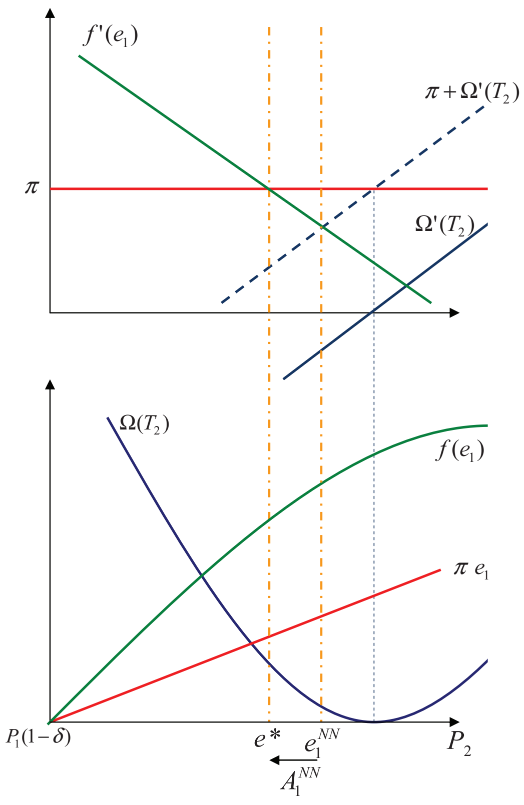

Figure 2: Emissions are higher with the damage function

CASE GG: $G_1 > 0, G_2 > 0$. If geoengineering is cheap and the initial pollution stock is high, geoengineering is used in both periods to counteract climate change.

The first-order conditions of the maximization program give the optimal levels of emission and geoengineering:

$$\begin{cases} e_1^{GG} = e^* - \dfrac{m\rho}{2\beta\kappa} \\ e_2^{GG} = e^* \\ G_1^{GG} = \dfrac{1}{\kappa}\left(P_1 - \gamma - \dfrac{m}{2\kappa}\right) > 0 \\ G_2^{GG} = \dfrac{1}{\kappa}\left(P_1(1-\delta) - \gamma + e^* - \dfrac{m\rho}{2\beta\kappa} - \dfrac{m}{2\kappa}\right) > 0. \end{cases}$$

It is worth noting that abatement in the first period is positive even if geoengineering is used. Abatement is positively related to the marginal cost of geoengineering π and to the discount rate ρ, and negatively related to geoengineering efficiency κ. Slackness conditions imply $\mu_1 = \mu_2 = 0$, $G_1^{GG} > 0$ and $G_2^{GG} > 0$. Because of the fixed cost of geoengineering, $G_1^{GG} > 0$ and $G_2^{GG} > 0$ are necessary, but not sufficient for geoengineering to be optimal. Therefore, if $G_1^{GG} < 0$ or $G_2^{GG} < 0$, the case GG is not optimal.

CASE NG: $G_1 = 0$**,** $G_2 > 0$. Geoengineering is only used at time $t = 2$. In the first period, the pollution stock is low and geoengineering is not optimal. Emissions at time $t = 1$ rise the pollution stock such that geoengineering becomes optimal at time $t = 2$. The first-order conditions of the maximization program give the optimal levels of emission and geoengineering:

$$\begin{cases} e_1^{NG} = e^* - \dfrac{m\rho}{2\beta\kappa} \\ e_2^{NG} = e^* \\ G_1^{NG} = 0 \\ G_2^{NG} = \dfrac{1}{\kappa}\Big(P_1(1-\delta) - \gamma + e^* - \dfrac{m\rho}{2\beta\kappa} - \dfrac{m}{2\kappa}\Big) > 0. \end{cases}$$

Again, abatement is positive in the first period even if emissions will be compensated by geoengineering in the second period. The complementary slackness condition at time $t = 1$ imposes $\mu_1^{NG} > 0$ (necessary condition), that is: $\mu_1^{NG} = m - 2\kappa(P_1 - \gamma) > 0$. At time $t = 2$, the slackness condition requires $G_2^{NG} > 0$. Therefore, if $\mu_1^{NG} < 0$ or $G_2^{NG} < 0$, the case NG is not optimal.

