A Simple Model of Global Refunding and Climate Change

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Abstract

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1 Introduction

The threat of climate change to the well-being of future generations appears to be substantial (see, e.g., Goulder and Pizer (forthcoming), Stern (2006), Nordhaus (2006), Tol (2006)). Mitigating climate change, however, is a global public good as each country's efforts to control emissions will benefit all countries in a non-exclusive and non-rival manner. Countries therefore have an incentive to free-ride on other countries' efforts to reduce greenhouse gas emissions. The prisoner's dilemma aspect of mitigating climate change and the absence of a supranational authority makes an international coordination both crucial and exceptionally difficult to achieve. Countries may either lack the incentive to sign an agreement and benefit from the signatories' abatement efforts or may not have incentives not to comply with promises made in an agreement.

There is a considerable body of literature addressing the underprovision of international pollution control. At the practical level the Kyoto Protocol, as the first significant international effort to reduce greenhouse gas emissions, has been criticised for being ineffective (see, e.g., Böhringer and Vogt (2003), Nordhaus and Boyer (1999), **?**, McKibbin and Wilcoxen (2002), Barrett (2003)). As a consequence, various other approaches to international coordination have been suggested. Aldy et al. (2003) summarize the alternatives, which include an international carbon tax and international technology standards. Recently, Gersbach (2007) has proposed a further alternative for an international agreement by allowing each country to determine its own emission tax while aggregate tax revenues are partially refunded to members in proportion to the relative emission reduction they achieve within a period.

A considerable body of research has examined the formation of international environmental agreements using game theoretic models. The main focus of this literature is the conditions leading to coalition formation by signing a multiliteral agreement. Such agreemnets must be self-enforcing since there is no supranational authority to enforce compliance. Two types of models have been used: two-stage games (Carraro (2000), Carraro and Siniscalco (1993, 1998), Chander and Tulkens (1992), Finus et al. (2006), Hoel (1992)) and infinitely repeated games (Asheim et al. (2006), Barrett (1994, 1999, 2003)). The former literature has emphasized that either stable coalitions are small or the abatement level that can be sustained in larger coalitions is small. The latter literature focusses on renegotiation proof agreements and shows the the allocation of abatement burdens is crucial for the formation of agreements. Similarily to the two-stage game frameworks, it is unlikely that a grand coalition is formed or when it is formed it will achieve very little. Moreover, sub-coalitions may be better for its members than the grand coalition and regional agreements can Pareto dominate a regime based on a global treaty.

In this paper we examine the global refunding scheme (GRS) regarding to its potential for an international treaty. We consider a simple two-stage model, in which each country can freely set national abatement levels by choosing a national tax rate. Participation implies that and an initial payment and national abatement taxes are collected in a global fund, which is partially reimbursed in each period to member countries. Each country receives refunds in proportion to the relative emission reduction over the last period. The fraction of the fund which is not distributed to member countries is invested and earns profits, which create a growing incentive for member countries to comply with the agreement and to stay in the GRS.

2 Model World

We consider a world which lasts over two periods, $t = 1$ and $t = 2$. In this world there are n identical countries. The countries are is characterized by identical emission functions E, identical cost functions C and identical damage functions D.

Emissions of country i in period t are assumed to be a strictly decreasing linear function of emission taxes τ_t^i. No emission tax results in baseline emissions $\bar{e}$:

$$E = E(\tau_t^i) = \bar{e} - \epsilon\tau_t^i \ , \quad \text{with} \quad \epsilon > 0 \ , \quad i = 1, \ldots, n \ , \quad t = 1, 2 \ . \tag{1}$$

We further assume that positive emission taxes τ^i (and, thus, positive emission reductions compared to the baseline emissions) induce strictly increasing and convex abatement costs:

$$C = C(\tau_t^i) = \frac{\phi}{2}\left(\tau_t^i\right)^2 \ , \quad \text{with} \quad \phi > 0 \ , \quad i = 1, \ldots, n \ , \quad t = 1, 2 \ . \tag{2}$$

Global emissions, which are the sum of emissions of all countries, in period t accumulate the stock of greenhouse gases, s_t, according to the following equation of motion

$$s_t = (1-\gamma)s_{t-1} + \sum_{i=1}^{n} E(\tau_t^i) \ , \quad \text{with} \quad \gamma > 0 \ , \quad t = 1, 2 \ , \tag{3}$$

where γ denotes the constant and positive natural decay rate of greenhouse gases in the atmosphere.[1] The initial stock of greenhouse gases is denoted by s_0. Without loss of generality we assume that $s_0 = 0$. This simplifies further calculations without impacting qualitatively on our results.

