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ABSTRACT

International Emission Permit Markets with Refunding*

We propose a blueprint for an international emission permit market such as the EU trading scheme. Each country decides on the amount of permits it wants to offer. A fraction of these permits is grandfathered, the remainder is auctioned. Revenues from the auction are collected in a global fund and reimbursed to member countries in fixed proportions. We show that international permit markets with refunding lead to outcomes in which all countries tighten the issuance of permits and are better off compared to standard international permit markets. If the share of grandfathered permits is sufficiently small, we obtain approximately socially optimal emission reductions.

JEL Classification: H23, H41 and Q54
Keywords: climate change mitigation, global refunding scheme, international agreements, international permit markets and tradeable permits

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1 Introduction

Since 2005 the EU has been operating a greenhouse gas emission trading system among its member countries that involves large energy-intensive industries. It is expected that the emission trading system will be progressively broadened and also that emission permits will be auctioned to some degree.[1] The key issue in such an international trading system for emission allowances is to motivate member countries to reduce the amount of permits granted to domestic firms, thus causing them to abate more. As has been observed for the EU trading system, countries tend to issue permits generously to their domestic industries, often following business-as-usual scenarios (see, e.g., Carbone et al. 2008).

In this paper we propose a simple blueprint for an emission trading scheme with refunding that provides countries with incentives to considerably tighten the issuance of permits compared to a decentralized solution. The scheme works as follows: Member countries can participate in an international emission permit market operated by an administering central agency (henceforth CA). Each country decides individually how many emission permits it wants to offer. Some fraction of these permits is grandfathered to domestic firms, the rest is auctioned by the CA. The central idea of the refunding scheme is that revenues from the auction are collected in a global fund and (partly) reimbursed to participating countries. Each country receives a fixed share of total reimbursements per period The share is negotiated before the global refunding scheme starts operating.

Refunding of auctioned permits greatly reduces the incentives of governments to issue excessively generous permits to domestic producers. Without refunding, the issuance of a larger amount of permits creates large benefits, as domestic producers have to buy fewer permits or additional revenues are generated from the sale of permits. The associated increase of environmental damages caused by lower permit prices are shared among all countries. With refunding, the benefits accruing to a country by increasing the amount of permits are greatly reduced, as each country only receives a fixed share of the revenues from the total amount of auctioned permits. Environmental damages increase in the same way as without refunding. This produces incentives for all countries to tighten the issuance of emission permits.

[1] Detailed discussions and assessments of the European Greenhouse Gas Emission Trading System can be found in Sterner and Müller (2008) and Böhringer et al. (2005).

We develop a simple multi-period model of international permit markets with refunding as described above. Our main analytical results are as follows: We show that there exists a unique subgame perfect Nash equilibrium in the game, in which countries choose the schedule of permit issuance across all periods and the CA administers the auction of permits and the refunding of auctioning revenues. In equilibrium, all countries are better off compared to an international permit market without refunding. If the amount of grandfathered permits tends to zero then the equilibrium tends to the global social optimum.

The scheme we propose may help to ease political constraints. In particular, allowing for a mixture of auctioned and grandfathered permits balances the need to tighten emission caps and the desire of countries not to put domestic firms at a disadvantage over and against their foreign competitors. If these competitors are headquartered in countries that do not participate in the trading scheme, the fear is often particularly strong that a country doing its bit for the environment will lose investments and jobs.[2] Our proposed scheme might help to reduce this fear, as it can be designed in a way that makes all participating countries better off.

The paper is organized as follows: We start by relating our paper to the literature in Section 2. In Section 3 we introduce the global economy and international permit markets. In Section 4 we derive the socially optimal and decentralized solutions, which are the benchmarks for the analysis of the permit trading scheme with refunding, introduced in Section 5. In Sections 6 and 7 we show that the permit trading scheme with refunding can always implement a Pareto improvement compared to the decentralized solution and that, in particular cases, the social global optimum is achievable. In Section 8 we discuss some of our model assumptions. Section 9 concludes.

2 Relation to the Literature

Our paper draws on three strands of literature. First, there is a large body of literature addressing the underprovision of international pollution control. At the practical level, the Kyoto Protocol – the first significant international effort to reduce greenhouse gas emissions – has been criticized as ineffective (see, e.g., Böhringer and Vogt 2003,

[2]Politicians have proposed imposing a "carbon tariff" on imports from countries that do not participate in international treaties on climate change in order to shelter domestic industries (see Economist 2008).

Nordhaus and Boyer 1999, Schelling 2002, McKibbin and Wilcoxen 2002, and Barrett 2003). As a consequence, various other approaches to international coordination have been suggested. Aldy et al. (2003) summarize these alternatives, which include an international carbon tax and international technology standards.