CASE GN: $G_1 > 0$**,** $G_2 = 0$. Geoengineering is only used at time $t = 1$. In the first period, the pollution stock is high and geoengineering is optimal. Emissions at time $t = 1$ are low and the dissipation rate of CO_2 is high. Consequently, the pollution stock sharply decreases, and geoengineering is not optimal anymore in the second period. This case is of course not realistic, at least in the short-run. The first-order conditions of the maximization program give the optimal levels of emission and geoengineering:

$$\begin{cases} e_1^{GN} = e^* - \rho\dfrac{e^* + P_1(1-\delta) - \gamma}{\beta + \rho} \\ e_2^{GN} = \dfrac{\alpha - \pi}{2\beta} \\ G_1^{GN} = \dfrac{1}{\kappa}\Big(P_1 - \gamma - \dfrac{m}{2\kappa}\Big) \\ G_2^{GN} = 0. \end{cases}$$

Abatement in period 1 is high as the country anticipates that geoengineering will not be used in the second period. The two slackness necessary conditions are $G_1^{GN} > 0$ and $\mu_2^{GN} = \frac{2\beta\kappa\rho}{\beta+\rho}\Big[\frac{m}{2\kappa} - [P_1(1-\delta) - \gamma + e^* - \frac{m\rho}{2\beta\kappa}]\Big] > 0$. If one of these two conditions are not satisfied, the case NG is not optimal.

2.4. The optimal case

Until now, we computed the optimal levels of emission and geoengineering for each case. We still have to compare the discounted sum of consumption flows for each case, taking into account that the country has to pay a fixed cost to undertake geoengineering. Let us compare the four cases by plugging the optimal emission and geoengineering levels obtained for each case into $V(e_1, e_2, G_1, G_2)$. We find the following results.

Proposition 2.1. *Geoengineering at time 1 is optimal if the two following conditions are satisfied:*

$$\begin{cases} p < \Big[P_1 - \gamma - \dfrac{m}{2\kappa}\Big]^2 & (7) \\ P_1 - \gamma > \dfrac{m}{2\kappa}. & (8) \end{cases}$$

Proof Simple algebra gives $V_{GG} - V_{NG} = V_{GN} - V_{NN}$. Inequality (7) is derived from the following equivalences:

$$V_{GG} > V_{NG} \Leftrightarrow V_{GN} > V_{NN} \Leftrightarrow p < \Big[P_1 - \gamma - \tfrac{m}{2\kappa}\Big]^2.$$

The inequality (8) is derived from the complementary slackness conditions: $\mu_1^{NN} < 0$ and $\mu_1^{NG} < 0$ are necessary conditions for geoengineering to be optimal in the first period. □

Taken together, conditions (7) and (8) imply that geoengineering is optimal at time $t = 1$ if the temperature in the first period, $P_1 - \gamma$ would be high without the use of geoengineering, and if the price of geoengineering for a one-unit reduction in the temperature, $\frac{m}{\kappa}$, is low compared to the fixed cost of geoengineering p.

Proposition 2.2. *Geoengineering at time 2 is optimal if the two following conditions are satisfied:*

$$\begin{cases} \dfrac{\beta}{\beta+\rho}\Big[P_1(1-\delta) - \gamma + e^* - \dfrac{m\rho}{2\beta\kappa} - \dfrac{m}{2\kappa}\Big]^2 > p & (9) \\ P_1(1-\delta) - \gamma + e^* - \dfrac{m\rho}{2\beta\kappa} > \dfrac{m}{2\kappa}. & (10) \end{cases}$$

Proof The proof is similar. Simple algebra gives $V_{GG} - V_{GN} = V_{NG} - V_{NN}$. Inequality (7) is derived from the following equivalences:
$V_{GG} > V_{GN} \Leftrightarrow V_{NG} > V_{NN} \Leftrightarrow$ Inequality (9) holds.