The global stock of greenhouse gases in period t, s_t, gives rise to strictly increasing and strict convex damage, which is identical in all countries:

$$D = D(s_t) = \frac{\beta}{2} s_t^2 \ , \quad \text{with} \quad \beta > 0 \ , \quad t = 1, 2 \ . \tag{4}$$

Each country is assumed to set τ_t^i in each period such as to minimize the present value of total costs, given that all other countries act accordingly. Thus, we seek the Nash equilibria of the two stage abatement game all countries play against each other. Countries are assumed to discount outcomes in period $t = 2$ with the discount factor $\delta < 1$.

3 Social Optimum and Nash Equilibrium without Global Refunding

Before we introduce the global refunding scheme (GRS) in the next section, we investigate the global social optimum and the Nash equilibrium without an international agreement. As is well known from the literature, the latter is inefficient because the emissions of each individual country induce externalities on all other countries, which the individual countries do not take into account while choosing their emission taxes.

Both outcomes, the global social optimum and the Nash equilibrium are important baseline scenarios for any potential international agreement. Obviously, any agreement to be seriously considered has to outperform the Nash equilibrium. Moreover, an agreement is the "better" the closer its outcome resembles the global social optimum.

3.1 Global Social Optimum

Consider a global social planer who seeks to minimize the net present value of *global* costs of emission abatement and the sum of national damages stemming from green-

[1] Note that emissions accumulate the stock of greenhouse gases instantaneously. This is a useful assumption as we only consider two priods of time.

house gas emissions. That is

$$\min_{\{\tau_1^i\}_{i=1}^n,\{\tau_2^i\}_{i=1}^n} \sum_{t=1}^{2} \delta^{t-1} \left[\sum_{j=1}^{n} \frac{\phi}{2} (\tau_t^j)^2 + n\frac{\beta}{2} s_t^2 \right] \ , \tag{5}$$

subject to equation (3).

The corresponding Lagrangian yields:

$$\mathcal{L} = \sum_{t=1}^{2} \left\{ \delta^{t-1} \left[\sum_{j=1}^{n} \frac{\phi}{2} (\tau_t^j)^2 + n\frac{\beta}{2} s_t^2 \right] + \lambda_t^{GO} \left[(1-\gamma) s_{t-1} + \sum_{j=1}^{n} \left(\bar{e} - \epsilon \tau_t^j \right) - s_t \right] \right\} \ , \tag{6}$$

where λ_t^G denotes the Langrange multiplier or shadow price for the global stock of greenhouse gases in period t. The first order condition for an optimal solution are

$$\frac{\partial \mathcal{L}}{\partial \tau_t^i} \ = \ \phi \tau_t^i \delta^{t-1} - \epsilon \lambda_t^{GO} \ = \ 0 \ , \quad i = 1, \ldots, n \ , \ t = 1, 2 \ , \tag{7a}$$

$$\frac{\partial \mathcal{L}}{\partial s_t} \ = \ n\beta s_t \delta^{t-1} + (1-\gamma)\lambda_{t+1}^{GO} - \lambda_t^{GO} \ = \ 0 \ , \quad t = 1, 2 \ , \tag{7b}$$

where $\lambda_3^{GO} = 0$. These necessary conditions are also sufficient for a unique solution due to the strict convexity of the Lagrangian. Equation (7b) can be solved by backward induction to yield:

$$\lambda_t^{GO} = n\beta \sum_{k=t}^{2} \delta^{k-1} (1-\gamma)^{k-t} s_k \ , \quad t = 1, 2 \ . \tag{8}$$

Note that λ_t^{GO} equals the net present value of all *global* future damages stemming from a marginal unit of emissions in period t. Now, the interpretation of equation (7a) is straightforward. In the optimum, the costs incurred by a marginal increase of the emission tax τ_t^i equal the net present value of all avoided global future damages from the emissions abatet by the marginal increase of the emission tax.

