Sustainable Climate Treaties

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Abstract

We examine long-run treaties for mitigating climate change. Countries pay an initial fee into a global fund that is invested in long-run assets. In each period, part of the fund is distributed among the participating countries in relation to the emission reductions they have achieved in this period suitably rescaled by a weighting factor. We show that a suitably selected refunding scheme implements the globally optimal reductions of greenhouse gases in all periods as a unique subgame perfect equilibrium. The country-specific initial fees can be chosen to engineer a Pareto improvement and to ease participation. We also show that any planned abatement path as e.g. the one envisioned by the Paris Agreement in 2015 can be implemented by an appropriately chosen refunding scheme. Finally, we suggest ways for countries to raise money for the payment of initial fees that are neutral to tax payers and international capital markets.

JEL-Codes: Q540, H230, H410.

Keywords: climate change mitigation, refunding scheme, international agreements, sustainable treaty.

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1 Introduction

Motivation

International treaties on the provision of global public goods are plagued by the fundamental free-riding problem: each country's contribution will benefit all countries in a non-exclusive and non-rival manner. This prisoner's dilemma aspect and the absence of a supranational authority makes international coordination both crucial and exceptionally difficult to achieve. Countries may either lack the incentive to sign an agreement and benefit from the signatories' contributions or they may have incentives not to comply with promises made in an agreement.

In long-run problems extending over decades or even centuries, such as mitigating anthropogenic climate change, a second problem arises. Even if the free-riding problem has been solved, little is achieved if the international community fails to agree on a subsequent agreement when the first has expired. With respect to anthropogenic climate change, this is precisely the problem we face today. Although the first commitment period of the Kyoto Protocol has expired,[1] so far the international community has consistently failed to agree on a subsequent international agreement to reduce greenhouse gas emissions in Copenhagen (2009), Cancún (2010), Durban (2011), Doha (2012) and Warsaw (2013). Recently, a bottom-up approach relying on "nationally determined contributions" as detailed in Article 3 of the Paris Agreement (UNFCCC 2015) attempts to put in place a new international mechanism to significantly reduce greenhouse gas emissions.

Treaty and Main Insight

In this paper we propose and analyze climate treaties that involve a long-run refunding scheme (henceforth RS). The main idea of the RS is that all countries pay an initial fee into a global fund that is invested in long-run assets. Countries maintain full sovereignty over how much emissions they abate each year and what policy measures they use to do so. At the end of each year, part of the fund is paid out to countries in proportion to the relative GHG emission reductions they have achieved in that year, weighted by country-specific factors. We show in this paper that a suitably selected RS establishes a sustainable solution to the free-rider problem for arbitrary heterogeneities across countries. We do this in two steps. First, we characterize the RS that implements the globally optimal reductions of greenhouse gas emissions in each period and each country. The initial fees can be chosen to distribute the gains from cooperation and in particular to make each country better off compared to the decentralized solution. Second, we show that any abatement path the

[1] In which the industrialized countries of the world, so called Annex B countries, committed themselves to a reduction of greenhouse gas (GHG) emissions by 5.2% against 1990 levels over the period from 2008 to 2012.

world community agrees on can be implemented by a suitably chosen RS in the sense that countries will voluntarily comply with the pledges made in the agreement. By construction the RS will last forever as the fund will never be exhausted.

Model and Main Results
We study a multi-country model with country-specific emissions, abatement cost functions and damage functions. Our main formal results are as follows: First, the globally optimal solution minimizing the discounted values of global abatement costs and global damages prescribes uniquely determined emission abatement efforts for each period and each nation such that the cumulative global stock of GHGs converges to a steady state called long-run desired stock. If there is no treaty, countries will choose levels of abatement that fall considerably short of the globally optimal solution, while the stock of cumulative GHG emissions converges to a steady state well above the long-run desired stock.

Second, we show that initial fees and a feasible sequence of refunds can be devised in such a way that the RS implements socially optimal abatement levels in each period and each country as a unique subgame perfect equilibrium. By choosing suitable weighting factors and a sequence of refunds to countries, each country chooses the globally desired abatement levels. Marginal deviations would reduce abatement costs marginally but this gain is equal to the corresponding reduction of refunds and increase of damages.

Third, by setting appropriate initial fees, the first-best sustainable RS can not only achieve a Pareto improvement, but can implement any distribution of the cooperative gain, i.e. the difference of the net present value of total global costs between the decentralized solution and the social global optimum. This allows to separate efficiency and distributional concerns. The former is dealt with by the total amount of the initial fees and the refunding formula with the weighting factors. The latter is dealt with by the country-specific initial fees. Besides the analytical result we illustrate the working and impact of the refunding scheme in a numerical exercise that takes into account heterogeneities across countries.

Fourth, the international community may settle on other abatement paths than the global social optimum. We show that any given second-best abatement path can be implemented by a suitable refunding scheme with initial fees and country-specific weighting factors. For instance, "nationally determined contributions" as outlined in Article 3 of the Paris Agreement (UNFCCC 2015) could lead to a global abatement path and this path could be implemented by a suitably chosen RS. We call this treaty the second-best sustainable RS.

Fifth, as countries may want to renounce paying the initial fee and not sign the treaty, initial participation requires the well-known condition that countries be pivotal for the formation of the RS. That is, if any country defects, the treaty will fail.[2] Then initial participation will be part of a subgame perfect equilibrium. We suggest that differentiating initial fees across countries can ease participation.

Finally, we suggest different ways of financing the initial fees that are neutral to tax payers and international capital markets. Moreover, we outline how sustainable refunding schemes could be implemented in overlapping generation models.

Literature

The starting point for our scheme and its analysis is the large body of game-theoretic literature on the formation of international and self-enforcing environmental agreements[3] as there is no supranational authority to enforce contracts and to ensure participation and compliance during the duration of a treaty. This literature has provided important insights into the potentialities and limitations of international environmental agreements regarding the solution of the dynamic common-pool problem that characterizes climate change, as discussed and surveyed recently by Bosetti et al. (2009) and Hovi et al. (2013). Hovi et al. (2013) point out that there are three types of enforcement that are crucial for treaties to reduce global emissions substantially: countries must be given incentives for ratification with deep commitment, those countries that have committed deeply when ratifying should be given incentives to remain within the treaties, and they should be given incentives to comply with them.

The papers most closely related to our paper are Gersbach and Winkler (2007), Gerber and Wichardt (2009), Gersbach and Winkler (2012), and Gerber and Wichardt (2013) who also incorporate refunding schemes. Gerber and Wichardt (2009) and Gerber and Wichardt (2013) focus on the first commitment problem. In contrast, Gersbach and Winkler (2007) and Gersbach and Winkler (2012) are models that account for the specific particularities of the climate problem and focus on the second and third enforcement/commitment problem. In this paper we develop a model that differs from the two-period framework of Gersbach and Winkler (2012) in three important aspects: First, we focus on an infinite time horizon and are thus interested in whether a refunding scheme exists that is sustainable in the long-run under conditions of anthropogenic climate change. Second, we allow for countries being arbitrarily heterogeneous with respect to important characteristics of anthropogenic climate change.

[2]In practice, of course, only industrial countries will be called upon to set-up the climate fund. But even the participation of industrial countries remains a thorny issue, as we will discuss further in Section 6.

[3]Non-cooperative and cooperative approaches have been pursued. Many authors have stressed that the grand coalition is not stable if an individual defection does not destroy any coalition formation (e.g. Carraro and Siniscalco 1993, Eyckmans et al. 1993, Barrett 1994, Tol 1999, and Bosetti et al. 2009.) Typically, in such circumstances, stable coalitions only contain a limited number of countries (see, e.g., Hoel 1991, Carraro and Siniscalco 1992, and Finus and Altamirano-Cabrera 2006). d'Aspremont et al. (1983) has conducted an original analysis and has introduced the definitions for internally and externally stable coalitions. Pioneering in the modelling of coalition structures are Bloch (1997) and Yi (1997).

Third, we abandon the possibility that refunding to countries can be financed through national emission taxes, as such an instrument may be politically infeasible since countries might be reluctant to surrender tax sovereignty. In this paper the climate fund solely relies on initial fees by country. We are interested in what refunding can achieve under these circumstances and assess the order of magnitude of financial assets that are needed to finance such a refunding scheme. We also address the first commitment problem: In Section 6 we explore ways to ease the participation problem. Overall, we suggest that smaller or larger coalitions can achieve substantial emission reductions if they are able to set up an agency that can administer a refunding scheme on which coalition members have previously agreed. Finally, the sustainable treaties advanced in this paper are rule-based treaties, i.e. the treaties neither fix emission targets nor the carbon price. Instead, they fix a set of rules administered by an international agency that leaves countries full sovereignty over their domestic climate policy and its intensity. Yet, once countries have ratified the treaty and paid the initial fee, they have no incentive to exit, and they have incentives to choose the globally optimal level of abatement.

At least since Fershtman and Nitzan (1991) it is know that dynamic good problems pose more severe challenges than their static counterparts.[4] Our main contribution to this literature is as follows. We examine the most severe case when countries cannot commit to any future emission reductions,[5] as no international authority can enforce an agreement on such reductions. The dynamic public good problem is thus particularly severe. The treaties we advance in this paper essentially reduce the public good problem over an infinite horizon to a static problem in which counties are asked to contribute in the initial period to a global fund. Once the global fund has been set up, countries voluntarily choose socially optimal (first-best sustainable treaty) or any other socially desired emission levels (second-best sustainable treaty) in all subsequent periods.

Organization of the Paper

The paper is organized as follows: In the next section, we set up our model, for which in Section 3 we derive the social optimum and the decentralized solution as benchmark cases. The refunding scheme is introduced in Section 4, where the existence of the first- and second-best sustainable RS is also established. In Section 5 we illustrate our model numerically. In Sections 6 and 7 we discuss practical aspects of the RS, such as initial participation and

[4] Dynamic games on voluntary provision of public goods have been significantly developed (see Wirl 1996, Dockner and Sorger 1996, Sorger 1998, Marx and Matthews 2000). Recent contributions involve Dutta and Radner (2009) who examine agreements on mitigating climate change supported by inefficient Markov perfect equilibria. Harstad (2012) introduces incomplete contracts in dynamic games by allowing countries to contract on emission reductions but not on investment.

[5] If complete contracts on emission reductions could be written between countries, a first-best solution would be easily achieved.

how to raise initial fees. In Section 8, we discuss how sustainable refunding schemes can be implemented in an overlapping generation set-up. Section 9 concludes.

2 The Model

We consider a world with $n \geq 2$ countries characterized by country specific emission functions E_i, abatement cost functions C_i, and damage functions D_i over a finite time horizon T. As we consider T to be arbitrarily large, we shall also investigate the limit $T \to \infty$. Throughout the paper countries are indexed by i and j, and time is indexed by t.

Emissions of country i in period t are assumed to equal "business-as-usual" emissions ϵ_i (i.e., emissions arising if no abatement effort is undertaken) minus emission abatement a_t^i:[6]

$$E_i(a_t^i) = \epsilon_i - a_t^i \ , \quad i = 1, \ldots, n \ , \quad t = 0, \ldots, T \ . \tag{1}$$

We assume that emission abatement a_t^i is achieved by enacting some national environmental policy, which induces convex abatement costs in country i:[7]

$$C_i(a_t^i) = \frac{\alpha_i}{2} \left(a_t^i\right)^2 \ , \quad \text{with} \quad \alpha_i > 0 \ , \quad i = 1, \ldots, n \ , \quad t = 0, \ldots, T \ . \tag{2}$$

Cumulative global emissions, which are the sum of the emissions of all countries up to period t, are denoted by s_t:

$$s_{t+1} = s_t + \sum_{i=1}^{n} E_i(a_t^i) \ , \quad t = 0, \ldots, T \ , \tag{3}$$

where the initial stock of cumulative greenhouse gas emissions is denoted by s_0.

Recent scientific evidence suggests that global average surface temperature increase is—at least for economically reasonable time scales (i.e. several centuries)—approximately a linear function of cumulative global carbon emissions (see Allen et al. 2009, Matthews et al. 2009, Zickfeld et al. 2009, IPCC 2013). As a consequence, we consider strictly increasing and strictly convex damage for each country i to depend on cumulative global emissions s_t rather than on atmospheric greenhouse gas concentrations:

$$D_i(s_t) = \frac{\beta_i}{2} s_t^2 \ , \quad \text{with} \quad \beta_i > 0 \ , \quad i = 1, \ldots, n \ , \quad t = 0, \ldots, T \ . \tag{4}$$

[6] We do not restrict abatement to be at most as high as business-as-usual emissions, i.e. $a_t^i \leq \epsilon_i$. Thus, we allow for negative net emissions, for example via afforestation or carbon capture and sequestration technologies.

[7] This is a standard short-cut way of capturing aggregate abatement costs in country i (see, e.g., Falk and Mendelsohn 1993).

Countries are assumed to discount outcomes in period t with the discount factor δ^t with $0 < \delta < 1$. Finally, we introduce the following abbreviations for later reference:

$$\mathcal{E} = \sum_{i=1}^{n} \epsilon_i \ , \quad \mathcal{A} = \sum_{i=1}^{n} \frac{1}{\alpha_i} \ , \quad \mathcal{B} = \sum_{i=1}^{n} \beta_i \ , \quad \gamma_i = \frac{\beta_i}{\alpha_i} \ , \quad \Gamma = \sum_{i=1}^{n} \gamma_i \ . \tag{5}$$

3 Social Optimum and Decentralized Equilibrium

Before we introduce the refunding scheme (RS) in the next section, we characterize the global social optimum and the decentralized solution when no international agreement has been reached. As is well-known, the latter is inefficient because the emissions of each individual country impose negative externalities on all other countries that an individual country does not take into account when choosing the extend of its emission abatement.