The condition (10) is derived from the complementary slackness conditions: $\mu_2^{NN} < 0$ and $\mu_2^{GN} < 0$ are necessary conditions for geoengineering to be optimal in the second period. □

As $e_1^{GG} = e_1^{NG} = e^* - m\rho/2\beta\kappa$, proposition 2.2 may be interpreted as follows. Conditions (9) and (10) imply that geoengineering is optimal at time $t = 2$ if the temperature at time $t = 2$ without using geoengineering would be high and if the price of geoengineering for a one-unit reduction in the temperature, $\frac{m}{\kappa}$, is low compared to the fixed cost of geoengineering p. Strong preferences for the present (low ρ) increase the relative utility of geoengineering use at time $t = 2$.

These propositions should be contrasted with the results of Moreno-Cruz and Smulders (2010). In the present model, inequalities (7) and (9) induce that geoengineering may not be implemented even if the GHG stock generates climate damages. In Moreno-Cruz and Smulders (2010), geoengineering is always used in the presence of climate damages as the fixed cost is not considered.

Everything else being equal, we derive from these propositions that the initial concentration of GHGs in the atmosphere is higher when geoengineering is implemented.

Corollary 2.3. *Geoengineering is implemented in the short-run if the initial concentration of GHGs is high:*

$$P_1^{GG} > P_1^{GN} > P_1^{NN}. \tag{11}$$

Similarly, geoengineering is implemented in the long-run if the initial concentration of GHGs is high and if the dissipation of GHGs is low:

$$P_1^{GG} > P_1^{NG} > P_1^{NN}. \tag{12}$$

In the present analysis of the optimal case, I assumed that the fixed cost is paid each time geoengineering is used. Under this assumption, the fixed cost encompasses investments needed to maintain geoengineering capacities as well as indirect costs related to governance issues or conflict mitigation. If we assume that the fixed cost is paid only once, for example if the fixed cost is related to R&D investments needed to develop geoengineering techniques, then inequalities (7) and (9) are slightly modified for the case GG (the right-hand side of inequalities (7) and (9) is divided by $(1+\rho)$). Indeed, as the fixed cost is paid only once, using geoengineering in both periods becomes more attractive. The case GN becomes even irrelevant if G_2^{GG} is positive. This is always the case when the GHG stock is high enough to generate climate damages.

2.5. *Comparing abatement, geoengineering and temperature*

Let us first compare the abatement levels across the four cases. Regarding the level of emission in the first period, we have that:

$$\begin{aligned} e_1^{NN} - e_1^{NG} &= \frac{\rho}{\beta+\rho}\Big[\frac{m}{2\kappa} - [P_1(1-\delta) - \gamma + e^* - \frac{m\rho}{2\beta\kappa}]\Big] \\ &= \frac{\mu_2^{NN}}{2\beta\kappa}. \end{aligned}$$

As $\mu_2^{NN} < 0$ is a necessary condition for geoengineering to be optimal in the second period, we conclude that emissions in the first period are higher when geoengineering is used to compensate the global warming in the second period. Furthermore, as $P_1^{GN} > P_1^{NN}$ (corollary 2.3), and as emissions are negatively related to the initial pollution stock for cases GN and NN, we conclude that the following relations hold: $e_1^{GG} = e_1^{NG} > e_1^{NN}$ and $e_1^{NN} > e_1^{GN}$. Hence, the country increases its emissions at time $t = 1$ if it is anticipated that emissions will be compensated by the use of geoengineering in period 2. Conversely, the country reduces its emissions in the first period if geoengineering is not expected to be implemented in the second period. The following proposition summarizes this reasoning.

Proposition 2.4. *Abatement is reduced in the first period if the country anticipates that geoengineering will be used in the second period.*

This proposition confirms a fear which is common among opponents of geoengineering R&D. They argue that promoting research to develop these artificial techniques may give the false impression that environmental issues are resolved, and therefore discourage efforts to reduce emissions.

Regarding the level of emission in the second period, it is straightforward that: $e_2^{GG} = e_2^{NG} = e_2^{NN} = e_2^{GN}$. This set of equalities should be interpreted as an “end of life” effect: emissions at time 2 have no impact on damages as our model is limited to two periods. The long-run evolution of abatement is discussed in section 3.