Inserting equation (8) into the equation (7a) yields the $2n$ necessary and sufficient conditions for the $2n$ emission taxes τ_t^i for a global social optimum:

$$\phi \tau_t^i = n\epsilon\beta\delta^{1-t} \sum_{k=t}^{2} \delta^{k-1} (1-\gamma)^{k-t} s_k \ , \quad i = 1, \ldots, n \ , \ t = 1, 2 \ . \tag{9}$$

For fixed t, the right hand side of equation (9) is identical for any $i = 1, \ldots, n$. As a consequence, all countries set the same emission taxes τ_t in the global social optimum.

Inserting equation (3), yields a system of 2 linear equations for the optimal emission taxes $\tau_1^\star$ and $\tau_2^\star$:

$$\begin{aligned}
\tau_1^\star &= n^2\epsilon\beta\bar{e}\frac{\phi\big[1+\delta(1-\gamma)(2-\gamma)\big]+n^2\epsilon^2\beta}{(\phi+n^2\epsilon^2\beta)^2+\phi n^2\epsilon^2\beta\delta(1-\gamma)^2}\ , && \text{(10a)}\\
\tau_2^\star &= n^2\epsilon\beta\bar{e}\frac{\phi(2-\gamma)+n^2\epsilon^2\beta}{(\phi+n^2\epsilon^2\beta)^2+\phi n^2\epsilon^2\beta\delta(1-\gamma)^2}\ . && \text{(10b)}
\end{aligned}$$

Inserting $\tau_1^\star$ and $\tau_2^\star$ into the equation of motion for the greenhouse gas stock (3),we derive for the optimal stocks $s_1^\star$ and $s_2^\star$:

$$\begin{aligned}
s_1^\star &= n\phi\bar{e}\frac{\phi+n^2\epsilon^2\beta\big[1-\delta(1-\gamma)\big]}{(\phi+n^2\epsilon^2\beta)^2+\phi n^2\epsilon^2\beta\delta(1-\gamma)^2}\ , && \text{(11a)}\\
s_2^\star &= n\phi\bar{e}\frac{\phi(2-\gamma)+n^2\epsilon^2\beta}{(\phi+n^2\epsilon^2\beta)^2+\phi n^2\epsilon^2\beta\delta(1-\gamma)^2}\ . && \text{(11b)}
\end{aligned}$$

3.2 Nash Equilibrium

Now, consider a local planer for each country (e.g., government), who seeks to minimize *local* costs and damages given that all other countries act accordingly. Thus, one obtains the following optimization problem for country i:

$$\min_{\tau_1^i,\tau_2^i}\sum_{t=1}^{2}\delta^{t-1}\left[\frac{\phi}{2}(\tau_t^i)^2+\frac{\beta}{2}s_t^2\right]\ , \tag{12}$$

subject to equation (3).

Thus, the corresponding Lagrangian yields:

$$\mathcal{L}=\sum_{t=1}^{2}\left\{\delta^{t-1}\left[\frac{\phi}{2}(\tau_t^i)^2+\frac{\beta}{2}s_t^2\right]+\lambda_t^{NE}\left[(1-\gamma)s_t+\sum_{j=1}^{n}(\bar{e}-\epsilon\tau_t^j)-s_{t+1}\right]\right\}\ . \tag{13}$$

Again, λ_t^{NE} denotes the Lagrange multiplier or shadow price of the stock of greenhouse gases in period t. Hence, we derive the following necessary conditions

$$\begin{aligned}
\frac{\partial\mathcal{L}}{\partial\tau_t^i} &= \phi\tau_t^i\delta^{t-1}-\epsilon\lambda_t^{NE} = 0\ , \quad t=1,2\ , && \text{(14a)}\\
\frac{\partial\mathcal{L}}{\partial s_t} &= \beta s_t\delta^{t-1}+(1-\gamma)\lambda_{t+1}^{NE}-\lambda_t^{NE} = 0, \quad t=1,2\ , && \text{(14b)}
\end{aligned}$$

with $\lambda_3^{NE}=0$. Analogously to section 3.1, these necessary conditions are also sufficient for a unique solution due to the strict convexity of the Lagrangian. By backward induction we obtain the following formula for the shadow price λ_t^{NE}:

$$\lambda_t^{NE} = \beta \sum_{k=t}^{2} \delta^{k-1}(1-\gamma)^{k-t} s_k \ , \quad t = 1, 2 \ . \tag{15}$$

Inserting equation (15) into the equation (14a) yields the 2 necessary and sufficient conditions for the emission taxes τ_t^i for a local optimum of country i, given the emission taxes τ_t^j of all other countries:

$$\phi\tau_t^i = \epsilon\beta\delta^{1-t} \sum_{k=t}^{2} \delta^{k-1}(1-\gamma)^{k-t} s_k \ , \quad t = 1, 2 \ . \tag{16}$$