Second, ever since Montgomery (1972) showed that initial permit allocation schemes may be irrelevant for emission abatement, there has been an ongoing debate about whether free allocation of permits (grandfathering) or auctioning of permits is the superior form of permit allocation (see Requate 2005 and MacKenzie 2008 for surveys of this literature). We suggest that a mixture of grandfathered and auctioned permits, coupled with refunding, can provide appropriate incentives for countries to choose caps in an international climate agreement.

Third, our investigation is part of a recent body of literature on international emission trading. Chichilnisky et al. (2000) show that emission markets will allocate resources efficiently if and only if international transfers are made in order to equalize social marginal utilities of consumption. Caplan et al. (2003) show that efficient allocation obtains when autonomous regional governments choose their own emission levels in anticipation of interregional resource transfers operated by an altruistic international agency. Without international transfers permit trade can still yield substantial emissions reductions, as countries take account of the fact that they influence permit prices when they select their abatement target (Helm 2003) and general equilibrium feedback effects, such as carbon leakages and trade spillovers, may alter a country's incentive to restrict its own emissions (Carbone et al. 2008). We design an international scheme for controlling global pollution in which revenues from auctioning permits are collected and redistributed to member countries in fixed proportions.

3 The Model

We consider a dynamic model of a global economy with pollutive emissions consisting of n countries indexed by $i = 1, \ldots, n$. Time spans $T < \infty$ periods indexed by $t = 1, \ldots, T$.

3.1 The economy

Emissions of country i in period t are assumed to equal business-as-usual emissions e^i, i.e., the emissions arising when no abatement effort is undertaken minus emission abatement a^i:

$$E^i(a^i_t) = e^i - a^i_t \ , \quad a^i_t \in [0, e^i] \ , \quad i = 1, \dots, n \ , \quad t = 1, \dots, T \ . \tag{1}$$

We assume these emissions are caused by a representative firm in each country which faces convex abatement costs:[3]

$$C^i(a^i_t) = \frac{1}{2\phi_i} \left(a^i_t\right)^2 \ , \quad \phi_i > 0 \ , \quad i = 1, \dots, n \ , \quad t = 1, \dots, T \ . \tag{2}$$

Countries may differ in their abatement cost parameters ϕ_i. For ease of presentation, we introduce the abbreviations Φ for the sum of the abatement cost parameters and $\mathcal{E}$ for the sum of business-as-usual emissions:

$$\Phi = \sum_{i=1}^{n} \phi_i \ , \qquad \mathcal{E} = \sum_{i=1}^{n} e^i \ . \tag{3}$$

In period t, global emissions, which are the sum of the emissions of all countries, increase a pollution stock, s_t, according to the following equation of motion:

$$s_t = (1 - \gamma) s_{t-1} + \sum_{i=1}^{n} E^i(a^i_t) \ , \quad \gamma \in [0, 1] \ , \quad t = 1, \dots, T \ , \tag{4}$$

where γ denotes the constant decay rate of the pollution stock. The emissions accumulate the pollution stock instantaneously. The polar case $\gamma = 1$ represents the pure flow pollutant problem.

The pollution stock s_t causes strictly increasing and strictly convex damages for each country i:

$$D^i(s_t) = \frac{\beta_i}{2} s_t^2 \ , \quad \beta_i > 0 \ , \quad i = 1, \dots, n \ , \quad t = 1, \dots, T \ . \tag{5}$$

Countries may differ in their damage parameters β_i. For later use, we introduce the abbreviations $\mathcal{B}$ for the sum of the damage parameters and $\bar{\beta}$ for their average:

$$\mathcal{B} = \sum_{i=1}^{n} \beta_i \ , \qquad \bar{\beta} = \mathcal{B}/n \ . \tag{6}$$

Finally, countries are assumed to discount outcomes in period t with the discount factor δ^{t-1} where $\delta \leq 1$.

[3] This is a standard short cut for capturing the aggregate abatement costs of a country (see, e.g., Falk and Mendelsohn 1993).

3.2 International permit markets

All countries have access to an international permit market where emission permits valid for one period are traded. In each period, all countries individually decide about the amount of emission permits, $e^i - \epsilon_t^i$, they issue. Here ϵ_t^i denotes the reduction in emission permits of country i in period t compared to the business-as-usual emissions e^i. Of these permits the fraction $\mu \in [0, 1)$ is grandfathered to the representative firm.[4] We impose that $\epsilon_t^i \geq 0$ for all $i = 1, \dots, n$ and $t = 1, \dots, T$. Thus countries are not allowed to issue more permits than the business-as-usual emissions. We note that ϵ_t^i may exceed e^i, which means that a country reduces the amount of permits in the world by buying permits higher than the emissions produced.