Both the global social optimum and the decentralized outcome are important benchmarks in evaluating the performance of potential international agreements. While the decentralized outcome is realized if no agreement takes place, the social optimum is the ultimate goal an international agreement seeks to implement. Obviously, any agreement has to outperform the decentralized outcome in order to be seriously considered, and it is the "better," the closer its outcome is to the global social optimum.

3.1 Global social optimum

Consider a global social planner seeking to maximize *global* welfare, i.e., seeking to minimize the net present value of *total global costs* consisting of global costs of emission abatement and the sum of national environmental damages stemming from the pollution stock:

$$\min_{\{a_t^i\}_{t=0,\dots,T}^{i=1,\dots,n}} \sum_{t=0}^{T} \delta^t \sum_{i=1}^{n} \left[\frac{\alpha_i}{2} \left(a_t^i \right)^2 + \frac{\beta_i}{2} s_t^2 \right] \ , \tag{6}$$

by choosing optimal abatement paths $\{a_t^i\}_{t=1,\dots,T}$ for all countries i. There exists a unique global optimum in which the costs of abating an additional marginal unit of emissions have to equal the net present value of all mitigated future damages caused by this additional marginal unit:

Proposition 1 (Global Social Optimum)
For any time horizon $T \leq \infty$ there exists a unique social global optimum characterized by sequences of emission abatements for all countries i in all periods t, $a_t^{i\star}$, and a sequence for the stock of cumulative greenhouse gas emissions $s_t^\star$ $(i = 1, \dots, n; \ t = 0, \dots, T)$.

The proofs of all propositions and corollaries are given in the Appendix. As we are particularly interested in the long run, we state the following corollary:

Corollary 1 (Global Social Optimum in the Long Run)
For $T \to \infty$ the sequences of emission abatement and the stock of cumulative greenhouse gas emissions in the global social optimum converge to their steady state levels

$$a_i^{SO} = \frac{\mathcal{E}}{\alpha_i \mathcal{A}} \ , \quad i = 1, \ldots, n \ , \tag{7a}$$

$$s^{SO} = \frac{1-\delta}{\delta} \frac{\mathcal{E}}{\mathcal{A}\mathcal{B}} \ . \tag{7b}$$

Cumulative greenhouse gas emissions can only reach a steady state, when global net emissions go down to zero. In fact, $\sum_{i=1}^{n} a_i^{SO} = \mathcal{E}$, implying that in the steady state global business-a-usual emissions are abated. The cumulative stock of greenhouse gas emissions depends on how much emissions have been released until the full abatement steady state. Apart from the technological parameters $\mathcal{E}$, $\mathcal{A}$ and $\mathcal{B}$ this depends on the discount factor δ: The steady state stock of cumulative emissions s^{SO} is lower, the higher is the discount factor δ, as a higher δ increases the net present value of the future environmental damages caused by the stock of cumulative emissions.

3.2 Decentralized solution

Next we examine a decentralized system in the absence of an international treaty, where a local planner in each country (e.g., a government) seeks to minimize the *total local costs* consisting of local abatement costs and local environmental damages. We assume that local planners in all countries have perfect information about the business-as-usual emissions, abatement costs and environmental damage costs of all countries. In addition, we assume that in each period t local planners in all countries observe the stock of cumulative emissions s_t before they simultaneously decide on the abatement levels a_t^i. Thus, the decentralized solution is the subgame perfect Nash equilibrium outcome of the game, in which all local planners i in period t choose abatement levels a_t^i such as to minimize total local costs.

We solve the game by backward induction, starting from period T. It is useful to consider a typical step in this procedure. To this end, suppose that there exists a unique subgame perfect equilibrium for the subgame starting in period $t+1$ with a stock of cumulative greenhouse gas emissions s_{t+1}. For the moment, this is assumed to hold in all periods $t+1$ and will be verified in the proof of Proposition 2. Other details of the history of the game apart from the level of cumulative greenhouse gas emissions s_{t+1} do not matter, as only

s_{t+1} influences the payoffs of the subgame starting in period $t+1$ and the equilibrium is assumed to be unique.

Given the unique subgame perfect equilibrium for the subgame starting in period $t+1$ with the associated equilibrium payoff $W^i_{t+1}(s_{t+1})$, country i's best response in period t, $\bar{a}^i_t$, is determined by the solution of the optimization problem

$$V^i_t(s_t)|A^{-i}_t = \max_{a^i_t} \left\{ \delta W^i_{t+1}(s_{t+1}) - \frac{\alpha_i}{2}\left(a^i_t\right)^2 - \frac{\beta_i}{2} s^2_t \right\} \ , \tag{8}$$

subject to equation (3), $W^i_{T+1}(s_{T+1}) \equiv 0$, and given the sum of abatement efforts by all other countries $A^{-i}_t = \sum_{j\neq i} a^j_t$. The following proposition establishes the existence and uniqueness of a subgame perfect Nash equilibrium:

Proposition 2 (Decentralized Solution)
For any time horizon $T < \infty$, there exists a unique subgame perfect Nash equilibrium characterized by sequences of emission abatements for all countries i in all periods t, $\hat{a}^i_t$, and a sequence for the stock of cumulative greenhouse gas emissions $\hat{s}_t$ $(i = 1, \ldots, n;\ t = 0, \ldots, T)$.

In general, the decentralized solution falls short of the social global optimum in terms of total global costs, as local planners only take into account the reduction of environmental damages that an additional unit of abatement prevents in their own country and neglect the damage reductions in all other countries. As a consequence, aggregate abatement levels in the decentralized solution are lower compared to the global social optimum and, thus, cumulative greenhouse gas emissions are higher.[8]

Again, we are interested in the long run and take the limit for $T \to \infty$. The reason is that this equilibrium approximates the equilibrium for very large, but still finite time horizons T.[9]

[8] However, the global social optimum does not necessarily constitute a Pareto improvement over the decentralized solution. In particular, countries with low abatement and low environmental damage costs may be worse off under the global social optimum, as they suffer relatively little from the higher cumulative emissions in the decentralized solution but may experience considerably higher abatement costs under the global social optimum. Yet, if we allow for transfers, and assume that countries are not budget constrained with respect to these transfers, there always exists a transfer scheme such that the global social optimum is a Pareto optimal allocation.

[9] In infinite horizon models, further equilibria and even a continuum of equilibria can occur (Tsutsui and Mino 1990, Rowat 2007). However, it can be shown that the equilibrium we achieve by taking the limit $T \to \infty$ is the unique Markov perfect equilibrium in affine strategies (Lockwood 1996).

Corollary 2 (Decentralized Solution in the Long Run)
In the limit $T \to \infty$, the sequences of emission abatement and the greenhouse gas stock in the unique subgame perfect Nash equilibrium of the decentralized solution for finite time horizons T converge to the steady state levels

$$a_i^{DS} = \frac{\gamma_i \mathcal{E}}{\Gamma} \ , \quad i = 1, \ldots, n \ , \tag{9a}$$

$$s^{DS} = \frac{1-\delta}{\delta} \frac{\mathcal{E}}{\Gamma} \ . \tag{9b}$$

Also in the decentralized solution net emissions converge to zero, as $\sum_{i=1}^{n} a_i^{DS} = \mathcal{E}$. This is to be expected, as a steady state of cumulative greenhouse gases can only be reached if no additional emissions are released. Thus, the important question is to what extent differs the long run cumulative stock of emissions s^{DS} from its counterpart s^{SO} in the global social optimum. In general, this depends on the distribution of abatement cost parameters α_i and environmental damage cost parameters β_i across countries. If, however, all countries shared either identical abatement costs parameters ($\alpha_i = \alpha_j = \alpha$, $\forall\, i, j = 1, \ldots, n$) or the same damage cost parameters ($\beta_i = \beta_j = \beta$, $\forall\, i, j = 1, \ldots, n$), then $\Gamma = \mathcal{A}\mathcal{B}/n$. As a consequence, the long run stock of cumulative greenhouse gas emissions in the decentralized solution would be n times as high as the corresponding stock in the global social optimum. This reflects the well-known underprovision of emission abatement in the decentralized case due to the incentives for each country to free-ride on the emission abatements of all other countries. As these incentives increase with the number of countries n, the underprovision of abatement becomes more severe, the higher n is.

4 Refunding Scheme

In the following, we introduce a refunding scheme (RS) and analyze its potential for improving on the decentralized solution. The essential idea is that a global fund is established that refunds interest earnings to member countries in each period, proportionally to their relative emission reductions weighted by country specific refunding weights.

4.1 Rules of the RS

We consider a three-step procedure. First, participating countries negotiate the parameters of the RS. In particular, this includes the duration T of the treaty, the level of an initial fee f_0^i payable into a global fund by each participating country, a weighting scheme $\{\lambda_t^i\}_{i=1}^n$, and reimbursements R_t for all $t = 0, \ldots, T-1$. Second, in each period $t = 0, \ldots, T-1$

the fraction R_t of the fund is reimbursed to the participating countries in proportion to the emission reductions they have achieved relative to overall emission abatements in this period times the weighting scheme $\{\lambda_t^i\}_{i=1}^n$. The weighting scheme satisfies

$$\sum_{i\in S} \lambda_t^i = 1 \ , \quad t = 0, \dots, T-1 \ , \tag{10}$$

where S denotes the set of countries participating in the RS. The weighting scheme accounts for the fact that countries are heterogeneous with respect to business-as-usual emissions, abatement costs and environmental damage costs. The remaining assets of the fund are invested at the constant interest rate ρ per period, and the returns add to the global fund in the next period $t+1$. We assume that the interest rate ρ corresponds to the discount factor δ, i.e. $\rho = 1/\delta - 1$. Finally, in period T the fund is equally redistributed to the participating countries.

Thus, the fund at the beginning of period $t+1$ reads

$$f_{t+1} = (1+\rho)(f_t - R_t) \ , \quad t = 0, \dots, T-1 \ , \tag{11}$$

with an initial fund $f_0 = \sum_{i\in S} f_0^i$. Note that $f_{T+1} = 0$, or equivalently $R_T = f_T$. In addition, the refund r_t^i a member country i receives in period t yields

$$r_t^i = \begin{cases} \lambda_t^i R_t \frac{a_t^i}{\sum_{j\in S} a_t^j} \ , & t = 0, \dots, T-1 \ , \\ \frac{R_t}{|S|} \ , & t = T \ . \end{cases} \tag{12}$$

A set of initial fees $f_0^i \geq 0$ and refunds $R_t \geq 0$ is *feasible* if $f_t \geq 0$ for all $t = 0 \dots, T$ holds.

In order to analyze the potential of an RS to mitigate climate change, we proceed as follows: First, assuming that all countries participate in the RS in step one, we show that there exist a feasible set of initial fees f_0^i, a weighting scheme $\{\lambda_t^i\}_{i=1}^n$ and refunds R_t such that the RS implements the social global optimum as the unique subgame perfect Nash equilibrium. This is called a first-best sustainable RS. Second, we show that the RS may implement any feasible abatement path that all countries have agreed upon. These treaties are called second-best sustainable RSs.

4.2 First-best sustainable RS

We now show that—assuming all countries participate in the RS in the first place—for any given time horizon T there exists a feasible set of initial fees f_0^i, a weighting scheme $\{\lambda_t^i\}_{i=1}^n$ and refunds R_t such that the social global optimum is implemented as the unique subgame perfect Nash equilibrium of the RS. We call a treaty that exhibits this property *first-best sustainable refunding scheme*:

Proposition 3 (Existence of First-best Sustainable RS)
Given that all countries join the RS and given any time horizon $T < \infty$, there exists a set of initial fees f_0^i, a sequence of feasible refunds $R_t^\star$, and a weighting scheme $\{\lambda_t^{i\star}\}_{i=1}^n$ such that the outcome of the unique subgame perfect Nash equilibrium of the RS coincides with the social global optimum ($i = 1, \ldots, n;\ t = 0, \ldots, T$).

As shown in the proof of Proposition 3 in the Appendix, the first-best sustainable RS is characterized by a uniquely determined sequence of refunds $R_t^\star$ and a weighting scheme $\{\lambda_t^{i\star}\}_{i=1}^n$, $t = 0, \ldots, T-1$. Yet, the set of initial fees is not unambiguously determined. In fact, all sets of initial fees, the sum of which exceeds the minimal initial global fund $f_0^\star$ with

$$f_0^\star = \sum_{t=1}^{T-1} \left[\frac{R_t^\star}{(1+\rho)^t} \right] \ , \tag{13}$$

render a feasible first-best sustainable RS. The intuition is that the global fund needs the minimum size $f_0^\star$ in order to be able to pay sufficiently high refunds $R_t^\star$ such that countries stick to the socially optimal abatement levels in all periods. Any excess funds are redistributed in equal shares in the last period, in which the optimal abatement level is zero independently of the refund.

Even if we restrict attention to the first-best sustainable RS with minimal initial global fund $f_0^\star$, we are free in how to distribute the burden of raising the initial fund across countries. As a consequence, we can always find a feasible set of initial fees that renders the first-best sustainable RS a Pareto improvement over the decentralized solution.