Second, let us analyze the use of geoengineering over time. When geoengineering is optimal at time t, it is straightforward to see that the amount of geoengineering used is a linear function of the pollution stock:

$$G_t = \frac{1}{\kappa}(P_t - \gamma - \frac{m}{2\kappa}). \tag{13}$$

As the $1/\kappa$ is positive, we have the following property.

Proposition 2.5. *If geoengineering is optimal, the use of geoengineering increases as long as the pollution stock grows, that is, as long as emissions e_t are higher than the dissipation of the pollution stock δP_t.*

Finally, let us assess the impact of geoengineering availability on temperature. For a given initial pollution stock P_1, it is direct to see that the climate is colder in the first period when geoengineering is used as $T_1 = P_1 - \kappa G_1$. In the second period, the availability of geoengineering affects the temperature in two opposite directions. On the one hand, the direct effect of geoengineering is to decrease the temperature. On the other hand, the pollution stock is higher as abatement is reduced in the first period (proposition 2.4). For a given GHGs initial stock P_1, we have that: $T_2^{GG} - T_2^{NN} = T_2^{NG} - T_2^{NN} = \mu_2^{NN}/2\kappa\rho$. As $\mu_2^{NN} < 0$ is a necessary condition for geoengineering to be used, we conclude that the net impact of the two opposite effects on temperature is negative. The following proposition summarizes this statement.

Proposition 2.6. *Even if the availability of geoengineering reduces abatement, the temperature is lower when geoengineering is used.*

By plugging equation (13) into equation (2), we find that the temperature with geoengineering is constant and equal to:

$$T_{ss}^{Geo} = \gamma + \frac{m}{2\kappa} \tag{14}$$

This constant temperature is positively related to the optimal temperature, γ, and to the marginal cost of geoengineering, m. Conversely, this temperature is lower when geoengineering is highly effective, that is, if κ is high.

2.6. Graphical solution

The damage function and its marginal counterpart are represented by the blue lines in figures 3 and 4. Without geoengineering, the optimal level of emission is determined by the intersection between the marginal productivity of energy (the green line in the upper-part) and the sum of the marginal cost of energy and the second period marginal damages induced by emissions at time $t = 1$ (the dotted blue line in the upper-part). The amount available for consumption is equal to the blue area A. The brown area B represents the loss due to climate damages.

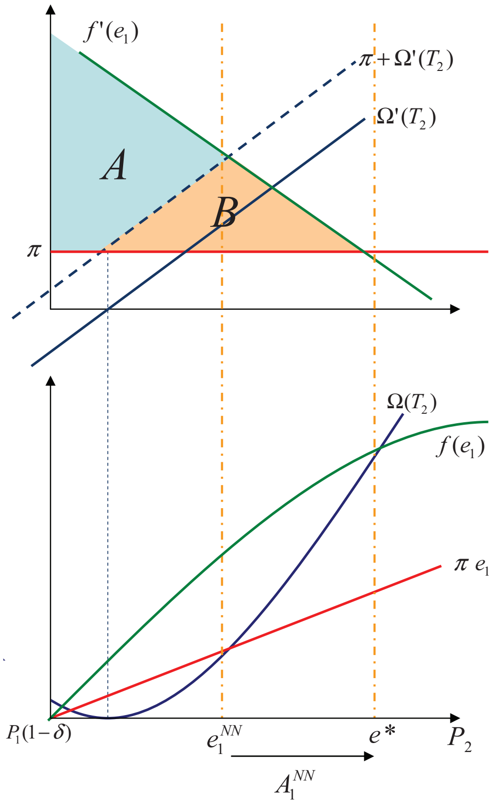

Figure 3: Potential gain from geoengineering

In figure 4, the fixed cost of geoengineering is represented by the area in red. The hatched red area is its variable cost: for a marginal increase of geoengineering, the marginal damages curve moves to the right such that climate damages decrease. Each unit of geoengineering costs m. The country will increase its use of geoengineering as long as the avoided damages are higher than the variable cost m. It is worth noting that first period abatement is reduced as climate damages are lower (proposition 2.4).