Firms in all countries need (at least) emission permits amounting to net emissions $e^i - a_t^i$ per period. As firms receive the grandfathered emission permits of their country, country i offers emission permits amounting to $e^i - a_t^i - \mu(e^i - \epsilon_t^i)$ in the market. All permits are traded on the international permit market at price p_t in each period. We denote the total amount of non-grandfathered emission permits per period by $\mathcal{P}_t = \sum_{i=1}^n (1 - \mu)(e^i - \epsilon_t^i)$. Cost-minimizing behavior of the representative firm in each country implies that marginal abatement costs equal the permit price:

$$p_t = \frac{a_t^i}{\phi_i} \qquad \Rightarrow \qquad a_t^i = \phi_i p_t \ , \quad i = 1, \dots, n \ , \quad t = 1, \dots, T \ . \tag{7}$$

A market equilibrium on the permit market requires

$$\sum_{i=1}^n e^i - \epsilon_t^i = \sum_{i=1}^n e^i - a_t^i = \sum_{i=1}^n e^i - \phi_i p_t \ , \quad t = 1, \dots, T \ , \tag{8}$$

which implies

$$p_t = \frac{\sum_{i=1}^n \epsilon_t^i}{\Phi} \ , \quad t = 1, \dots, T \ . \tag{9}$$

Equation (9) allows us to express emissions E^i, abatement costs C^i, and the pollution stocks s_t in terms of the permit price p_t:

$$E^i(p_t) = e^i - \phi_i p_t \ , \quad i = 1, \dots, n \ , \quad t = 1, \dots, T \ , \tag{10}$$

$$C^i(p_t) = \frac{\phi_i}{2} p_t^2 \ , \quad i = 1, \dots, n \ , \quad t = 1, \dots, T \ , \tag{11}$$

$$s_t(p_t) = (1 - \gamma) s_{t-1} + \mathcal{E} - \Phi p_t \ , \quad t = 1, \dots, T \ . \tag{12}$$

[4] As is well known from the literature (see Montgomery 1972), the fraction μ has no effect on the equilibrium permit price and the permit allocation in the decentralized solution, as discussed in Section 4.2. However, μ influences both the permit price and the permit allocation in the case of a refunding scheme. We shall discuss this point in Sections 6 and 7.

4 Social Optimum and Decentralization

In this section we characterize the global social optimum and the decentralized solution, which will serve as benchmarks for the discussion of the permit markets with refunding. All results derived hold for any $\gamma \in [0,1]$ and $T < \infty$. To sharpen the intuition, we provide closed form solutions for the equilibrium prices p_t and the stocks of greenhouse gases s_t for the case of a flow pollutant ($\gamma = 1$).

4.1 Global social optimum

We start with the social global optimum. Consider a global social planner seeking to minimize the net present value of the *global total costs* consisting of global costs of emission abatement and the sum of national environmental damages stemming from the pollution stock. The social planner's problem is given as

$$\min_{\{p_t\}_{t=1}^T} \sum_{t=1}^{T} \delta^{t-1} \left(\frac{\Phi}{2} p_t^2 + \frac{\mathcal{B}}{2} s_t^2 \right) , \tag{13}$$

subject to equation (12).

We obtain the corresponding Lagrangian:

$$\mathcal{L} = \sum_{t=1}^{T} \left\{ \delta^{t-1} \left(\frac{\Phi}{2} p_t^2 + \frac{\mathcal{B}}{2} s_t^2 \right) + \lambda_t^{GO} \left[(1-\gamma) s_{t-1} + \mathcal{E} - \Phi p_t - s_t \right] \right\} , \tag{14}$$

where λ_t^{GO} denotes the Langrange multiplier or shadow price of the pollution stock s_t in period t. The necessary conditions are

$$\lambda_t^{GO} = \delta^{t-1} p_t , \quad t = 1, \ldots, T , \tag{15a}$$

$$\lambda_t^{GO} = \mathcal{B} \sum_{k=t}^{T} \delta^{k-1} (1-\gamma)^{k-t} s_k , \quad t = 1, \ldots, T . \tag{15b}$$

As the Lagrangian is strictly convex, the necessary conditions are also sufficient and yield a unique solution:

$$p_t = \mathcal{B} \sum_{k=t}^{T} \left[\delta (1-\gamma) \right]^{k-t} s_k , \quad t = 1, \ldots, T . \tag{16}$$

The following proposition states the optimal permit prices $p_t^\star$ and the corresponding pollution stocks $s_t^\star$:

Proposition 1 (Global Social Optimum)
Given the optimization problem (13), the optimal emission permit prices $p_t^\star$ *and optimal pollution stocks* $s_t^\star$ *are given by the unique solution of the following system of linear equations* $(t = 1, \ldots, T)$*:*

$$p_t^\star = \frac{\mathcal{B}\sum_{k=t}^{T}[\delta(1-\gamma)]^{k-t}\left[s_0(1-\gamma)^k + \mathcal{E}\sum_{l=1}^{k}(1-\gamma)^{k-l} - \Phi\sum_{l=1,l\neq t}^{k}(1-\gamma)^{k-l}p_l^\star\right]}{1+\mathcal{B}\Phi\sum_{k=t}^{T}\left[\delta(1-\gamma)^2\right]^{k-t}} \quad ,\text{(17a)}$$

$$s_t^\star = s_0(1-\gamma)^t + \sum_{k=1}^{t}(1-\gamma)^{t-k}(\mathcal{E} - \Phi p_k^\star) \ . \quad \text{(17b)}$$

For $\gamma = 1$ *we derive for* $p_t^\star$ *and* $s_t^\star$

$$p_t^\star = \frac{\mathcal{B}\mathcal{E}}{1+\mathcal{B}\Phi} \ , \quad s_t^\star = \frac{\mathcal{E}}{1+\mathcal{B}\Phi} \ . \quad (18)$$

The proof of Proposition 1 is given in the Appendix.

According to equation (9), the permit price p_t depends on the aggregate reduction of permits, $\sum_{i=1}^{n}\epsilon_t^i$. Hence, for the global social optimum, only the sum of all ϵ_t^i is determined but not the distribution among the countries. However, the abatement efforts of each country are uniquely determined by virtue of equation (7). To ensure that these are feasible, we assume for the remainder of the paper

Assumption 1
For all countries $i = 1, \ldots, n$ *and all periods* $t = 1, \ldots, T$ *the following condition holds:*

$$e^i \geq \phi_i p_t^\star \ , \quad (19)$$

where $p_t^\star$ *denotes the permit price in the global social optimum.*

Throughout the paper, permit prices will never exceed the permit prices in the social global optimum $p_t^\star$. This assures that abatement levels as determined by equation (7) are always feasible.

4.2 Decentralized solution

Next we examine a decentralized system where a local planner in each country (e.g., a government) seeks to minimize *total local costs* consisting of local abatement costs and local environmental damages. Each country chooses its own sequence of emission permit reductions, taking the actions of other countries as given. We are looking for subgame perfect Nash equilibria of this game. The problem for country i is given as follows:

$$\min_{\{\epsilon_t^i\}_{t=1}^T} \sum_{t=1}^T \delta^{t-1} \left\{ \frac{\phi_i}{2} p_t^2 + \frac{\beta_i}{2} s_t^2 + p_t \big[e^i - \phi_i p_t - \mu(e^i - \epsilon_t^i) \big] - (1-\mu) p_t (e^i - \epsilon_t^i) \right\} \ , \quad (20)$$

subject to equations (9), (12) and $\epsilon_t^i \geq 0, \ t = 1, \ldots, T$.

Denoting the shadow price of the pollution stock s_t in period t by $\lambda_t^{i\,DS}$, the corresponding Lagrangian yields

$$\mathcal{L} = \sum_{t=1}^T \left\{ \delta^{t-1} \left(\frac{\beta_i}{2} s_t^2 - \frac{\phi_i}{2} p_t^2 + \epsilon_t^i p_t \right) + \lambda_t^{i\,DS} \big[(1-\gamma) s_{t-1} + \mathcal{E} - \Phi p_t - s_t \big] \right\} \ . \quad (21)$$

We see that the Lagrangian is independent of μ, the fraction of emission permits grandfathered to firms in each period, which is a reflection of the well-known finding that auctioning and grandfathering induce the same abatement efforts.

Analogously to Section 4.1, the necessary conditions, which due to the strict convexity of the Lagrangian are also sufficient for a unique solution, are given by

$$\lambda_t^{i\,DS} = \delta^{t-1} \left(p_t + \frac{\epsilon_t^i - \phi_i p_t}{\Phi} \right) \ , \quad t = 1, \ldots, T \ , \quad (22a)$$

$$\lambda_t^{i\,DS} = \beta_i \sum_{k=t}^T \delta^{k-1} (1-\gamma)^{k-t} s_k \ , \quad t = 1, \ldots, T \ . \quad (22b)$$

Thus we derive the following reaction function for country i in period t:

$$\epsilon_t^i - \phi_i p_t = \Phi \left(\beta_i \sum_{k=t}^T \left[\delta(1-\gamma) \right]^{k-t} s_k - p_t \right) \ , \quad t = 1, \ldots, T \ . \quad (23)$$

The set of conditions (23) for all countries i and all periods t determines the subgame perfect equilibrium. For the permit price p_t summing over all n countries and using $\sum_{i=1}^n \epsilon_t^i = \Phi p_t$ yields

$$p_t = \bar{\beta} \sum_{k=t}^T \left[\delta(1-\gamma) \right]^{k-t} s_k \ , \quad t = 1, \ldots, T \ . \quad (24)$$

Inserting p_t back into conditions (23), we obtain

$$\epsilon_t^i = \left(\frac{\phi_i}{\Phi} + \frac{\beta_i - \bar{\beta}}{\bar{\beta}} \right) \Phi p_t \ , \quad i = 1, \ldots, n \ , \quad t = 1, \ldots, T \ . \quad (25)$$

For the remainder of the paper we impose the following assumption that assures that $\epsilon_t^i \geq 0$ for all $i = 1, \ldots, n$ and $t = 1, \ldots, T$ in the decentralized solution.