Proposition 4 (First-best Sustainable RS is Pareto Improvement)
Consider a first-best sustainable RS characterized by the minimal sum of initial payments $f_0^\star$, a weighting scheme $\{\lambda_t^{i\star}\}_{i=1}^n$, and a sequence of refunds $R_t^\star$. Then there exists a feasible set of initial fees f_0^i satisfying $\sum_{i \in S} f_0^i = f_0^\star$ such that the outcome of the first-best sustainable RS constitutes a Pareto improvement over the decentralized solution.

The intuition for this result is that compared to the decentralized solution all countries are better off under the first-best sustainable RS if their initial fee was zero. As a consequence, there is a positive initial fee $\hat{f}_0^i$ that would leave country i equally well off under the RS compared to the decentralized solution. In the proof of Proposition 4 in the Appendix, we show that the sum $\hat{f}_0 = \sum_{i \in S} \hat{f}_0^i$ exceeds $f_0^\star$. As a consequence, we can set the initial fee below $\hat{f}_0^i$ making all countries better off.

In fact, by setting appropriate initial fees f_0^i the first-best sustainable RS cannot only achieve a Pareto improvement, but can in fact implement any distribution of the cooperation gain, i.e. the difference of the net present value of the total global costs between the decentralized solution and the social global optimum, as long as $f_0^i \geq 0$. If we allowed initial fees to be negative for at least some countries we could even implement any possible distribution of the cooperation gain. This property of the first-best RS to disentangle efficiency and distributional concerns is helpful in achieving initial participation, as we shall discuss in Section 6.

4.3 Second-best sustainable RS

In Proposition 3 we showed that the RS can implement the global social optimum as a unique subgame perfect Nash equilibrium given all countries join the RS in the first place. Yet, the RS is much more powerful, as we show in the following.

To this end, we introduce a *second-best abatement path* $\tilde{a}_t^i$ $(i = 1, \ldots, n;\ t = 0, \ldots, T)$, which has the property that it lies in between the abatement paths of the decentralized solution and the social global optimum for all countries $i = 1, \ldots, n$ and all time periods $t = 0, \ldots, T$:

$$\hat{a}_t^i < \tilde{a}_t^i \leq a_t^{i\star} \ , \qquad i = 1, \ldots, n; \quad t = 0, \ldots, T \ . \tag{14}$$

Note that, by construction, all second-best abatement paths obeying conditions (14) are feasible and optimal in the last period T, as $\tilde{a}_T^i = 0$ for all $i = 1, \ldots, n$. Then, the following Proposition holds:

Proposition 5 (Existence of Second-best Sustainable RS)
Given that all countries join the RS and given any time horizon $T < \infty$, there exists a minimum initial global fund f_0, a sequence of feasible refunds R_t and weighting schemes $\{\lambda_t^i\}_{i=1}^n$ such that the outcome of the unique subgame perfect Nash equilibrium of the RS coincides with any given second-best abatement path $\tilde{a}_t^i$ $(i = 1, \ldots, n;\ t = 0, \ldots, T)$.

The intuition is that while the refunds R_t and the weighting scheme $\{\lambda_t^i\}_{i=1}^n$ are uniquely determined by the abatement path that is to be implemented, there is nothing particular about the socially optimal abatement path. Any path that ensures positive refunds and weighting schemes is, thus, implementable by the RS.

This feature of the RS may be important, as, in general, international climate policy is not shaped along standard economic cost-benefit analyses such as the derivation of the global social optimum in Section 3.1. In fact, the single most promising policy goal that is about to achieve global consensus is to limit greenhouse gas emissions to such an extent that the global mean surface temperature increase is not exceeding 2°C against preindustrial levels (see, for example, EU 2005, UNFCCC 2009 and UNFCCC 2015). As the global mean surface temperature increase is predominantly determined by cumulative greenhouse gas emission, such a temperature goal can be translated into a stock of permissible cumulated greenhouse gas emissions, a so called *global carbon budget*. Starting from the current stock of cumulative greenhouse gas emissions, estimates for this remaining carbon budget roughly range between 500 and 1000 trillion tonnes of carbon (GtC) (Allen et al. 2009, Meinshausen et al. 2009, Zickfeld et al. 2009).[10] Thus, Proposition 5 says that once the world community has agreed on an abatement path, the RS is able to implement it as a unique subgame perfect Nash equilibrium no matter how ambitious this abatement path is compared to the social global optimum. In particular, the RS is compatible with the idea of "nationally determined contributions", as detailed in Article 3 of the Paris Agreement (UNFCCC 2015).

5 Numerical Illustration

To give an idea of the order of magnitude needed for the initial fund f_0 to implement the first-best sustainable RS, we run a numerical exercise. Due to the highly stylized model, the results are rather a numerical illustration than a quantitative analysis.

We follow the RICE-2010 model (Nordhaus 2010) in dividing the world into twelve regions, each of which we assume to act as a "country", as detailed in Section 2.[11] We also take the "business-as-usual" emissions for all twelve regions from Nordhaus (2010). The RICE-2010 model assumes a backstop technology the price of which decreases over time and fully crowds out fossil fuel based energy technologies by 2265. As a consequence, global CO_2 emissions drop to zero in 2265 in the baseline scenario in which cumulative global CO_2 emissions of 5629.6 GtC have been released into the atmosphere (we assume that cumulative global CO_2 emissions prior to 2015 amount to 500 GtC).

We calibrate our model in such a way that the global social optimum in our model resembles the optimal solution of the RICE-2010 model as closely as possible. Therefore, we calibrate the relative damage parameters for each region by fitting quadratic functions to the damage functions used in the RICE-2010 model. Then we re-scale all damage parameters such that damages in the uncontrolled (baseline) case in the year 2095 amount to 12 trillion USD or 2.8% of global output as in Nordhaus (2010: 11723). To calibrate abatement cost parameters,

[10]The main obstacles for translating an upper temperature bound for mean global surface temperature into a carbon budget are scientific uncertainties concerning the equilibrium climate sensitivity and the climate-carbon cycle feedback (see, e.g., Friedlingstein et al. 2011 and Zickfeld et al. 2009).

[11]The twelve regions are: United States of America (US), European Union (EU), Japan, Russia, Eurasia, China, India, Middle East (MidEast), Africa, Latin America (LatAm), other high income countries (OHI) and Rest of the World (Others).

Region	α_i [tril. USD/GtC^2]	β_i [tril. USD/GtC^2]	TC_i^{soc} [tril. USD]	TC_i^{dec} [tril. USD]
US	0.161499	$6.25746 \cdot 10^{-6}$	2.66	2.77
EU	0.332095	$7.04069 \cdot 10^{-6}$	2.87	3.12
Japan	1.25744	$7.15619 \cdot 10^{-6}$	2.77	3.16
Russia	0.587259	$5.09146 \cdot 10^{-6}$	1.98	2.25
Eurasia	0.848427	$5.77336 \cdot 10^{-6}$	2.27	2.55
China	0.0815835	$6.00258 \cdot 10^{-6}$	2.73	2.67
India	0.250927	$9.88645 \cdot 10^{-6}$	4.06	4.38
MidEast	0.219416	$8.54831 \cdot 10^{-6}$	3.56	3.79
Africa	0.557812	$1.06524 \cdot 10^{-5}$	4.26	4.71
LatAm	0.407672	$6.28888 \cdot 10^{-6}$	2.58	2.78
OHI	0.578531	$6.92033 \cdot 10^{-6}$	2.74	3.06
Other	0.250107	$8.64079 \cdot 10^{-6}$	3.66	3.84

Table 1: Calibrated abatement and damage cost parameters and the resulting net present value of total local abatement and damage costs in the social global optimum and the decentralized equilibrium for all twelve regions.

we average the abatement cost parameter for each region over the period from 2015–2095. We then re-scale abatement cost parameters for all regions such that the long-run global aggregate emissions in the social optimum resemble long-run global aggregate emissions in the optimal solution of the RICE-2010 model. Table 1 shows the calibrated abatement and damage cost parameters for all twelve world regions. Finally, we set the discount rate ρ to 5% per year, which corresponds to a discount factor of $\delta = 0.6139$ for each ten year period.[12]

Of course, it is not possible to calibrate our simple theoretical model to a sophisticated integrated assessment model as RICE 2010 such that the social optimal solutions match perfectly. In the Appendix, we show time paths of emissions and cumulative emissions for the baseline scenario, the decentralized equilibrium and the global social optimum in our calibrated model and in the RICE-2010 model for all world regions. In the global social optimum of both the RICE-2010 model and our calibrated model, the long-run cumulative global emissions after 2015 amount to 920.8 GtC (equaling 1420.8 GtC given cumulative global emissions of 500 GtC before 2015), which lies close to the upper bound of the carbon budget that is compatible with a 2°C target. In the decentralized equilibrium, long-run cumulative global emissions after 2015 would amount to 2751.1 GtC, which is well beyond even the most optimistic carbon budget that can avoid at least the most severe consequences of anthropogenic climate change.

The upper part of Figure 1 shows global emissions and cumulative global emissions for the business-as-usual scenario, the decentralized equilibrium and global social optimum in the

[12] In line with the RICE-2010 model we use ten year periods. However, we usually express all values in per annum terms.

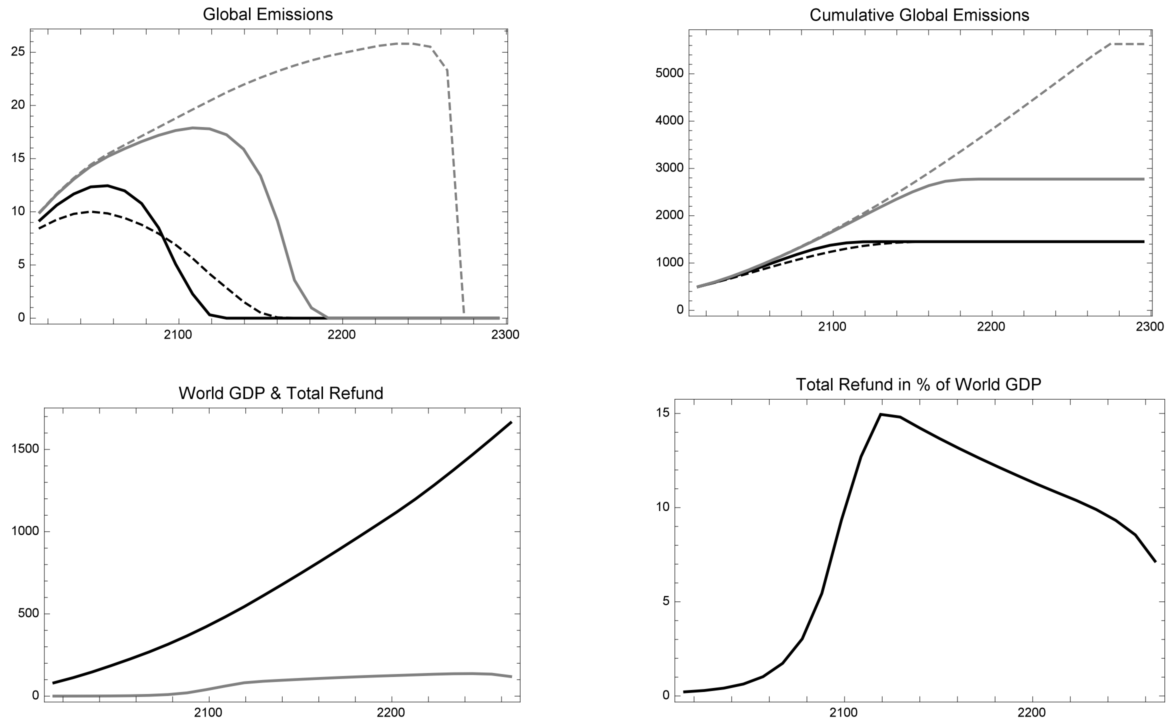

Figure 1: Global emissions (upper left) and cumulative global emissions (upper right) for business-as-usual scenario (dashed gray), decentralized equilibrium (solid gray) and the global social optimum in the RICE-2010 (dashed black) and our calibrated model (solid black). Development of the world GDP (black) and the absolute refund per period in the first-best RS (gray) are shown in the lower left corner. The lower right corner shows the refund per period in the first-best RS relative to world GDP.

RICE-2010 and our calibrated model. We find that in the global social optimum of our calibrated model, peak emissions are higher than in the social optimum of the RICE-2010 model but emissions go to zero more quickly. Despite these differences, cumulative global emissions of the social optimum match reasonably. The lower part of Figure 1 shows the development of the world GDP (which we took from the RICE-2010 model). In addition, we calculate the global refund per year that is necessary to induce all countries to abate emissions in line with the global social optimum (first-best sustainable RS).

We observe that refunds in the first-best sustainable RS are rather low in the beginning. In fact, in 2015 the first-best sustainable RS has to issue refunds in the amount of 0.18 tril. USD per year or 0.22% of world GDP. However, refunds rise considerably over time. In relative terms, they peak in 2115 just short of 15% of world GDP or 81.3 tril. USD per year. From 2125 onwards, relative refunds decline, since even in the decentralized solution emissions start to drop after 2125. Refunds in the first-best sustainable RS vary substantially across regions. For example, refunds for the US stay well below 7% of US GDP, while for Russia, refunds peak around 45% of Russia' GDP in 2115. Refunding shares for all periods and all twelve regions are given in Table 2 in the Appendix.