The set of the necessary and sufficient conditions (16) for all countries i uniquely determines the Nash equilibrium. Again, the right hand side is identical for all countries i. As a consequence, in the Nash equilibrium all countries set the same emission taxes $\hat{\tau}_t$. We derive for the emssion taxes $\hat{\tau}_1$ and $\hat{\tau}_2$

$$\hat{\tau}_1 \;=\; n\epsilon\beta\bar{e}\frac{\phi\big[1+\delta(1-\gamma)(2-\gamma)\big]+n\epsilon^2\beta}{(\phi+n\epsilon^2\beta)^2+\phi n\epsilon^2\beta\delta(1-\gamma)^2} \ , \tag{17a}$$

$$\hat{\tau}_2 \;=\; n\epsilon\beta\bar{e}\frac{\phi(2-\gamma)+n\epsilon^2\beta}{(\phi+n\epsilon^2\beta)^2+\phi n\epsilon^2\beta\delta(1-\gamma)^2} \ . \tag{17b}$$

and for the stocks $\hat{s}_1$ and $\hat{s}_2$:

$$\hat{s}_1 \;=\; n\phi\bar{e}\frac{\phi+n\epsilon^2\beta\big[1-\delta(1-\gamma)\big]}{(\phi+n\epsilon^2\beta)^2+\phi n\epsilon^2\beta\delta(1-\gamma)^2} \ , \tag{18a}$$

$$\hat{s}_2 \;=\; n\phi\bar{e}\frac{\phi(2-\gamma)+n\epsilon^2\beta}{(\phi+n\epsilon^2\beta)^2+\phi n\epsilon^2\beta\delta(1-\gamma)^2} \ . \tag{18b}$$

From equation (15) we see that in the Nash equilibrium the shadow price for the stock of greenhouse gases, λ_t^{NE}, only accounts for *local* damages. In fact, abating emissions in country i induces a positive externality for all other countries $j \neq i$, as it reduces the global stock of greenhouse gases and, thus, the damages in all countries. In the Nash equilibrium these positive externalities are not taken into account. As a consequence, the shadow price in the Nash equilibrium is lower than in the global social optimum. Accordingly, optimal abatement (respectively emission tax) is higher in the global social optimum.[2]

[2]This result is well known from public economics. The public good *emission reduction* is provided in suboptimal amount, because the producer (country i) is not sufficiently compensated by the consumers (countries $i \neq j$) of the public good.

4 Global Refunding Scheme

Instead of playing the Nash equilibrium as outlined in section 3.2, countries can choose to participate in a golbal refunding scheme (GRS). Members are free to choose national emission taxes τ_t^i but agree to pay an initial fee to a global fund. In addition, the emission tax revenues of all countries in all periods are collected in the fund, too. In each period t, a central agency decides about the fraction $(1 - \alpha_t)$ of the fund's assets which is invested and earns interest ρ per period. The remaining fraction α_t is reimbursed to the participating countries.

In the following, we analyze the capability for a GRS to overcome the prisoner's dilemma structure of mitigating climate change. First, we explain the rules and the timing of payments and refunds in detail. Second, we show that given that all countries sign the treaty and all countries comply with the agreement, a central agency can choose parameters such that the global social optimum is achieved. Third, we show that the GRS is self-enforcing in the sense that, given that all countries have signed the agreement in the first period, all countries comply with the GRS in the second period.

4.1 Rules and timing of the GRS

The timing of the GRS is illustrated in figure 1. At the beginning of period $t = 1$ countries decide whether to sign the GRS or not. Then, the central agency (CA) anounces the identical initial payments i_0 for all participating countries, which are transferred to a global fund f_1. It also announces the fractions α_1 and α_2 of the funds, which are reimbursed to the member countries in periods $t = 1$ and $t = 2$, and the baseline emissions Θ_1 and Θ_2, which have to be undercut by member countries to be eligible for a refund. Given this information, countries choose national emission taxes and participating countries transfer national emission tax revenues to the global fund f_1. At the end of period $t = 1$ the CA reimburses the fraction α_1 of the fund f_1 to member countries. Each member country recieves a share in proportion to the relative greenhouse gas reductions compared to the baseline emissions Θ_1. The remaining fund earns interest ρ and is transferred to the next period's fund f_2.