Assumption 2

For all countries $i = 1, \dots, n$ the following condition holds:

$$\beta_i \geq \bar{\beta}\left(1 - \frac{\phi_i}{\Phi}\right) \ . \tag{26}$$

Thus we do not need to check explicitly for the non-negativity of all ϵ_t^i $(i = 1, \dots, n;\ t = 1, \dots, T)$, and equations (24) and (25) determine the Nash equilibrium given by the following proposition.

Proposition 2 (Decentralized Solution)

There exists a unique subgame perfect Nash equilibrium $(\hat{p}_t, \hat{\epsilon}_t^i, \hat{s}_t)$ of the decentralized solution given by the unique solution of the following system of linear equations $(i = 1, \dots, n;\ t = 1, \dots, T)$:

$$\hat{p}_t = \frac{\bar{\beta}\sum_{k=t}^{T}[\delta(1-\gamma)]^{k-t}\left[s_0(1-\gamma)^k + \mathcal{E}\sum_{l=1}^{k}(1-\gamma)^{k-l} - \Phi\sum_{l=1,l\neq t}^{k}(1-\gamma)^{k-l}\hat{p}_l\right]}{1 + \bar{\beta}\Phi\sum_{k=t}^{T}\left[\delta(1-\gamma)^2\right]^{k-t}} \ , \tag{27a}$$

$$\hat{\epsilon}_t^i = \left(\frac{\phi_i}{\Phi} + \frac{\beta_i - \bar{\beta}}{\bar{\beta}}\right)\Phi\hat{p}_t \ , \tag{27b}$$

$$\hat{s}_t = s_0(1-\gamma)^t + \sum_{k=1}^{t}(1-\gamma)^{t-k}(\mathcal{E} - \Phi\hat{p}_k) \ . \tag{27c}$$

For $\gamma = 1$ we derive for $\hat{p}_t$, $\hat{s}_t$ and $\hat{\epsilon}_t^i$ $(i = 1, \dots, n)$

$$\hat{p}_t = \frac{\bar{\beta}\mathcal{E}}{1 + \bar{\beta}\Phi} \ , \quad \hat{s}_t = \frac{\mathcal{E}}{1 + \bar{\beta}\Phi} \ , \quad \hat{\epsilon}_t^i = \left(\phi_i + \Phi\frac{\beta_i - \bar{\beta}}{\bar{\beta}}\right)\frac{\bar{\beta}\mathcal{E}}{1 + \bar{\beta}\Phi} \ . \tag{28}$$

The proof of Proposition 2 is given in the Appendix.

In the decentralized solution, all countries only account for *local* damages. As a consequence, the optimal abatement levels and permit prices are lower and the optimal pollution stocks are higher compared to the global social optimum. Moreover, a country chooses higher emission permit reductions in the decentralized solution the higher ϕ_i is (i.e., the lower abatement costs are) and the higher β_i is (i.e., the higher environmental damage is). In line with Helm (2003), countries exhibiting above-average environmental damage buy permits, while countries with below-average environmental damage sell permits, independently of the level of their abatement costs. Note that no active trading occurs if countries are homogeneous with respect to marginal damages (i.e., $\beta_i = \bar{\beta}$, $\forall\, i = 1, \ldots, n$), as in this case all countries issue emission permits equal to their net emissions.

5 Permit Markets with Refunding

In the following we introduce a refunding scheme and analyze its potential for improving on the decentralized solution. The essential idea is that aggregate revenues from auctioning permits are refunded to member countries in fixed proportions.

5.1 Institutional set-up

We consider a two-step procedure. In the first step, the n countries negotiate the fraction μ of grandfathered emission permits and the fractions ρ_t^i that each country receives from the aggregate auctioning revenues in each period. The relative refunding shares ρ_t^i may depend on time. In the second step, the central agency (CA) handles the transactions on the permit market, collects the revenues and redistributes them to member countries. In each period t, the CA decides on the absolute total refunds by choosing a fraction α_t of the auction revenues to be redistributed to the countries. The CA seeks to set α_t such that in each period the permit price is as close as possible to the permit price in social global optimum.[5] If $\alpha_t < 1$, i.e., not all auctioning revenues are redistributed to member countries, the remaining revenues are transferred to the next period.