The net present value of the fund needed to finance the first-best sustainable RS is substantial and amounts to 4.7% of 2015 world GDP. In addition, the global social optimum that is achieved by the first-best sustainable RS is not a Pareto improvement. In fact, in our calibrated model, China is slightly worse off under the social global optimum compared to the decentralized equilibrium (see Table 1). As a consequence, we discuss how to raise the initial fund and address distribution issues in the following sections.

6 Initial Participation

So far, we have focused on the capacity of an RS to induce countries to implement first-best or second-best sustainable refunding schemes. To achieve this, all countries have to agree on the appropriate parameters (initial fees and refunding parameters). We observe that a sustainable RS, as developed in this paper, transforms the intertemporal climate-policy problem into a standard, static public-goods problem. Once all countries have made their initial contribution, and have agreed on the refunding parameters, countries follow the envisioned path of abatement voluntarily and would be worse off by forfeiting refunds. In the following, we discuss how solution procedures developed in the literature on the private supply of public goods can be applied to motivate countries to make initial payments.

6.1 The standard ideal solution

At the initial level, when countries are pondering whether to sign the treaty and to pay the initial fee, the free-rider problem remains present. Especially if the number of countries n is large, each country may be better off by not signing the treaty. If all other countries participate, the country would benefit from all other countries' abatement efforts, without having to pay the initial fee and to compete for refunds.

To solve this free-rider problem by a standard procedure, the RS could be incorporated in a two-stage game (Gerber and Wichardt 2009). In the first stage, countries decide whether to participate in a sustainable and Pareto improving RS by paying the initial fee. The treaty only becomes effective if all countries sign and pay the initial fee. Otherwise, the treaty is cancelled and initial fees already paid are returned. If all countries have signed, we can proceed to the second stage, in which the treaty is executed as outlined in Section 4.

It is straightforward to see that it is a weakly dominant strategy for all countries to sign the treaty and pay the initial fee. All countries are better off if the treaty becomes effective than they are with the decentralized solution that results if the treaty is cancelled.

6.2 Difficulties in achieving initial participation

In practice, the preceding conceptual solution has to be supplemented by additional considerations. This holds, in particular, when countries are not identical, as this paper assumes.

Making larger countries pivotal

The ideal solution lies in making countries – and in particular large countries – pivotal for the formation of the RS. In order to achieve such a scenario, about ten to twenty of the largest greenhouse gas emitters must coordinate on the agreement that the RS will fail if any of them defects.[13]

Sequential procedures

As full participation by all countries at once is unlikely, it is useful to resort to sequential procedures where a subset of countries makes a start and the others follow later (see Andreoni 1998, Varian 1994). For the RS we might envision four steps. First, as suggested in the last paragraph, a set of large and mainly wealthy countries could initiate the system by paying initial fees. Second, smaller rich countries could follow, which would increase the initial wealth. In the third and fourth steps, larger and smaller developing countries could be invited to join the RS. Regarding the payment of initial fees, they should be treated differently, as we will discuss next.

Differentiated initial fees

As already discussed in Section 4, successful implementation of the RS only depends on successfully raising the minimum initial global fund f_0 but not on the individual countries' contributions to it. Thus the RS is able to disentangle efficiency from distributional concerns. Yet, in reality the distribution of initial fees to raise the initial global fund is of great importance. For example, many developing countries may lack the necessary wealth to pay the initial fees or countries in transition may refute to pay high initial fees arguing that the current atmospheric greenhouse gas concentrations are predominantly the historic responsibility of industrialized countries. To induce participation, payment of initial fees could be differentiated according to different distributional criteria such as wealth, current greenhouse emissions or historic responsibility with respect to atmospheric greenhouse gas

[13] In practice countries must be mutually stubborn and insist on full participation by this core group before going ahead.

concentrations. Thus, the RS is compatible with the concept of "common but differentiated responsibilities and respective capabilities", as detailed in Article 4 of the Paris Agreement (UNFCCC 2015).

Once the RS has been initiated, incentives to abate are independent of initial contributions. In such circumstances, countries with low initial fees would voluntarily join the system, as they can always choose the same emission reduction policy under the RS as without, but they can benefit from the refunds if it is in their interest. Indeed, the prospect of earning refunds will motivate them to abate more. Hence, allocating the burden to pay the initial fees is a powerful tool in implementing transfers across countries.

7 Raising Initial Fees

Also differentiated initial fees cannot circumvent the problem that the sustainable refunding scheme relies on successfully raising the minimum initial global fund. As this fund may be quite large, we outline two ways in which it might be financed.

7.1 Repeated payments

Raising the minimum initial fund in full at the beginning of the treaty is not necessary. We can also achieve the first- and second-best sustainable RS by repeatedly paying a smaller amount of money. To see this, let $\{R_t\}_{t=1}^{T}$ be the sequence of refunds of a (first- or second-best) RS. In addition, we define the sequence of fees $f_t(\Delta)$ for a time span time span $\Delta > 0$ by

$$f_t(\Delta) = \sum_{\tau=1}^{\Delta} \frac{R_{t+\tau}}{(1+\rho)^{\tau}} \ . \tag{15}$$

If $f_t(\Delta)$ is paid into the fund at times $t = 0, \Delta, 2\Delta, \ldots$, the net present value of the fund is equal to the minimum initial global fund $f_0 = \sum_{t=1}^{T-1} \left[\frac{R_t}{(1+\rho)^t}\right]$ and, thus, the RS is implementable.

With the repeated payments scheme we face a trade-off between high initial fees and the property of the sustainable RS to transform an intertemporal climate-policy problem into a static public-goods problem. In particular, if the time span Δ is short, the solution of the climate-change problem relies on the repeated commitment of all countries, as the initial participation problem would have to be solved whenever new payments have to be made. Therefore Δ should not be too small.[14]

[14] Sustained participation can also be fostered by not completely depleting the fund and hence making exit

7.2 Borrowing and capital markets

If the repeated solution to the initial participation problem turns out to be a major obstacle to international cooperation, raising the initial fees by allowing countries to borrow money may be more advisable. Countries could then borrow either from the international capital market or directly from the administering agency of the RS.

Suppose that capital markets are perfect and all countries borrow the entire amount of their initial fees f_0^i required for the sustainable RS. Let μ $(0 \leq \mu \leq 1)$ denote the fraction of f_0^i borrowed from the international capital market, implying that the remainder $(1 - \mu)f_0^i$ is borrowed from the administering agency running the RS. Then, for all values of μ, borrowing by countries does not affect international capital markets.

To see this, recall that perfect capital markets imply that countries may borrow or lend freely at the per-period interest rate ρ. Further, borrowing by countries increases demand for capital on the international capital market by a total of μf_0. As the administering agency lends a total of $(1 - \mu)f_0$ to the countries, it can invest μf_0 in the capital market and thus supply increases by the same amount. Hence, the equilibrium in the capital market is not affected.[15]

Thus, raising the money needed for the initial payments is no problem under the assumption of perfect capital markets. In practice, at least two types of deviations from perfect capital markets have to be taken into account. A country may default against the administering agency or default in general. First, if μ is small, countries might be tempted to renounce high abatement efforts and to default on their interest-rate obligations to the administering agency. The country would lose all claims to refunds. However, as such refunds are small when abatement efforts are small, such a strategy may be profitable. For say $\mu = 0$, a country could choose to default against the administering agency and could free-ride on the abatement efforts of other countries even if it has signed the treaty and has borrowed from the administering agency. Such considerations suggest that countries should borrow mainly on the international capital market.

Second, if countries borrow a large amount on international capital markets, the default risk may rise if outstanding government debt is already at a high level. If the country needs to pay a larger interest rate than the risk-free rate, as investors demand a positive risk premium, further borrowing may increase the default risk as refunds are insufficient to cover interest-rate payments. In such cases, it is useful for part of the initial fund to be raised by taxes over several periods.

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costly (Gerber and Wichardt 2013).

[15] As the administering agency needs to invest its wealth in the capital market, borrowing by countries to pay the initial fee does not *a priori* crowd out private investments.

7.3 Reaction to Unforeseen Shocks

The design of both the first-best and the second-best optimal RS rests on the bold assumption that all exogenous parameters are constant and, in particular, known ex ante. It is perceivable or even likely that initial expectations about the discount/interest rate δ, the abatement cost parameters α_i, the damage cost parameters β_i, and the business-as-usual emissions ϵ_i turn out to be incorrect and at some time t new information on one or several of these parameter arrives.

It is obvious that a change in the exogenously given parameters would change the socially optimal paths and the long-run steady state values of abatement and the greenhouse gas stock. Accordingly, also the necessary refunds for the first-best optimal RS would change.[16]

To accommodate unforeseen changes in the exogenous parameters the RS could include a clause that the values of these parameters are re-evaluated on a regular basis (e.g., every ten years) and that the fund's wealth is corrected accordingly either by raising additional money from or paying back wealth to member countries.

8 Sustainable Climate Treaties in Overlapping Generation Frameworks

So far, we have focused on the properties of a sustainable refunding scheme and on how the implementation of such a scheme can be eased through repeated payments or through the use of capital markets. Still, we have assumed so far that the interest of countries can be represented by a long-lived social planner.

The implementation of sustainable refunding schemes is more difficult in overlapping generation models in which each generation is predominantly concerned about its own welfare. Then, setting up a refunding scheme hurts the old (existing) generations and benefits future generations – and possibly young existing generations – via two channels. First, the benefits from higher abatement today mainly accrue to future generations. This was the focus of important papers by Bovenberg and Heijdra (1998, 2002).[17] Public debt policies can help redistribute the welfare gains from increased abatement more equally across generations. Essentially, by issuing (more) public debt today and by having future generations pay it back, the welfare of current generations can be increased at the expense of future generations. Additional effects such as a potential crowding out of physical capital investments

[16] However, whether a change in the exogenous parameters increases or decreases the necessary level of global fund depends, in most cases, on the whole set of exogenous parameters, and the comparative static results for the global fund of the first-best sustainable RS are in most cases ambiguous.

[17] How public debt can be used to strike an intergenerational bargain in the context of climate change is also addressed by Dennig et al. (2015) who propose several focal bargaining points.

and the reduction of distortionary taxation affect the balance between current and future generations.

Second, current generations must set-up the fund and thus are, in principle, required to channel some of their savings towards the payment of initial fees. Since the global fund also invests, such savings may not necessarily decrease capital accumulation, but as future generations inherit the global fund for their own refunding, setting up the global fund decreases the welfare of current generations. Again, to redistribute the burden of setting up the global fund more equally across generations, one might implement repeated payments, as discussed in subsection 7.1, or again, public debt can be incurred to increase the disposable income of current old generations.

The use of public debt to engineer trade among generations and to ease the implementation of sustainable refunding schemes opens up the possibilities to achieve Pareto-improving climate policies. However, since future generations will have to abate more than current generations – as they need to keep the total stock of greenhouse gases in the atmosphere constant – the use of public debt to compensate current generations for their abatement efforts is less pronounced if equity objectives across generations are given a weight as important as efficiency objectives.

9 Conclusion

The RS provides a simple blueprint for an international treaty on climate change. It is governed by a very small number of parameters. The RS is no panacea, as free-rider problems have no perfect solutions, but it might be wiser to focus attention on schemes like the RS than on Kyoto-style treaties in which little can be done to induce countries to fulfill their promises.

The practical implementation of the refunding schemes developed in this paper requires a variety of additional considerations. In the last three sections, we have discussed how to achieve initial participation, and we have outlined several ways of raising initial fees. Other issues, such as governance of the administering agency or uncertainty regarding damage and abatement costs will need thorough investigation in future research.