Finally, the country will implement geoengineering if and only if the brown area A in figure 3 is bigger than the brown area A'+A" in figure 4, or, similarly, if the brown area A" is bigger than the red area p. This condition is the graphical equivalent of inequality (9).

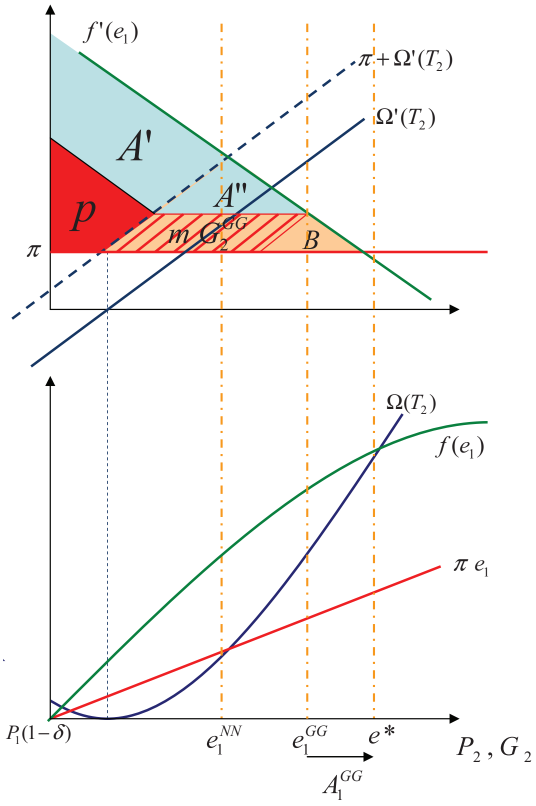

Figure 4: Optimal geoengineering

3. Discussion: A long-term scenario

Even without an infinite-horizon model, a realistic analysis of the long-term use of abatement and geoengineering is possible thanks to the 2-periods model. Figure 5 represents the long-run evolution of emissions, pollution stock, geoengineering and temperature, depending on whether the country undertakes geoengineering (plain lines) or not (dotted lines). If the initial GHG stock is low (i.e. at the preindustrial level), conditions (7) to (10) are not satisfied and geoengineering is not implemented. Emissions are high because future damages due to current emissions are low. Abatement may even be negative if the initial stock of pollution is such that the initial temperature is below its optimal level γ. The pollution stock increases over time. Consequently, emissions diminish because their impact on damages becomes more and more harmful.

If geoengineering is cheap, geoengineering becomes optimal when the pollution stock exceeds a certain threshold. Because the country anticipates the implementation of geoengineering, emissions will be increased even before the threshold is reached (proposition 2.4). Hence, the long-term level of emission and the long-term stock of pollution will be higher when geoengineering is undertaken. However, the temperature is lower when geoengineering is used, even if abatement is reduced (proposition 2.6).

Because of the fixed cost (accounted for in inequalities (7) to (10)), geoengineering is not always implemented, even if the GHG stock generates climate damages. When the pollution stock and the climate damages are high enough, geoengineering will be suddenly used in large quantities. Indeed, by plugging equation (13) into a generalized formula for inequalities (7) and (9), we have $0 < p \leq \kappa^2 G_t^2$. Consequently, the temperature jumps abruptly from a high level to a low level, which may disrupt sensible climate equilibrium or fragile ecosystems. Once geoengineering is implemented, the temperature remains constant at a level slightly above the optimal temperature γ (taking into account that the variable price of geoengineering, m, is low). Emissions remain constant, and geoengineering increases proportionally to the pollution stock so as to maintain the temperature constant. Abatement is also constant, and positive.

This long-term analysis should be contrasted with the results of Moreno-Cruz and Smulders (2010). As there is no fixed cost in their model, geoengineering is always used in presence of climate damages. Moreover, as geoengineering may be used in very small quantities, Moreno-Cruz and Smulders (2010) would not be able to find a jump in geoengineering and temperature. However, this jump is important to characterize as rapid changes may have dramatic effects if the environment and ecosystems are not able to adapt as fast.