In each period $t = 1, \ldots, T$, the CA first announces the refunding share α_t. Then countries choose emission permit reductions ϵ_t^i, and permit trading takes place. Finally, the CA refunds the revenues to the member countries.

5.2 Reaction functions and equilibrium price

By virtue of equation (9), the total amount of auctioned emission permits per period can be written as

$$\mathcal{P}_t = (1-\mu)(\mathcal{E} - \Phi p_t) \ , \quad t = 1 \ldots, T \ , \tag{29}$$

[5] We exclude the possibility that the CA can commit to an entire path $\{\alpha_t\}_{t=1}^T$ of refunding shares in period $t = 1$.

and the total revenues from auctioning in period t equal

$$\mathcal{R}_t = p_t \mathcal{P}_t = p_t(1-\mu)(\mathcal{E} - \Phi p_t) \ , \quad t = 1, \ldots, T \ . \tag{30}$$

$\mathcal{R}_t$ is a concave quadratic function of p_t exhibiting a maximum at $p_t = \frac{\mathcal{E}}{2\Phi}$. We focus on the case where revenues $\mathcal{R}_t$ are an increasing function of the permit price p_t. Thus we impose the following assumption for the remainder of the paper:

Assumption 3
For all periods $t = 1, \ldots, T$ the following condition holds:

$$\mathcal{E} - 2\Phi_i p_t^\star > 0 \ , \tag{31}$$

where $p_t^\star$ denotes the permit price in the global social optimum.

Condition (31) also implies that total abatement in the global social optimum in each period is lower than half of the total business-as-usual emissions $\mathcal{E}$.

The absolute refund r_t^i for country i in period t reads

$$r_t^i = \rho_t^i \alpha_t \mathcal{R}_t = \rho_t^i \alpha_t p_t (1-\mu)(\mathcal{E} - \Phi p_t) \ , \quad i = 1, \ldots, n \ , \quad t = 1, \ldots, T \ , \tag{32}$$

with $\sum_{i=1}^n \rho_t^i = 1$ for all $t = 1 \ldots, T$. Given μ, ρ_t^i, α_t and the choices of all other countries, each country solves the following optimization problem:

$$\min_{\{\epsilon_t^i\}_{t=1}^T} \sum_{t=1}^T \delta^{t-1} \left\{ \frac{\phi_i}{2} p_t^2 + \frac{\beta_i}{2} s_t^2 + p_t \left[(1-\mu) e^i + \mu \epsilon_t^i - \phi_i p_t \right] - r_t^i \right\} \ , \tag{33}$$

subject to equations (9), (12), (32) and $\epsilon_t^i \geq 0, \ t = 1, \ldots, T$.

This yields the following Lagrangian:

$$\begin{aligned} \mathcal{L} \ = \ & \sum_{t=1}^T \Bigg\{ \delta^{t-1} \left[\frac{\beta_i}{2} s_t^2 + (1-\mu) p_t (e^i - \rho_t^i \alpha_t \mathcal{E}) + \mu p_t \epsilon_t^i + p_t^2 \left((1-\mu) \rho_t^i \alpha_t \Phi - \frac{\phi_i}{2} \right) \right] \\ & + \lambda_t^{i\,REF} \left[(1-\gamma) s_{t-1} + \mathcal{E} - \Phi p_t - s_t \right] \Bigg\} \ , \end{aligned} \tag{34}$$

where $\lambda_t^{i\,REF}$ denotes the Lagrange multiplier or shadow price of the pollution stock s_t. Then the necessary conditions for an optimal solution are $(i = 1, \ldots, n; \ t = 1, \ldots, T)$

$$\lambda_t^{i\,REF} \ = \ \delta^{t-1} \left\{ \frac{1-\mu}{\Phi} (e^i - \rho_t^i \alpha_t \mathcal{E}) + \mu \left(p_t + \frac{\epsilon_t^i}{\Phi} \right) + p_t \left[2(1-\mu) \rho_t^i \alpha_t - \frac{\phi_i}{\Phi} \right] \right\} \ , \tag{35a}$$

$$\lambda_t^{i\,REF} \ = \ \delta^{t-1} \beta_i s_t + (1-\gamma) \lambda_{t+1}^{i\,REF} \ . \tag{35b}$$

If the Lagrangian (34) is jointly convex in all ϵ_t^i and s_t, these necessary conditions are also sufficient for a best response of country i in each period. Convexity, however, is not guaranteed but depends, in particular, on the distribution parameters ρ_t^i and α_t. The following proposition gives the necessary and sufficient conditions for the Lagrangian (34) to be convex.