At the beginning of period $t = 2$ member countries decide if they leave the GRS, in which case the loose any claims on payments from the global fund. In case countries leave the GRS, the CA may announce an updated refund fraction α_2 and baseline

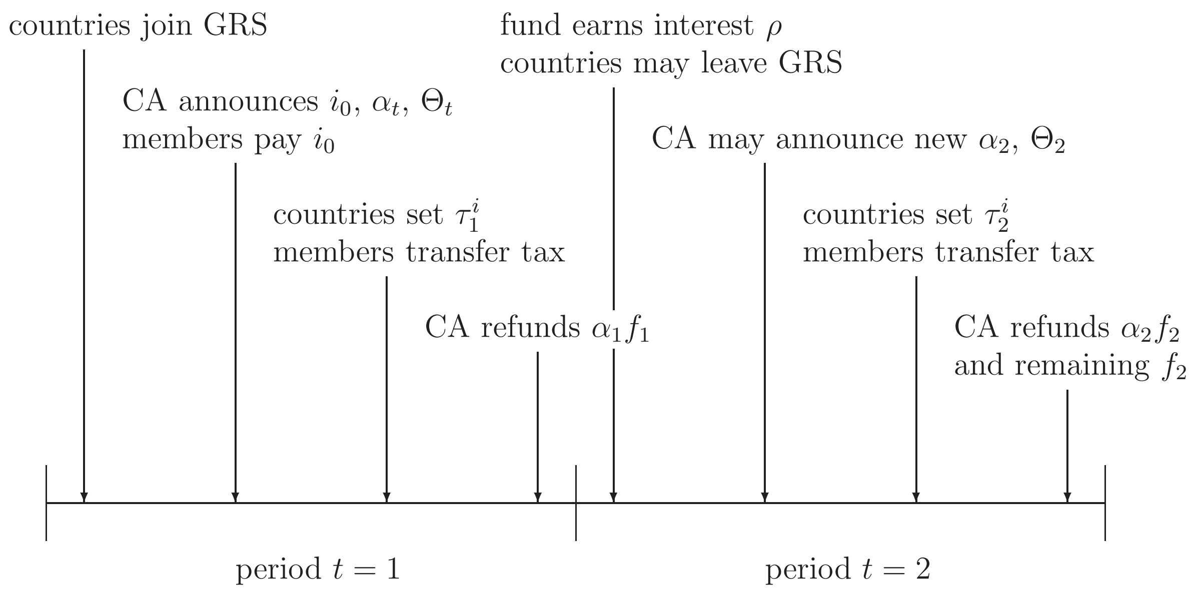

Figure 1: An illustration of the timing of the global refunding scheme.

emission Θ_2. Again, all countries set national emission tax levels and member countries transfer emission tax revenues to the global fund. At the end of period $t = 2$ the CA refunds the fraction α_2 to the member countries according to the refunding rule. In case that $\alpha_2 < 1$, the remaining fund f_2 is equally among the member countries by a lump-sum transfer.

Formally, the refund r_t^i, which a member country i receives in period t, equals

$$r_t^i = \max\left[\alpha_t f_t \frac{\Theta_t - (\bar{e} - \epsilon\tau_t^i)}{\sum_{j\in GRS}^{n}\left[\Theta_t - (\bar{e} - \epsilon\tau_t^j)\right]}, 0\right] \ , \quad t = 1, 2 \ , \tag{19}$$

where α_t is the fraction of the fund f_t which is refunded in period t. The assets of the fund f_t at the end of period t before repayments are made is given by:

$$f_1 = f_0 + \sum_{i\in GRS} \tau_1^i(\bar{e} - \epsilon\tau_1^i) \ , \tag{20a}$$

$$f_2 = (1+\rho)(1-\alpha_1)f_1 + \sum_{i\in GRS} \tau_2^i(\bar{e} - \epsilon\tau_2^i) \ , \tag{20b}$$

where f_0 is the sum of all initial payments of all member countries. We assume the interest rate ρ to correspond to the disount factor δ, i.e.:

$$\rho = \frac{1}{\delta} - 1 \ . \tag{21}$$

In the following we investigate the incentives to reduce greenhouse gas emissions created by the GRS in detail.