Our long-run analysis also underlines disconcerting intergenerational issues. Indeed, while current generations will anticipate the use geoengineering by increasing their emissions, future generations will have to reduce their emissions, to bear the cost of sustaining geoengineering and will suffer from its negative side-effects. If emissions are not mitigated, future generations may even not have the choice to use geoengineering, especially in presence of “tipping points”. Furthermore, geoengineering will have to be sustained for centuries in order to avoid dramatic consequences induced by a sharp increase in temperature (Goes et al., 2009). Hence, the forthcoming availability of geoengineering methods increases the intergenerational negative transfer from now to the future. This is particularly objectionable as current generations from developed countries already live beyond the means of Earth system.

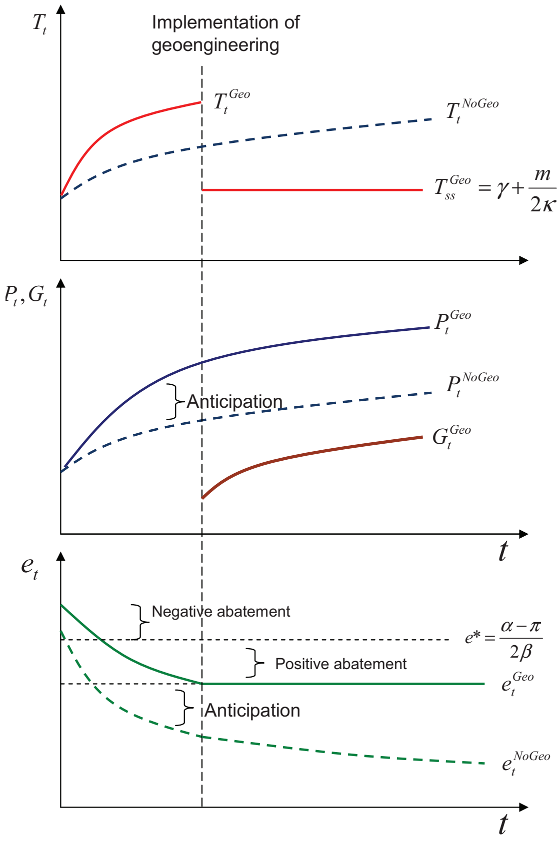

Figure 5: Long-run scenario: emissions, temperature, pollution stock and geoengineering

4. Conclusion

Geoengineering is troubling. Indeed, while it is expected to have a high cost-effectiveness at preventing damages from global warming, it will nevertheless generate worrying side-effects. For example, the two most popular SRM methods, clouds albedo enhancement and sulfate aerosols injections are expected to have non-uniform effects, and to induce significant regional climate changes. Furthermore, Stratospheric sulfate injection may have adverse consequences on stratospheric ozone and biological productivity, and cloud albedo enhancement will affect weather patterns and ocean currents.

In this paper, I showed that geoengineering availability will also induce indirect side-effects, both in the short- and the long-run. Using a two-period dynamic model with climate change, in which geoengineering may be used as an alterative to abatement, I deduced the conditions under which geoengineering is undertaken. I confirmed the fear of geoengineering opponents who argue that the anticipation of geoengineering availability will dangerously decrease abatement in the short, and in the long-run. Furthermore, I showed that the optimal path of geoengineering use is characterized by a jump, which will in turn induce a sharp and sudden decrease in temperature. This abrupt temperature drop may prove to be particularly damaging for fragile ecosystems and vulnerable regions. These indirect consequences raise disturbing intergenerational issues. The net benefit from geoengineering for current generations is positive as they may increase their emissions without engaging in costly abatement. For future generations, the situation appears to be much worse: as they inherit a higher stock of pollution, they may be compelled to implement geoengineering in order to prevent catastrophic climate damages and to avoid reaching “tipping points”. Consequently, future generation will have to support the negative side-effects of geoengineering, as well as to bear the full cost of geoengineering, which includes R&D investments as well as the capacities required for maintaining high levels of geoengineering for centuries.

These conclusions underline the need of an urgent research agenda paired with large-scale experiments of promising geoengineering methods, in order to assess the effectiveness and the dangerousness of each methods, and to share more equally the whole cost of geoengineering across generations.

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