Proposition 3 (Convexity of the Lagrangian)
The Lagrangian (34) is jointly convex in all ϵ_t^i and s_t if and only if the following condition holds for all $i = 1, \ldots, n$ and $t = 1, \ldots, T$:

$$2(1-\mu)\rho_t^i \alpha_t \geq \frac{\phi_i}{\Phi} - 2\mu \ . \tag{36}$$

The proof of Proposition 3 is given in the Appendix.

If condition (36) holds, the reaction function for each country $i = 1, \ldots, n$ and for each period $t = 1, \ldots, T$ is given by

$$\frac{1-\mu}{\Phi}(e^i - \rho_t^i \alpha_t \mathcal{E}) + \mu \left(p_t + \frac{\epsilon_t^i}{\Phi} \right) + p_t \left[2(1-\mu)\rho_t^i \alpha_t - \frac{\phi_i}{\Phi} \right] = \beta_i \sum_{k=t}^{T} [\delta(1-\gamma)]^{k-t} s_k \ . \tag{37}$$

For the permit price p_t summing equation (37) over all n countries yields

$$p_t = \frac{\mathcal{B} \sum_{k=t}^{T} [\delta(1-\gamma)]^{k-t} s_k - \frac{\mathcal{E}}{\Phi}(1-\mu)(1-\alpha_t)}{\mu(n+1) + 2(1-\mu)\alpha_t - 1} \ , \quad t = 1, \ldots, T \ . \tag{38}$$

We note that the reaction functions as constructed in equation (37) take into account that changes in the permit issuance of one country in one period impacts on the permit issuance of all other countries and its own reaction in future periods. This impact works through changes in the future pollution stock and associated changes in future permit prices. Hence the reaction functions (37) enable us to construct subgame perfect Nash equilibria.

6 No Grandfathered Permits

In this section we examine the polar case where all permits are auctioned. This case is the most telling illustration of the virtues of the refunding scheme.

6.1 Welfare

For $\mu = 0$, the equations (37) and (38) reduce to ($i = 1, \ldots, n;\ t = 1, \ldots, T$):

$$\frac{1}{\Phi}(e^i - \rho_t^i \alpha_t \mathcal{E}) + p_t \left[2\rho_t^i \alpha_t - \frac{\phi_i}{\Phi}\right] = \beta_i \sum_{k=t}^{T} [\delta(1-\gamma)]^{k-t} s_k \ , \tag{39a}$$

$$p_t = \frac{\mathcal{B} \sum_{k=t}^{T} [\delta(1-\gamma)]^{k-t} s_k - \frac{\mathcal{E}}{\Phi}(1-\alpha_t)}{2\alpha_t - 1} \ , \tag{39b}$$

For $\mu = 0$, the reaction function (37) is independent of ϵ_t^i. As a consequence, the Nash equilibrium is unique only with respect to the permit price p_t but not with respect to the distribution of the emission permit reductions ϵ_t^i. We observe that equation (39b) becomes identical to equation (16), the necessary and sufficient condition for a global social optimum, if and only if $\alpha_t = 1$. If we insert $\alpha_t = 1$ and $p_t = p_t^\star$ back into equation (39a) and take into account that $\beta_i \sum_{k=t}^{T} [\delta(1-\gamma)]^{k-t} s_k = \frac{\beta_i}{\mathcal{B}} p_t^\star$ by virtue of equation (16), we find that for both equations (39a) and (39b) to hold simultaneously the relative refunds ρ_t^i have to equal

$$\rho_t^i = \frac{e^i - \Phi p_t^\star \left(\frac{\beta_i}{\mathcal{B}} + \frac{\phi_i}{\Phi}\right)}{\mathcal{E} - 2\Phi p_t^\star} \ , \quad i = 1, \ldots, n \ , \quad t = 1, \ldots, T \ . \tag{40}$$

Thus, if the relative refunding rule ρ_t^i is given by equation (40) and the CA sets $\alpha_t = 1$ for all $t = 1, \ldots, T$, the permit price $p_t^\star$ of the social global optimum is implemented as the unique subgame perfect Nash equilibrium. The following proposition summarizes this result:

Proposition 4 (Refunding without Grandfathered Permits)
For $\alpha_t = 1$ and ρ_t^i, as given by equation (40), the socially optimal permit prices $p_t^\star$ and pollution stocks $s_t^\star$ as given by Proposition 1 are supported as the unique subgame perfect Nash equilibrium if

$$\rho_t^i \geq \frac{\phi_i}{2\Phi} \ , \tag{41}$$

holds for all $i = 1, \ldots, n$ and $t = 1, \ldots, T$.

The proof of Proposition 4 is given in the Appendix. Note that uniqueness refers to the permit prices, pollution stocks and abatement levels but not to individual countries' permit reductions, which are indeterminate.