Appendix

Proof of Proposition 1

We show existence and uniqueness of the social global optimum by solving the optimization problem (6) for any time horizon T. To this end, we introduce the following recursive value function in period t:

$$V_t(s_t) = \max_{\{a_t^i\}_{i=1}^n} \left\{ \delta V_{t+1}(s_{t+1}) - \sum_{i=1}^n \left[\frac{\alpha_i}{2} \left(a_t^i\right)^2 - \frac{\beta_i}{2} s_t^2 \right] \right\} , \tag{A.1}$$

where $V_t(s_t)$ represents the negative of the total global costs accruing from period t onwards discounted to period t. The social global planner's problem is to maximize (A.1) for $t = 0, \ldots, T$ subject to equation (3) and $V_{T+1}(s_{T+1}) \equiv 0$. Then, the following first-order conditions are necessary for a global optimum:

$$\alpha_i a_t^i = -\delta V'_{t+1}(s_{t+1}) \ , \quad i = 1, \ldots, n \ , \quad t = 0, \ldots, T \ . \tag{A.2}$$

In addition, differentiating $V_t(s_t)$ with respect to s_t and applying the envelope theorem yields

$$-V'_t(s_t) = \mathcal{B} s_t - \delta V'_{t+1}(s_{t+1}) \ , \quad t = 0, \ldots, T \ . \tag{A.3}$$

In each period t, the right-hand side of equation (A.2) is identical for all countries i. This implies

$$\alpha_i a_t^i = \alpha_j a_t^j \ , \quad i, j = 1, \ldots, n \ , \quad t = 0, \ldots, T \ . \tag{A.4}$$

Rewriting (A.2) to yield

$$V'_{t+1}(s_{t+1}) = -\frac{\alpha_i}{\delta} a_t^i \ , \tag{A.5}$$

and inserting into (A.3), we eliminate the value function and obtain

$$a_{t+1}^i = \left(\frac{1}{\delta} + \mathcal{AB} \right) a_t^i - \frac{\mathcal{B}}{\alpha_i} s_t - \frac{\mathcal{BE}}{\alpha_i} \ , \tag{A.6}$$

where we used the relationship $A_t = \sum_{j=1}^n a_t^j = \sum_{j=1}^n \alpha_i a_t^i \frac{1}{\alpha_j} = \alpha_i a_t^i \mathcal{A}$ from (A.4). Summing up this equation for all $i = 1, \ldots, n$ yields the corresponding difference equations for the aggregate abatement level $A_t = \sum_{i=1}^n a_t^i$:

$$A_{t+1} = \left(\frac{1}{\delta} + \mathcal{AB} \right) A_t - \mathcal{AB} s_t - \mathcal{ABE} \ . \tag{A.7}$$

Equation (A.7) together with the equation of motion (3) yields the system of linear first-order difference equations

$$\begin{pmatrix} A^\star_{t+1} \\ s^\star_{t+1} \end{pmatrix} = \begin{pmatrix} \frac{1}{\delta} + \mathcal{AB} & -\mathcal{AB} \\ -1 & 1 \end{pmatrix} \begin{pmatrix} A^\star_{t} \\ s^\star_{t} \end{pmatrix} + \begin{pmatrix} -\mathcal{ABE} \\ \mathcal{E} \end{pmatrix} , \tag{A.8}$$

the general solution of which is given by

$$\begin{pmatrix} A^\star_{t+1} \\ s^\star_{t+1} \end{pmatrix} = \begin{pmatrix} A^{SO} \\ S^{SO} \end{pmatrix} + B_1(T) v_1 \lambda_1^t + B_2(T) v_2 \lambda_2^t , \tag{A.9}$$

where (A^{SO}, s^{SO}) are the stationary states obtained by setting $A^\star_{t+1} = A^\star_t = A^{SO}$ and $s^\star_{t+1} = s^\star_t = s^{SO}$, hence

$$A^{SO} = \mathcal{E} , \quad s^{SO} = \frac{1-\delta}{\delta} \frac{\mathcal{E}}{\mathcal{AB}} , \tag{A.10}$$

and v_i and $\lambda_i, \ i = 1, 2$ are the Eigen vectors and the Eigen values, respectively, of the 2×2 matrix in (A.8). $B_i(T), \ i = 1, 2$ are constants that have to be determined in such a way that the initial and final conditions are satisfied.

Calculating Eigen values and vectors yields

$$\lambda_{1/2} = \frac{1 + \delta + \delta\mathcal{AB} \pm \sqrt{(1 + \delta + \delta\mathcal{AB})^2 - 4\delta}}{2\delta} \tag{A.11a}$$

$$= 1 + \frac{1 - \delta + \delta\mathcal{AB} \pm \sqrt{(1 - \delta + \delta\mathcal{AB})^2 + 4\delta^2\mathcal{AB}}}{2\delta} \tag{A.11b}$$

$$v_1 = \begin{pmatrix} 1 - \lambda_1 \\ 1 \end{pmatrix} , \quad v_2 = \begin{pmatrix} 1 - \lambda_2 \\ 1 \end{pmatrix} . \tag{A.11c}$$

From equations (A.11a) and (A.11b) we obtain

$$\lambda_1 > 1 > \lambda_2 > 0 . \tag{A.12}$$

Then the general solution is given by

$$A^\star_t = A^{SO} + B_1(T)(1 - \lambda_1)\lambda_1^t + B_2(T)(1 - \lambda_2)\lambda_2^t , \tag{A.13a}$$

$$s^\star_t = s^{SO} + B_1(T)\lambda_1^t + B_2(T)\lambda_2^t . \tag{A.13b}$$

We determine $B_1(T)$ and $B_2(T)$ from the initial level of cumulative greenhouse gas emsisions,

s_0, and the terminal condition for emission abatement, $A_T = 0$:

$$B_1(T) = \frac{A^{SO} + (s_0 - s^{SO})(1-\lambda_2)\lambda_2^T}{(1-\lambda_2)\lambda_2^T + (\lambda_1 - 1)\lambda_1^T} \ , \tag{A.14a}$$

$$B_2(T) = -\frac{A^{SO} - (s_0 - s^{SO})(\lambda_1 - 1)\lambda_1^T}{(1-\lambda_2)\lambda_2^T + (\lambda_1 - 1)\lambda_1^T} \ . \tag{A.14b}$$

Inserting back into equations (A.13) yields the unique global social optimum in terms of aggregate abatement levels A_t. By virtue of (A.4) individual abatement levels a_t^i are given by:

$$a_t^i = \frac{A_t}{\alpha_i \mathcal{A}} \ . \tag{A.15}$$

□

Proof of Corollary 1

For large T we obtain for $B_1(T)$ and $B_2(T)$ from the proof of Proposition 1

$$B_1^\infty \equiv \lim_{T\to\infty} B_1(T) = 0 \ , \qquad B_2^\infty \equiv \lim_{T\to\infty} B_2(T) = s_0 - s^{SO} \ , \tag{A.16}$$

implying for the solution (A.13) in the limit case $T \to \infty$

$$A_t^\star = A^{SO} + (s_0 - s^{SO})(1-\lambda_2)\lambda_2^t \ , \tag{A.17a}$$

$$s_t^\star = s^{SO} + (s_0 - s^{SO})\lambda_2^t \ , \tag{A.17b}$$

which we can also write as a policy rule $a_t(s_t)$:

$$A_t^\star(s_t^\star) = A^{SO} + (1-\lambda_2)(s_t^\star - s^{SO}) \ . \tag{A.18}$$

From the proof of Proposition 1 we know that $0 < \lambda_2 < 1$. Thus we obtain from (A.17)

$$\lim_{t\to\infty} A_t^\star = A^{SO} \ , \qquad \lim_{t\to\infty} s_t^\star = s^{SO} \ . \tag{A.19}$$

Again, individual countries's abatement levels are given by:

$$a_i^{SO} = \frac{A^{SO}}{\alpha_i \mathcal{A}} \ . \tag{A.20}$$

□

Proof of Proposition 2

We show the existence of a unique subgame perfect Nash equilibrium by backward induction. To this end, we first differentiate equation (8) with respect to a_t^i and set it equal to zero to obtain:

$$\alpha_i a_t^i = -\delta {W_{t+1}^i}'(s_{t+1}) \ . \tag{A.21}$$

In addition, applying the envelope theorem to equation (8) yields

$$-V_t^{i\prime}(s_t)|A_t^{-i} = \beta_i s_t - \delta {W_{t+1}^i}'(s_{t+1}) \ . \tag{A.22}$$

Second, note that country i's optimization problem in period t is concave if and only if

$$\delta {W_{t+1}^i}''(s_{t+1}) - \alpha_i < 0 \ . \tag{A.23}$$

Starting in period T, recall that $W_{T+1}^i(s_{T+1}) \equiv 0$, which implies that the optimization problem of all countries is strictly concave. As a consequence, equation (A.21) characterizes country i's best response which is given by $\bar{a}_T^i = 0$ independently of the emission abatement choices of all other countries. As a consequence, $\hat{a}_T^i = 0$ is the unique and symmetric Nash equilibrium for the subgame starting in period T given the stock of cumulative greenhouse gas emissions s_T. The equilibrium pay-off is given by $W_T^i(s_T) = V_T^i(s_T)|\hat{A}_T^{-i}$ and is strictly concave:

$$W_T^i(s_T) = -\frac{\beta_i}{2} s_T^2 \qquad \Rightarrow \qquad {W_T^i}''(s_T) = -\beta_i \ . \tag{A.24}$$

As a consequence, the optimization problem of all countries i in period $T-1$ is strictly concave, too.

Now assume there exists a unique subgame perfect Nash equilibrium for the subgame starting in period $t+1$ with a stock of greenhouse gas emissions of s_{t+1} yielding equilibrium pay-offs $W_{t+1}^i(s_{t+1})$ with $W_{t+1}''(s_{t+1}) < 0$. Then the optimization problem in period t is strictly concave for all countries i, implying there exists a unique best response $\bar{a}_t^i$ for country i given the emission abatements of all other countries $j \neq i$, which is given implicitly by

$$\alpha_i \bar{a}_t^i = -\delta {W_{t+1}^i}'(\bar{s}_{t+1}) \ , \tag{A.25}$$

where $\bar{s}_{t+1} = s_t + \mathcal{E} - \bar{a}_t^i - A_t^{-i}$. As, by assumption, $-{W_{t'}^i}'(s_{t'}) = -V_{t'}^{i\prime}(s_{t'})|\hat{A}_{t'}^{-i}$ for all

$t' \geq t+1$ we can exploit (A.22) to obtain:

$$a_t^i = \delta \hat{a}_{t+1}^i + \delta \gamma_i (s_t + \mathcal{E} - A_t) \ . \tag{A.26}$$

Summing up over all countries $i = 1, \ldots, n$, we obtain the following equation for the aggregate abatement level A_t:

$$A_t = \delta \hat{A}_{t+1} + \delta \Gamma (s_t + \mathcal{E} - A_t) \ , \tag{A.27}$$

which yields the unique aggregate abatement level in the subgame perfect Nash equilibrium

$$\hat{A}_t = \frac{\delta \hat{A}_{t+1} + \delta \Gamma (s_t + \mathcal{E})}{1 + \delta \Gamma} \ . \tag{A.28}$$

Inserting $\hat{A}_t$ back into equation (A.26) yields the unique equilibrium abatement level of country i:

$$\hat{a}_t^i = \delta \hat{a}_{t+1}^i + \delta \gamma_i (s_t + \mathcal{E} - \hat{A}_t) \ . \tag{A.29}$$

Differentiating (A.22) with respect to s_t, we obtain

$$V_t^{i\prime\prime}(s_t)|A_t^{-i} = \delta {W_{t+1}^i}^{\prime\prime}(\bar{s}_{t+1}) - \beta_i \ . \tag{A.30}$$

As $W_t^{i\prime\prime}(s_t) = V_t^{i\prime\prime}(s_t)|\hat{A}_t^{-i}$, this implies that the equilibrium pay-off $W_t^i(s_t)$ is strictly concave for all countries $i = 1, \ldots, n$.

Working backwards until $t = 0$ yields unique sequences of emission abatements $\hat{a}_t^i$ for all countries i and the corresponding sequence of the stock of cumulative greenhouse gas emissions $\hat{s}_t$ ($i = 1, \ldots, n$; $t = 0, \ldots, T$) that constitute the unique subgame perfect Nash equilibrium outcome of the decentralized system. □

Proof of Corollary 2

From equations (A.28) and (3), we obtain the following system of first-order difference equations from equations for the aggregate abatement level $\hat{A}_t$ and the stock of cumulative greenhouse gas emissions $\hat{s}_t$ that characterize the subgame perfect Nash equilibrium outcome in the decentralized solution:

$$\begin{pmatrix} \hat{A}_{t+1} \\ \hat{s}_{t+1} \end{pmatrix} = \begin{pmatrix} \frac{1}{\delta} + \Gamma & -\Gamma \\ -1 & 1 \end{pmatrix} \begin{pmatrix} \hat{A}_t \\ \hat{s}_t \end{pmatrix} + \begin{pmatrix} -\Gamma \mathcal{E} \\ \mathcal{E} \end{pmatrix} \ . \tag{A.31}$$

Following the same solution technique as described in the proof of Proposition 1, we derive for the sequences of aggregate emission abatement and the stock of cumulative greenhouse gas emissons in the subgame perfect Nash equilibrium

$$\hat{A}_t = A^{DS} + B_1(T)(1-\mu_1)\mu_1^t + B_2(T)(1-\mu_2)\mu_2^t \ , \tag{A.32a}$$

$$\hat{s}_t = s^{DS} + B_1(T)\mu_1^t + B_2(T)\mu_2^t \ . \tag{A.32b}$$

where (A^{DS}, s^{DS}) denote the steady state of (A.31) given by

$$A^{DS} = \mathcal{E} \ , \quad s^{DS} = \frac{1-\delta}{\delta}\frac{\mathcal{E}}{\Gamma} \ , \tag{A.33}$$

μ_1 and μ_2 equal

$$\begin{aligned} \mu_{1/2} &= \frac{1+\delta+\delta\Gamma \pm \sqrt{(1+\delta+\delta\Gamma)^2 - 4\delta}}{2\delta} \\ &= 1 + \frac{1-\delta+\delta\Gamma \pm \sqrt{(1-\delta+\delta\Gamma)^2 + 4\delta^2\Gamma}}{2\delta} \ , \end{aligned} \tag{A.34}$$

which immediately implies $\mu_1 > 1 > \mu_2 > 0$, and $B_1(T)$ and $B_2(T)$ depend on the time horizon T and the initial stock of greenhouse gases s_0

$$B_1(T) = \frac{A^{DS} + (s_0 - s^{DS})(1-\mu_2)\mu_2^T}{(1-\mu_2)\mu_2^T + (\mu_1 - 1)\mu_1^T} \ , \tag{A.35a}$$

$$B_2(T) = -\frac{A^{DS} - (s_0 - s^{DS})(\mu_1 - 1)\mu_1^T}{(1-\mu_2)\mu_2^T + (\mu_1 - 1)\mu_1^T} \ . \tag{A.35b}$$