4.2 Full Participation Outcome

In a first step, we assume that all countries join the GRS in period $t = 1$ and all countries decide to stay in the GRS in period $t = 2$. We will call this the full participation assumption. Given this assumption, we derive the necessary and sufficient conditions for the optimal emission taxes τ_t^i. In addition, we show that under this assumption the CA can always announce initial payments i_0, distribution fractions α_1 and α_2 and baseline emissions Θ_1 and Θ_2, such that the global social optimum is achieved. For a more convenient presentation, we assume that $r_t^i > 0$ for all countries i and periods t and verify this assumption ex post. Thus, given that all countries i participate in the global refunding system, each country i solves the following optimization problem:

$$\min_{\tau_1^i,\tau_2^i} \sum_{t=1}^{2} \delta^{t-1} \left[\frac{\phi}{2}(\tau_t^i)^2 + \frac{\beta}{2}s_t^2 + \tau_t^i(\bar{e} - \epsilon\tau_t^i) - \alpha_t f_t \frac{\Theta_t - (\bar{e} - \epsilon\tau_t^i)}{\sum_{j=1}^n \left[\Theta_t - (\bar{e} - \epsilon\tau_t^j)\right]} \right] \tag{22}$$

subject to equations (3) and (20).

This implies the following Lagragian

$$\begin{aligned} \mathcal{L} \;=\; & \sum_{t=1}^{2} \Bigg\{ \delta^{t-1} \left[\frac{\phi}{2}(\tau_t^i)^2 + \frac{\beta}{2}s_t^2 + \tau_t^i(\bar{e} - \epsilon\tau_t^i) - \alpha_t f_t \frac{\Theta_t - (\bar{e} - \epsilon\tau_t^i)}{\sum_{j=1}^n \left[\Theta_t - (\bar{e} - \epsilon\tau_t^j)\right]} \right] \\ & + \lambda_t^{GRS} \left[(1-\gamma)s_{t-1} + \sum_{j=1}^{n} (\bar{e} - \epsilon\tau_t^j) - s_t \right] \Bigg\} \\ & + \mu_1^{GRS} \left[f_0 + \sum_{j=1}^{n} \tau_1^j(\bar{e} - \epsilon\tau_1^j) - f_1 \right] \\ & + \mu_2^{GRS} \left[\frac{(1-\alpha_1)}{\delta} f_1 + \sum_{j=1}^{n} \tau_2^j(\bar{e} - \epsilon\tau_2^j) - f_2 \right] , \end{aligned} \tag{23}$$

where λ_t^{GRS} and μ_t^{GRS} denote the Lagrange multipliers or shadow prices of the stock of grenhouse gases s_t and the fund f_t.

The necessary conditions for an optimal solution are:

$$
\begin{aligned}
\frac{\partial \mathcal{L}}{\partial \tau_t^i} &= \delta^{t-1}\left[\phi\tau_t^i + (\bar{e}-2\epsilon\tau_t^i) - \epsilon\alpha_t f_t \frac{\sum_{j\neq i}\left[\Theta_t - (\bar{e}-\epsilon\tau_t^j)\right]}{\left\{\sum_{j=1}^n\left[\Theta_t - (\bar{e}-\epsilon\tau_t^j)\right]\right\}^2}\right] && \text{(24a)}\\
&\quad - \epsilon\lambda_t^{GRS} + (\bar{e}-2\epsilon\tau_t^i)\mu_t^{GRS} \;=\; 0\;, \quad t=1,2\;, \\
\frac{\partial \mathcal{L}}{\partial s_t} &= \beta s_t\delta^{t-1} + (1-\gamma)\lambda_{t+1}^{GRS} - \lambda_t^{GRS} \;=\; 0\;, \quad t=1,2\;, && \text{(24b)}\\
\frac{\partial \mathcal{L}}{\partial f_t} &= -\alpha_t\delta^{t-1}\frac{\Theta_t - (\bar{e}-\epsilon\tau_t^i)}{\sum_{j=1}^n\left[\Theta_t - (\bar{e}-\epsilon\tau_t^j)\right]} + \frac{1-\alpha_t}{\delta}\mu_{t+1}^{GRS} && \text{(24c)}\\
&\quad - \mu_t^{GRS} \;=\; 0\;, \quad t=1,2\;,
\end{aligned}
$$

with $\lambda_3^{GRS}=0$ and $\mu_3^{GRS}=0$. In the case that the Lagrangian is strictly convex at least along the optimal path[3], these necessary conditions are also sufficient for a unique solution. By backward induction, we obtain the following formulae for the shadow prices λ_t^{GRS} and μ^{GRS}:

$$
\begin{aligned}
\lambda_t^{GRS} &= \beta\sum_{k=t}^{2}\delta^{k-1}(1-\gamma)^{k-t}s_k\;, \quad t=1,2\;, && \text{(25)}\\
\mu_t^{GRS} &= -\sum_{k=t}^{2}\alpha_k\delta^{k-1}\left(\frac{1-\alpha_k}{\delta}\right)^{k-t}\frac{\Theta_t-(\bar{e}-\epsilon\tau_t^i)}{\sum_{j=1}^n\left[\Theta_k-(\bar{e}-\epsilon\tau_k^j)\right]}\;, \quad t=1,2\;. && \text{(26)}
\end{aligned}
$$

Inserting equations (25) and (26) into condition (24a) yields the following 2 necessary and sufficient conditions for country i:

$$
\begin{aligned}
\phi\tau_t^i &= -(\bar{e}-2\epsilon\tau_t^i)\left[1-\sum_{k=t}^{2}\alpha_k(1-\alpha_k)^{k-t}\frac{\Theta_t-(\bar{e}-\epsilon\tau_t^i)}{\sum_{j=1}^n\left[\Theta_k-(\bar{e}-\epsilon\tau_k^j)\right]}\right] && \text{(27)}\\
&\quad + \epsilon\beta\sum_{k=t}^{2}\left[\delta(1-\gamma)\right]^{k-t}s_k + \epsilon\alpha_t f_t\frac{\sum_{j\neq i}\left[\Theta_t-(\bar{e}-\epsilon\tau_t^j)\right]}{\left\{\sum_{j=1}^n\left[\Theta_t-(\bar{e}-\epsilon\tau_t^j)\right]\right\}^2}\;, \quad t=1,2\;.
\end{aligned}
$$

As all n countries are identical we only consider symmetric equilibria. Thus, all countries set the same emission taxes, i.e., $\tau_t^i=\tau_t\;\forall\, i$. Then, equations (27) reduces to:

$$
\begin{aligned}
\phi\tau_t &= -(\bar{e}-2\epsilon\tau_t^i)\left[1-\sum_{k=t}^{2}\frac{\alpha_k}{n}(1-\alpha_k)^{k-t}\right] + \epsilon\beta\sum_{k=t}^{2}\left[\delta(1-\gamma)^{k-t}\right]s_k && \text{(28)}\\
&\quad + \frac{(n-1)\epsilon\alpha_t f_t}{n^2\left[\Theta_t-(\bar{e}-\epsilon\tau_t)\right]}\;, \quad t=1,2\;.
\end{aligned}
$$

[3]Convexity of the Lagrangian hinges in particular on the value of the exogenous parameter ϵ and the values of the baseline emissions Θ_t. In fact, for any given ϵ it is possible to find Θ_t high enough for the Lagrangian to be strictly convex.

By inserting s_t and f_t we derive a system of two quadratic equations in τ_1 and τ_2, which is (at least in principle) solvable.

However, we are more interested in the question how the central agency has to set the parameters f_0, α_t and Θ_t in order to achieve the global social optimum as derived in section 3.1. If we insert $\tau_1^\star$ and $\tau_2^\star$ into equations (28) and take into account that equation (9) hold in the global social optimum, we derive

$$\frac{n-1}{n}\phi\tau_t^\star = (2\epsilon\tau_t^\star - \bar{e})\left[1 - \sum_{k=t}^{2}\frac{\alpha_k}{n}(1-\alpha_k)^{k-t}\right] + \frac{(n-1)\epsilon\alpha_t f_t}{n^2\left[\Theta_t - (\bar{e} - \epsilon\tau_t^\star)\right]}\,, \quad t = 1, 2\,, \tag{29}$$

which is an overdetermined system of equations as we have only 2 equations for 5 unknown variables. This implies that the central agency has some degree of freedom how to implement the global social optimum. In fact, we will assume that $\alpha_2 = 1$, which implies no lump-sum transfers at the end of period $t = 2$. Thus, we determine the values of f_0 and α_1 dependend on the baseline emissions Θ_1 and Θ_2. This additional degree of freedom will become important in the next section, when we consider under what conditions no country has an incentive to leave the agreement at the beginning of period $t = 2$.

5 Numerical Example

6 Discussion

7 Conclusion

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