For large T we obtain for $B_1(T)$ and $B_2(T)$

$$B_1^\infty \equiv \lim_{T\to\infty} B_1(T) = 0 \ , \qquad B_2^\infty \equiv \lim_{T\to\infty} B_2(T) = s_0 - s^{DS} \ , \tag{A.36}$$

implying for the solution (A.32) in the limit case $T \to \infty$

$$\hat{A}_t = A^{DS} + (s_0 - s^{DS})(1-\mu_2)\mu_2^t \ , \tag{A.37a}$$

$$\hat{s}_t = s^{DS} + (s_0 - s^{DS})\mu_2^t \ , \tag{A.37b}$$

which we can also write as a policy rule $A_t(s_t)$:

$$\hat{A}_t(\hat{s}_t) = A^{DS} + (1-\mu_2)(\hat{s}_t - s^{DS}) \ . \tag{A.38}$$

From (A.34) we know that $0 < \mu_2 < 1$. Thus, we obtain from (A.37)

$$\lim_{t\to\infty} \hat{A}_t = A^{DS} \ , \qquad \lim_{t\to\infty} \hat{s}_t = s^{DS} \ . \tag{A.39}$$

From equation (A.29) we obtain for the steady state abatement level of country i:

$$a_i^{DS} = \frac{\gamma_i \mathcal{E}}{\Gamma} \ . \tag{A.40}$$

□

Proof of Proposition 3

To prove the proposition, first assume that all countries have joined a feasible RS characterized by a weighting scheme $\{\lambda_t^i\}_{i=1}^n$ and a sequence of refunds R_t by paying an initial fee f_0^i. We shall analyze the subgame perfect Nash equilibria of the RS by backward induction. In every step of the backward induction, we show that

1. the objective function of each country i is strictly concave,
2. there exits a feasible weighting scheme $\{\lambda_t^{i\star}\}_{i=1}^n$ and a feasible refund $R_t^\star$ such that the socially optimal abatement levels $a_t^{i\star}$ are consistent with the necessary and sufficient conditions of subgame perfect Nash equilibrium of the subgame starting in period t and
3. the socially optimal abatement levels $a_t^{i\star}$ are the unique solution solving the the necessary and sufficient conditions of the subgame perfect Nash equilibrium of the subgame starting in period t,

given the socially optimal abatement levels ${a_{t+1}^i}^\star$ constitute the unique subgame perfect Nash equilibrium outcome of the subgame starting in period $t+1$.

Assuming that there exists a unique subgame perfect equilibrium for the subgame starting in period $t+1$ with a stock of cumulative greenhouse gas emissions s_{t+1}, we denote country i's equilibrium payoff for this subgame by $W_{t+1}^i(s_{t+1})$. Then country i's best response in period t, $\bar{a}_t^i$, is determined by the solution of the optimization problem

$$V_t^i(s_t)|A_t^{-i} = \max_{a_t^i} \left\{ \delta W_{t+1}^i(s_{t+1}) - \frac{\alpha_i}{2}(a_t^i)^2 - \frac{\beta_i}{2} s_t^2 + r_t^i \right\} \ , \tag{A.41}$$

subject to equation (3), $W_{T+1}^i(s_{T+1}) \equiv 0$, and given the sum of the abatement efforts of all other countries $A_t^{-i} = \sum_{j \neq i} a_t^j$. Differentiating equation (A.41) with respect to a_t^i and setting it equal to zero yields

$$\alpha_i \bar{a}_t^i = -\delta {W_{t+1}^i}'(\bar{s}_{t+1}) + \left. \frac{\partial r_t^i}{\partial a_t^i} \right|_{a_t^i = \bar{a}_t^i} \ , \tag{A.42}$$

where $\bar{s}_{t+1} = s_t + \mathcal{E} - \bar{a}_t^i - A_t^{-i}$ and

$$\frac{\partial r_t^i}{\partial a_t^i} = \begin{cases} \lambda_t^i R_t \dfrac{A_t^{-i}}{(a_t^i + A_t^{-i})^2} \ , & t = 1, \dots, T-1 \ , \\ 0 \ , & t = T \ . \end{cases} \tag{A.43}$$

Applying the envelope theorem yields

$$-V_t^{i\prime}(s_t)|A_t^{-i} = \beta_i s_t - \delta W_{t+1}^{i}{}'(s_{t+1}) \ . \tag{A.44}$$

Starting with period $t = T$, we first note that the maximization problem of all countries is strictly concave, as $W_{T+1}(s_{T+1}) \equiv 0$ and $r_T = f_T/n$. Thus, equation (A.42) characterizes the best response for all countries $i = 1, \dots, n$, which is given by $\bar{a}_T^i = 0$ independently of the abatement choices of all other countries. As a consequence $\hat{a}_T^i = 0$ for all $i = 1, \dots, n$ is the subgame perfect Nash equilibrium of the game starting in period T and is also the socially optimal abatement level in period T. Then, the equilibrium pay-off is given by $W_T^i(s_T) = V_T^i(s_T)|\hat{A}_T^{-i}$, which is strictly concave:

$$W_T^i(s_T) = -\frac{\beta_i}{2} s_T^2 + \frac{f_T}{n} \qquad \Rightarrow \qquad W_T''(s_T) = -\beta_i \ . \tag{A.45}$$

Now, we analyze the subgame starting in period t assuming that their exists a weighting scheme $\{\lambda_t^{i\star}\}_{i=1}^n$ and a sequence of refunds $R_t^\star$ for $t = t+1, \dots, T-1$ such that the outcome of the unique subgame perfect Nash equilibrium of the subgame starting in period $t+1$ coincides with the social global optimum given the socially optimal stock of cumulative greenhouse gas emissions $s_t^\star$. In addition, we assume that $W_{t+1}^i(s_{t+1})$ is strictly concave. Then, also the optimization problem of country i in period t is strictly concave

$$\delta W_{t+1}^{i}{}''(s_{t+1}) - \alpha_i + \frac{\partial^2 r_t^i}{(\partial a_t^i)^2} < 0 \ . \tag{A.46}$$

As a consequence, there exists a unique best response $\bar{a}_t^i$ for all countries i given the emission abatements of all other countries $j \neq i$, which is given implicitly by (A.42):

$$\alpha_i \bar{a}_t^i - \lambda_t^i R_t \frac{A_t^{-i}}{(\bar{a}_t^i + A_t^{-i})^2} = -\delta W_{t+1}^{i}{}'(\bar{s}_{t+1}) \ . \tag{A.47}$$

As, by assumption, $-W_{t'}^{i\prime}(s_{t'}) = -V_{t'}^{i\prime}(s_{t'})|\hat{A}_{t'}^{-i}$ for all $t' \geq t+1$ we can exploit equation

(A.44) to obtain the following Euler equation:

$$\alpha_i \bar{a}_t^i - \lambda_t^i R_t \frac{A_t^{-i}}{(\bar{a}_t^i + A_t^{-i})^2} = \delta\beta_i \bar{s}_{t+1} + \delta\alpha_i a_{t+i}^{i\ \star} - \delta\lambda_{t+1}^{i\ \star} R_{t+1}^\star \frac{A_{t+1}^{-i\ \star}}{(A_{t+1}^\star)^2} \ . \tag{A.48}$$

Inserting $\bar{s}_{t+1} = s_t + \mathcal{E} - \bar{a}_t^i - A_t^{-i}$ yields:

$$\alpha_i \bar{a}_t^i + \delta\beta_i(\bar{a}_t^i + A_t^{-i}) - \lambda_t^i R_t \frac{A_t^{-i}}{(\bar{a}_t^i + A_t^{-i})^2} = C_t^{i\star} \ , \tag{A.49}$$

with

$$C_t^{i\star} = \delta\beta_i(s_t + \mathcal{E}) + \delta\alpha_i a_{t+i}^{i\ \star} - \delta\lambda_{t+1}^{i\star} R_{t+1}^\star \frac{A_{t+1}^{-i\ \star}}{(A_{t+1}^\star)^2} \ . \tag{A.50}$$

First, we show that there exist unique $\lambda_t^{i\star}$ and $R_t^\star$ such that choosing the socially optimal abatement level $a_t^{i\star}$ is an equilibrium strategy for all countries $i = 1, \ldots, n$. Inserting the socially optimal abatement levels $a_t^{i\star}$ and rearranging equation (A.49), we obtain

$$\lambda_t^{i\star} R_t^\star = (A_t^\star)^2 \left(\alpha_i \frac{a_t^{i\star}}{A_t^{-i\star}} + \delta\beta_i \frac{A_t{}^\star}{A_t^{-i\star}} - \frac{C_t^{i\star}}{A_t^{-i\star}} \right) \ . \tag{A.51}$$

Taking into account that the weighting scheme adds up to one, i.e. $\sum_{i=1}^n \lambda_t^{i\star} = 1$, yields

$$R_t^\star = (A_t^\star)^2 \sum_{i=1}^n \left(\alpha_i \frac{a_t^{i\star}}{A_t^{-i\star}} + \delta\beta_i \frac{A_t{}^\star}{A_t^{-i\star}} - \frac{C_t^{i\star}}{A_t^{-i\star}} \right) \ , \tag{A.52a}$$

$$\lambda_t^{i\star} = \frac{\alpha_i \frac{a_t^{i\star}}{A_t^{-i\star}} + \delta\beta_i \frac{A_t{}^\star}{A_t^{-i\star}} - \frac{C_t^{i\star}}{A_t^{-i\star}}}{\sum_{i=1}^n \left(\alpha_i \frac{a_t^{i\star}}{A_t^{-i\star}} + \delta\beta_i \frac{A_t{}^\star}{A_t^{-i\star}} - \frac{C_t^{i\star}}{A_t^{-i\star}} \right)} \ . \tag{A.52b}$$

We now show that the socially optimal abatement levels $a_t^{i\star}$ are the unique solution to the Euler equations of all countries $i = 1, \ldots, n$ given the weighting scheme $\lambda_t^{i\star}$ and the refund $R_t^\star$. To this end, we express equation (A.49) in terms of a_t^i and A_t and solve for a_t^i:

$$a_t^i = A_t \underbrace{\frac{\lambda_t^{i\star} R_t^\star + C_t^{i\star} A_t - \delta\beta_i A_t^2}{\lambda_t^{i\star} R_t^\star + \alpha_i A_t^2}}_{\equiv h_t^i(A_t)} = A_t h_t^i(A_t) \ . \tag{A.53}$$

Summing-up over all n countries yields

$$\sum_{i=1}^n h_t^i(A_t) = 1 \ , \tag{A.54}$$

which has to hold for $A_t = A_t^\star$ and is a necessary condition for a Nash equilibrium. Differentiating $h_t^i(A_t)$ with respect to A_t, we obtain:

$$h_t^{i\prime}(A_t) = \frac{\lambda_t^{i\star} R_t^\star C_t^{i\star} - 2(\alpha_i + \delta\beta_i)\lambda_t^{i\star} R_t^\star A_t - \alpha_i C_t^{i\star} A_t^2}{(\lambda_t^{i\star} R_t^\star + \alpha_i A_t^2)^2} \ . \tag{A.55}$$

Seeking the roots of $h_t^{i\prime}(A_t)$ yields

$$h_t^{i\prime}(A_t) = 0 \qquad \Leftrightarrow \qquad \underbrace{\lambda_t^{i\star} R_t^\star C_t^{i\star}}_{\equiv x>0} - \underbrace{2(\alpha_i + \delta\beta_i)\lambda_t^{i\star} R_t^\star}_{\equiv y>0} A_t - \underbrace{\alpha_i C_t^{i\star}}_{\equiv z>0} A_t^2 \ , \tag{A.56}$$

$$\Leftrightarrow \qquad x - yA_t - zA_t^2 = 0 \ , \tag{A.57}$$

$$\Leftrightarrow \qquad A_t = -\frac{y \pm \sqrt{y^2 + 4xz}}{2z} \ . \tag{A.58}$$

Thus, for every $h_t^i(A_t)$ there exist one positive collective abatement level $\tilde{A}_t^i$ such that $h_t^{i\prime}(\tilde{A}_t^i) = 0$. In addition it holds (taking into account equation (A.51)):

$$h_t^i(0) = 1 \ , \qquad h_t^i(A_t^\star) = \frac{\alpha_i a_t^{i\star} A_t^\star \lambda_t^{i\star} R_t^\star \left(1 - \frac{A_t - i^\star}{A_t^\star}\right)}{\lambda_t^{i\star} R_t^\star + \alpha_i (A_t^\star)^2} \in [0,1] \ , \tag{A.59a}$$

$$h_t^{i\prime}(0) = \frac{C_t^{i\star}}{\lambda_t^{i\star} R_t^\star} > 0 \ , \qquad h_t^{i\prime}(A_t^\star) < 0 \ . \tag{A.59b}$$

Thus, all $h_t^i(A_t)$ start at 1 for $A_t = 0$ increase monotonically for increasing A_t until $\tilde{A}_t^i$ and decrease monotonically afterwards. At $A_t^\star$, all $h_t^i(A_t^\star) \in [0,1]$ are monotonically decreasing. As a consequence, there exists no other value A_t' such that $\sum_{i=1}^n h_t^i(A_t') = 1$. Then, only the socially optimal abatement levels $a_t^{i\star}$ solve the Euler equations of all countries simultaneously for the weighting scheme $\lambda_t^{i\star}$ and the refund $R_t^\star$.

Differentiating (A.44) with respect to s_t, we obtain

$$V_t^{i\prime\prime}(s_t)|A_t^{-i} = \delta W_{t+1}^{i}{}^{\prime\prime}(\bar{s}_{t+1}) - \beta_i \ . \tag{A.60}$$

As $W_t^i(s_t) = V_t^i(s_t)|\hat{A}_t^{-i}$, this implies that the equilibrium pay-off $W_t^i(s_t)$ is strictly concave for all countries $i = 1, \ldots, n$.

Working backwards to $t = 1$ yields a the unique subgame perfect Nash equilibrium outcome that is given by the socially optimal abatement levels $a_t^{i\star}$ and the corresponding stock of cumulative greenhouse gas emissions $s_t^\star$ ($i = 1, \ldots, n$; $t = 0, \ldots, T$).

Finally, we show that the first-best sustainable refunding scheme is feasible, i.e. the weighting scheme $\{\lambda_t^{i\star}\}_{i=1}^n$ and the refund $R_t^\star$ are non-negative for all $t = 0, \ldots, T-1$. As $W_t^i(s_t) = V_t^i(s_t)|\hat{A}_t^{-i}$, we can consecutively apply equation A.44, insert into equation A.42 and evaluate in the subgame perfect Nash equilibrium:

$$\alpha_i a_t^{i\star} - \lambda_t^{i\star} R_t^\star \frac{A_t^{-i\star}}{(A_t^\star)^2} = \delta\beta_i \sum_{\tau=t+1}^{T} \delta^{\tau-(t+1)} s_\tau^\star \ , \quad t = 0, \ldots, T-1 \ . \tag{A.61}$$

Following the same procedure in the global social optimum yields:

$$\alpha_i a_t^{i\star} = \delta\mathcal{B} \sum_{\tau=t+1}^{T} \delta^{\tau-(t+1)} s_\tau^\star \ , \quad t = 0, \ldots, T-1 \ . \tag{A.62}$$

Comparing both equations implies that $\{\lambda_t^{i\star}\}_{i=1}^n > 0$ and $R_t^\star > 0$ for all $t = 0, \ldots, T-1$.
□

Proof of Proposition 5

Replicating the proof of Proposition 5 it is trivial to show that there exist uniquely determined sequences of refunds $\tilde{R}_t$ and weighting schemes $\{\tilde{\lambda}_t^i\}_{i=1}^n$ such that the second-best abatement path $\tilde{a}_t^i$ is implemented as the unique subgame perfect Nash equilibrium of the RS.

However, it remains to show that the RS is feasible, i.e. the weighting scheme $\{\tilde{\lambda}_t^i\}_{i=1}^n$ and the refund $\tilde{R}_t$ are non-negative for all $t = 0, \ldots, T-1$, for all second-best abatement paths $\tilde{A}_t^i$. Analogously to equation A.61, we obtain:

$$\alpha_i \tilde{a}_t^i - \tilde{\lambda}_t^i \tilde{R}_t \frac{\tilde{A}_t^{-i}}{\tilde{A}_t^2} = \delta\beta_i \sum_{\tau=t+1}^{T} \delta^{\tau-(t+1)} s_\tau^\star \ , \quad t = 0, \ldots, T-1 \ . \tag{A.63}$$

The corresponding equation in the decentralized solution yields:

$$\alpha_i \hat{a}_t^i = \delta\beta_i \sum_{\tau=t+1}^{T} \delta^{\tau-(t+1)} \hat{s}_\tau \ , \quad t = 0, \ldots, T-1 \ . \tag{A.64}$$

By construction $\tilde{a}_t^i > \hat{a}_t^i$ for all $i = 1, \ldots, n$ and $t = 0, \ldots, T-1$. As a consequence, it also holds that $\hat{s}_t > \tilde{s}_t$ for all $t = 0, \ldots, T$. This, in turn, implies that $\{\tilde{\lambda}_t^i\}_{i=1}^n > 0$ and $\tilde{R}_t > 0$ for all $t = 0, \ldots, T-1$. □

Numerical Illustration

In the following, we present additional results from the numerical illustration.

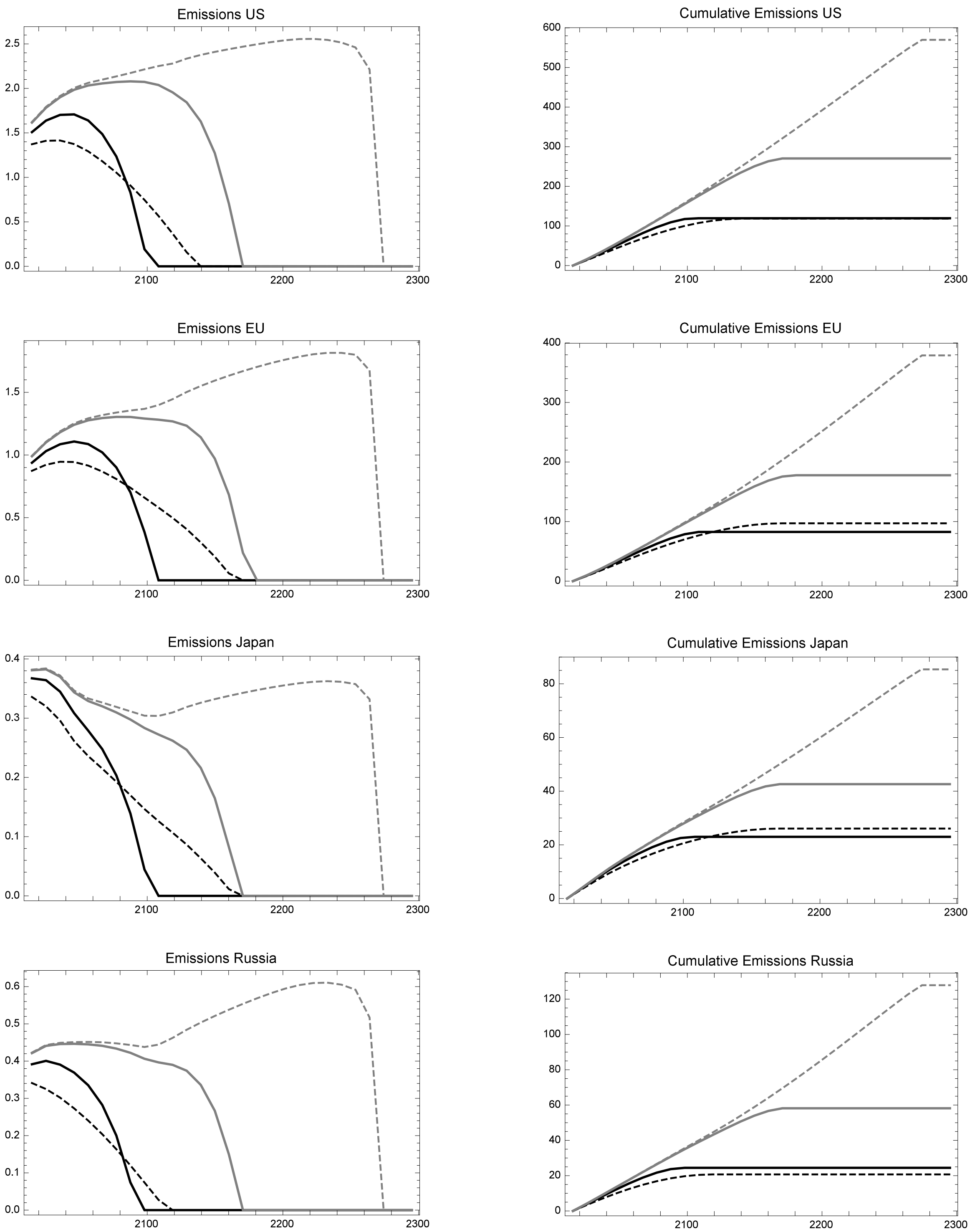

Figure 2: Emissions (left) and cumulative emissions (right) for business-as-usual scenario (dashed gray), decentralized equilibrium (solid gray) and the global social optimum in the RICE-2010 (dashed black) and our calibrated model (solid black) for US, EU, Japan and Russia.

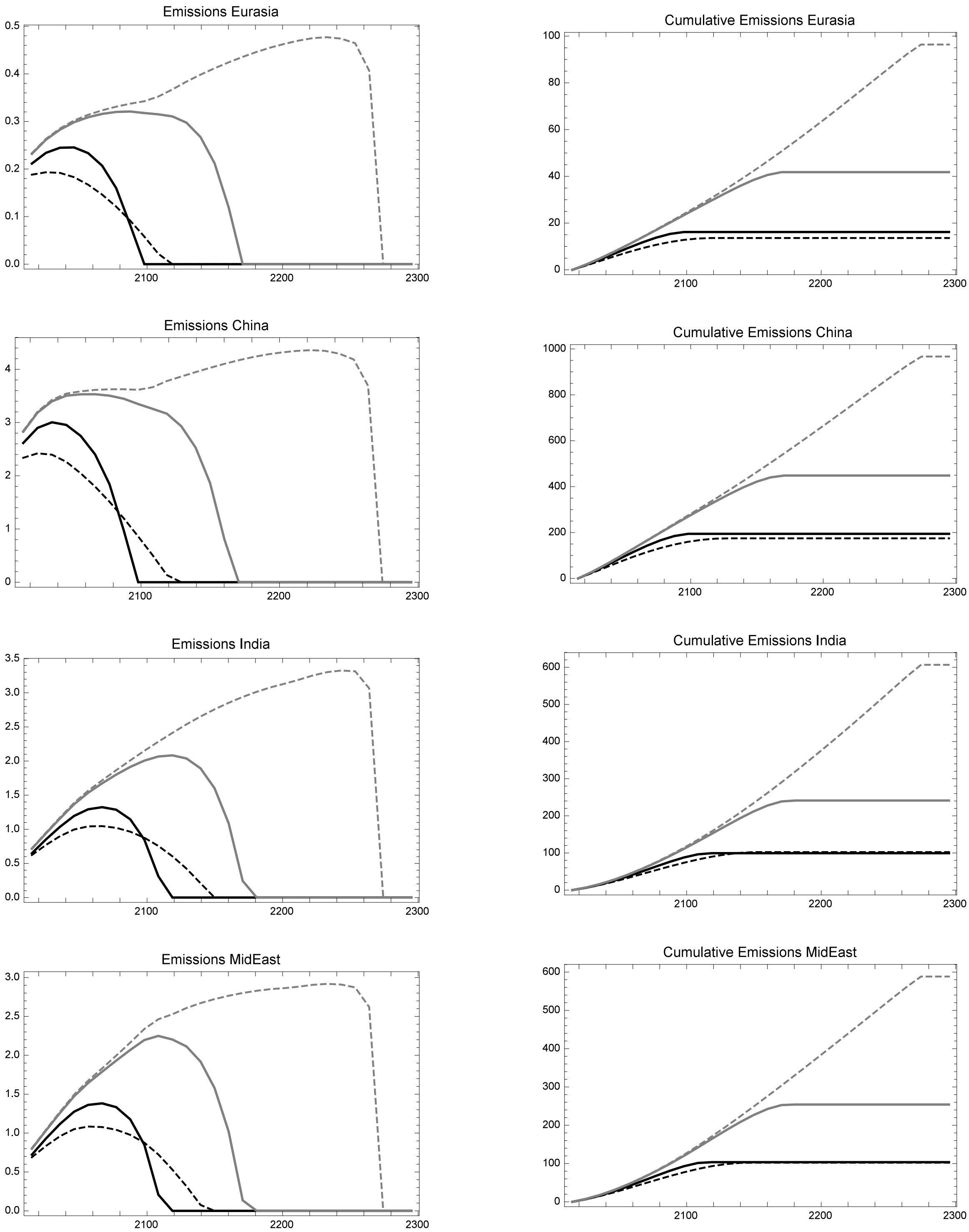

Figure 3: Emissions (left) and cumulative emissions (right) for business-as-usual scenario (dashed gray), decentralized equilibrium (solid gray) and the global social optimum in the RICE-2010 (dashed black) and our calibrated model (solid black) for Eurasia, China, India and MidEast.

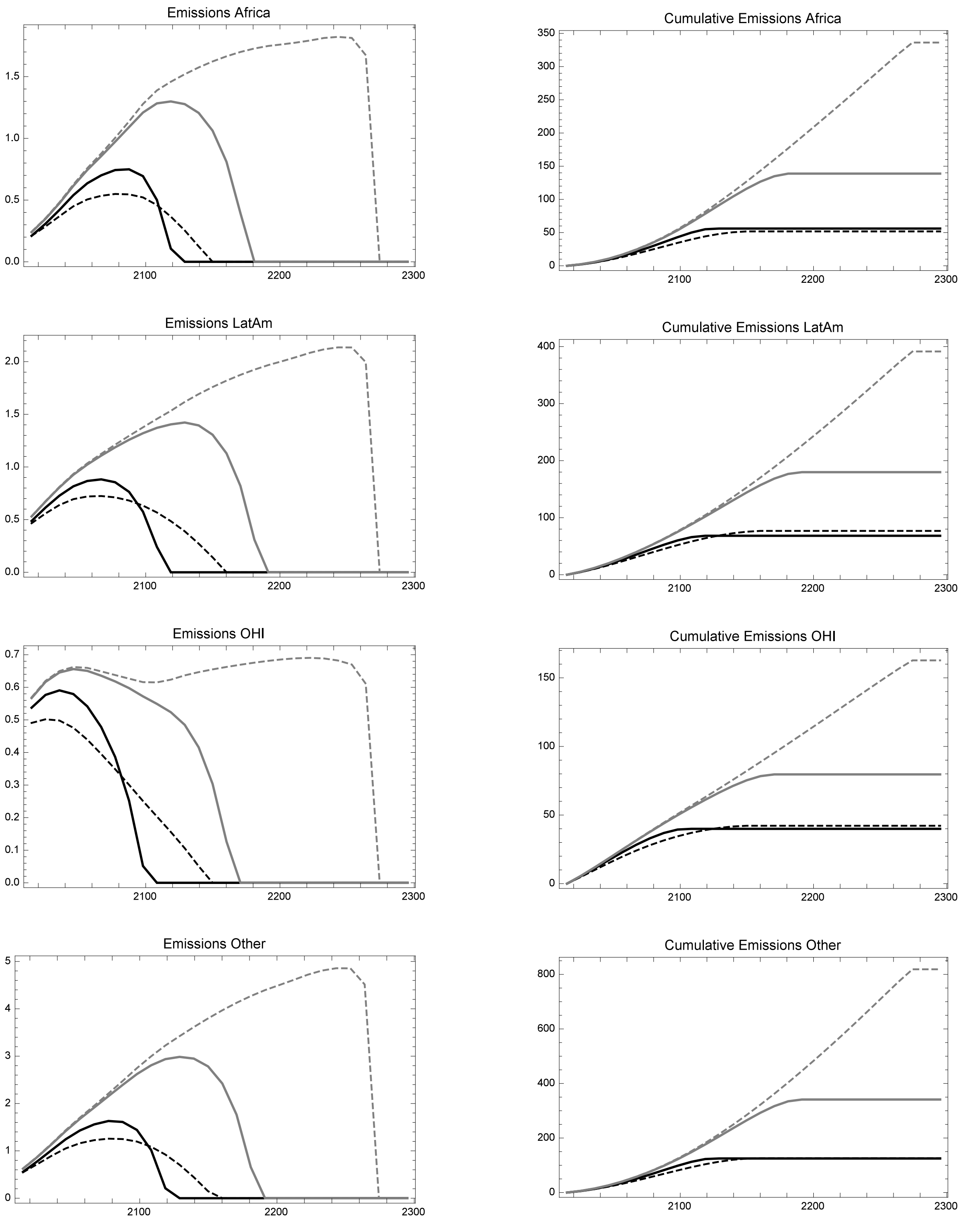

Figure 4: Emissions (left) and cumulative emissions (right) for business-as-usual scenario (dashed gray), decentralized equilibrium (solid gray) and the global social optimum in the RICE-2010 (dashed black) and our calibrated model (solid black) for Africa, LatAm, OHI and Other.

Period	2015	2025	2035	2045	2055	2065	2075	2085	2095	2105	2115	2125	2135	2145	2155	2165	2175	2185	2195	2205	2215	2225	2235	2245	2255
$R[t]$ [tril. USD/a]	0.18	0.32	0.61	1.17	2.31	4.65	9.57	19.96	39.42	61.19	81.33	90.47	96.62	102.40	107.83	112.92	117.62	121.89	125.64	129.47	133.34	136.18	136.92	133.78	119.05
$R[t]$ [% World GDP]	0.22	0.29	0.41	0.63	1.02	1.73	3.03	5.44	9.34	12.71	14.95	14.81	14.23	13.67	13.14	12.64	12.16	11.69	11.24	10.80	10.38	9.90	9.32	8.55	7.16
λ_{US} [%]	4.19	4.17	4.19	4.25	4.35	4.52	4.76	5.07	5.69	5.73	5.59	5.57	5.56	5.55	5.54	5.53	5.53	5.54	5.56	5.60	5.66	5.77	5.97	6.32	6.93
Refund US [tril. USD/a]	0.01	0.01	0.03	0.05	0.10	0.21	0.46	1.01	2.24	3.51	4.55	5.04	5.37	5.68	5.97	6.25	6.51	6.75	6.99	7.25	7.55	7.86	8.18	8.46	8.26
Refund US [% GDP]	0.05	0.07	0.10	0.16	0.28	0.52	1.00	1.99	3.95	5.60	6.64	6.68	6.54	6.39	6.24	6.09	5.93	5.77	5.61	5.49	5.41	5.33	5.26	5.18	4.81
λ_{EU} [%]	5.39	5.36	5.39	5.46	5.60	5.82	6.13	6.51	6.97	7.09	6.86	6.81	6.79	6.76	6.75	6.73	6.73	6.73	6.75	6.79	6.86	6.99	7.23	7.65	8.38
Refund EU [tril. USD/a]	0.01	0.02	0.03	0.06	0.13	0.27	0.59	1.30	2.75	4.34	5.58	6.16	6.56	6.93	7.27	7.60	7.91	8.21	8.48	8.79	9.15	9.52	9.90	10.23	9.98
Refund EU [% GDP]	0.06	0.08	0.13	0.22	0.38	0.72	1.40	2.83	5.49	7.91	9.22	9.21	8.95	8.70	8.45	8.21	7.97	7.73	7.50	7.30	7.15	7.02	6.90	6.75	6.24
λ_{Japan} [%]	5.39	5.36	5.39	5.46	5.60	5.82	6.13	6.51	6.97	7.09	6.86	6.81	6.79	6.76	6.75	6.73	6.73	6.73	6.75	6.79	6.86	6.99	7.23	7.65	8.38
Refund Japan [tril. USD/a]	0.01	0.01	0.03	0.05	0.10	0.21	0.45	1.01	2.19	3.53	4.66	5.18	5.53	5.86	6.17	6.47	6.75	7.01	7.25	7.53	7.86	8.19	8.53	8.84	8.63
Refund Japan [% GDP]	0.17	0.26	0.43	0.80	1.48	2.84	5.67	11.73	23.89	35.45	42.53	42.71	41.69	40.68	39.66	38.63	37.58	36.52	35.46	34.61	33.99	33.45	32.93	32.29	29.91
$\lambda_{\mathrm{Russia}}$ [%]	3.08	3.06	3.07	3.11	3.18	3.30	3.49	3.92	4.12	4.11	4.09	4.10	4.10	4.11	4.12	4.12	4.13	4.15	4.17	4.21	4.26	4.36	4.51	4.79	5.26
Refund Russia [tril. USD/a]	0.01	0.01	0.02	0.04	0.07	0.15	0.33	0.78	1.62	2.52	3.33	3.70	3.96	4.21	4.44	4.66	4.86	5.06	5.24	5.45	5.69	5.93	6.18	6.41	6.26
Refund Russia [% GDP]	0.24	0.36	0.58	0.99	1.76	3.31	6.53	14.04	27.07	38.10	44.89	44.44	42.75	41.12	39.55	38.03	36.57	35.16	33.80	32.74	31.98	31.33	30.71	30.02	27.72
$\lambda_{\mathrm{Eurasia}}$ [%]	3.42	3.41	3.42	3.46	3.55	3.68	3.89	4.25	4.63	4.64	4.62	4.63	4.63	4.64	4.65	4.65	4.67	4.68	4.70	4.74	4.81	4.91	5.09	5.40	5.93
Refund Eurasia [tril. USD/a]	0.01	0.01	0.02	0.04	0.08	0.17	0.37	0.85	1.83	2.84	3.76	4.18	4.48	4.75	5.01	5.26	5.49	5.71	5.91	6.14	6.41	6.69	6.97	7.22	7.06
Refund Eurasia [% GDP]	0.55	0.72	1.03	1.58	2.61	4.55	8.40	16.55	31.25	42.43	48.80	47.40	44.79	42.41	40.23	38.23	36.39	34.70	33.13	31.81	30.76	29.85	29.00	28.11	25.76
λ_{China} [%]	4.81	4.78	4.80	4.87	4.99	5.18	5.46	5.95	6.37	5.98	5.81	5.76	5.74	5.73	5.73	5.72	5.73	5.73	5.75	5.79	5.86	5.97	6.18	6.54	7.17
Refund China [tril. USD/a]	0.01	0.02	0.03	0.06	0.12	0.24	0.52	1.19	2.51	3.66	4.72	5.21	5.55	5.87	6.17	6.46	6.73	6.99	7.23	7.50	7.81	8.13	8.46	8.75	8.54
Refund China [% GDP]	0.07	0.09	0.13	0.21	0.35	0.63	1.18	2.35	4.45	5.74	6.50	6.39	6.11	5.85	5.59	5.36	5.14	4.93	4.74	4.57	4.44	4.33	4.22	4.11	3.78
λ_{India} [%]	6.15	6.13	6.16	6.26	6.42	6.68	7.04	7.48	7.91	8.59	8.90	8.91	8.94	8.97	9.00	9.03	9.06	9.09	9.14	9.21	9.35	9.57	9.93	10.55	11.60
Refund India [tril. USD/a]	0.01	0.02	0.04	0.07	0.15	0.31	0.67	1.49	3.12	5.26	7.24	8.06	8.64	9.19	9.70	10.19	10.65	11.08	11.48	11.93	12.47	13.03	13.60	14.12	13.81
Refund India [% GDP]	0.24	0.27	0.34	0.48	0.75	1.24	2.18	3.99	7.00	10.06	11.94	11.59	10.96	10.39	9.87	9.40	8.96	8.57	8.20	7.88	7.60	7.35	7.11	6.88	6.28
$\lambda_{\mathrm{MidEast}}$ [%]	5.42	5.40	5.43	5.51	5.65	5.87	6.19	6.57	6.97	7.73	7.80	7.77	7.77	7.76	7.75	7.75	7.75	7.75	7.77	7.81	7.91	8.08	8.37	8.87	9.74
Refund MidEast [tril. USD/a]	0.01	0.02	0.03	0.06	0.13	0.27	0.59	1.31	2.75	4.73	6.34	7.03	7.51	7.95	8.36	8.75	9.11	9.45	9.76	10.12	10.55	11.00	11.46	11.87	11.59
Refund MidEast [% GDP]	0.17	0.20	0.27	0.39	0.63	1.07	1.92	3.57	6.33	9.53	11.53	11.53	11.22	10.93	10.64	10.36	10.09	9.83	9.57	9.33	9.13	8.95	8.77	8.56	7.90
$\lambda_{\mathrm{Africa}}$ [%]	6.27	6.25	6.28	6.38	6.55	6.81	7.18	7.62	8.03	8.35	9.07	9.27	9.29	9.30	9.32	9.33	9.35	9.37	9.39	9.45	9.57	9.78	10.14	10.77	11.83
Refund Africa [tril. USD/a]	0.01	0.02	0.04	0.07	0.15	0.32	0.69	1.52	3.16	5.11	7.37	8.39	8.97	9.53	10.05	10.54	10.99	11.42	11.80	12.24	12.75	13.32	13.89	14.40	14.09
Refund Africa [% GDP]	0.45	0.47	0.54	0.69	0.99	1.57	2.62	4.56	7.58	10.21	12.80	12.83	12.22	11.67	11.17	10.71	10.29	9.92	9.57	9.26	8.99	8.71	8.45	8.17	7.46
λ_{LatAm} [%]	3.83	3.81	3.83	3.88	3.98	4.13	4.34	4.61	4.87	5.33	5.63	5.65	5.67	5.69	5.71	5.73	5.75	5.77	5.80	5.85	5.94	6.07	6.30	6.70	7.36
Refund LatAm [tril. USD/a]	0.01	0.01	0.02	0.05	0.09	0.19	0.42	0.92	1.92	3.26	4.58	5.11	5.48	5.83	6.16	6.47	6.76	7.04	7.29	7.57	7.92	8.27	8.63	8.96	8.77
Refund LatAm [% GDP]	0.10	0.12	0.17	0.25	0.41	0.72	1.32	2.51	4.57	6.81	8.49	8.41	8.12	7.84	7.58	7.33	7.10	6.87	6.65	6.45	6.29	6.14	5.99	5.84	5.37
λ_{OHI} [%]	23.07	23.15	23.06	22.78	22.26	21.45	20.28	18.64	16.87	15.48	14.45	14.21	14.12	14.04	13.96	13.89	13.81	13.71	13.58	13.37	13.02	12.44	11.48	9.84	7.06
Refund OHI [tril. USD/a]	0.04	0.07	0.14	0.27	0.51	1.00	1.94	3.72	6.65	9.47	11.75	12.85	13.64	14.38	15.06	15.68	16.24	16.71	17.06	17.31	17.35	16.94	15.72	13.16	8.40
Refund OHI [% GDP]	0.80	1.14	1.75	2.84	4.83	8.47	15.02	26.52	43.97	57.55	65.01	64.61	62.94	61.27	59.58	57.81	55.96	53.98	51.82	49.53	46.85	43.23	37.99	30.19	18.31
λ_{Other} [%]	30.21	30.33	30.21	29.83	29.14	28.07	26.51	24.33	22.01	21.21	21.45	21.62	21.67	21.72	21.76	21.78	21.77	21.72	21.60	21.36	20.88	20.03	18.56	15.96	11.48
Refund Other [tril. USD/a]	0.05	0.10	0.18	0.35	0.67	1.31	2.54	4.86	8.68	12.98	17.45	19.56	20.94	22.24	23.46	24.59	25.61	26.48	27.14	27.65	27.84	27.28	25.41	21.35	13.66
Refund Other [% GDP]	1.28	1.42	1.74	2.29	3.27	4.90	7.51	11.60	17.01	21.36	24.58	24.05	22.68	21.42	20.27	19.21	18.21	17.26	16.32	15.34	14.24	12.90	11.15	8.72	5.21

Table 2: Global refund per year in tril. USD and as share of world GDP, and refunding shares and refunds for all twelve world regions.

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