Proposition 4 says that if $\alpha_t = 1$ and ρ_t^i is as given by equation (40), the social optimum can be implemented as a decentralized outcome by enacting a refunding scheme.

Condition (41) and equation (40) impose constraints on the degree of heterogeneity between countries. A direct corollary of Proposition 4 is

Corollary 1 (Homogeneous Countries)
If countries are homogeneous, condition (41) is always fulfilled.

The proof of Corollary 1 is given in the Appendix.

The intriguing insight from Proposition 4 and Corollary 1 is that collecting the revenues from auctioning permits and refunding them in fixed proportions can overcome the global public good problem associated with the decentralized solution. The intuition in the homogeneous case where $\rho_t^i = \frac{1}{n}$ $(i = 1, \ldots, n;\ t = 1, \ldots, t)$ is as follows: Suppose that $n - 1$ countries choose $\epsilon_t^i = e^i - \phi_i p_t^\star$. In the decentralized solution without refunding, country n has strong incentives to be much more generous to its domestic industries as a decrease of ϵ_t^n directly and fully benefits the country due to the generation of additional revenues from the sale of permits. In the system with refunding, an increase of ϵ_t^n reduces aggregate and refunded revenues as the permit price declines. Thus incentives for a country to be particularly generous to domestic industries under refunding is greatly reduced. This lowers the sum of abatement costs and environmental damgages at national and aggregate levels.

6.2 Participation

We next examine the willingness of countries to participate in the refunding scheme in the first place. A minimum requirement is that countries are not worse off with the refunding scheme than they would be with the decentralized solution. We start with the homogeneous case.

Proposition 5 (Pareto Improvement without Grandfathered Permits)
If countries are homogeneous, the outcome of the game in which each country i solves the optimization problem (33) subject to equations (9), (12), (32), (40), and $\alpha_t = 1$ is always Pareto superior compared to the decentralized solution given by Proposition 2.

The proof of Proposition 5 is given in the Appendix. However, when countries are sufficiently heterogeneous the participation constraint for countries with low marginal damages may be violated, as illustrated in the following example:

Suppose that

$$n = 2 \ , \quad e^1 = e^2 = \frac{\mathcal{E}}{2} \ , \quad \phi_1 = 0 \ , \phi_2 = \Phi, \quad \beta_1 = \mathcal{B} \ , \beta_2 = 0, \quad \gamma = 1 \ . \tag{42}$$

We assume $T = 1$.[6] Thus we consider the case of a flow pollutant with two countries that exhibit identical business-as-usual emissions e^i but are completely heterogeneous with respect to their abatement cost parameters ϕ_i and their environmental damage parameters β_i. Country 1 has prohibitively high abatement costs ($\phi_1 = 0$) and suffers high environmental damage ($\beta_1 = \mathcal{B}$), while country 2 has low abatement costs ($\phi_2 = \Phi$) and suffers no environmental damage at all ($\beta_2 = 0$). According to Proposition 2, ϵ^i in the decentralized solution is given as

$$\hat{\epsilon}^1 = \frac{\mathcal{B}\mathcal{E}\Phi}{2 + \mathcal{B}\Phi} \ , \quad \hat{\epsilon}^2 = 0 \ . \tag{43}$$

Total costs $\hat{K}_i := \frac{\beta_i}{2}\hat{s}^2 + \frac{\phi_i}{2}\hat{p}^2 + \Phi\hat{p}^2\left(\frac{\beta_i - \bar{\beta}}{\bar{\beta}}\right)$ for both countries amount to

$$\hat{K}_1 = \frac{\mathcal{B}\mathcal{E}^2}{2 + \mathcal{B}\Phi} \ , \quad \hat{K}_2 = -\frac{\mathcal{B}^2\mathcal{E}^2\Phi}{2(2 + \mathcal{B}\Phi)^2} \ . \tag{44}$$

With the refunding scheme, we derive for $\mu = 0$ from the refunding rule (40)

$$\rho^1 = \rho^2 = \frac{1}{2} \ . \tag{45}$$

Note that condition (41) holds for both ρ^i. According to Proposition 4, the permit price $p^\star$ and the corresponding pollution stock $s^\star$ of the global social optimum as given by Proposition 1 are supported as the unique subgame perfect Nash equilibrium. In this case, the total costs $K_i^\star := \frac{\beta_i}{2}(s^\star)^2 + p^\star(e^i - \rho^i\mathcal{E}) + (p^\star)^2\left(\rho^i\Phi - \frac{\phi}{2}\right)$ under refunding equal

$$K_1^\star = \frac{\mathcal{B}\mathcal{E}^2}{2 + 2\mathcal{B}\Phi} \ , \quad K_2^\star = 0 \ . \tag{46}$$

Comparing $\left(\hat{K}_1, \hat{K}_2\right)$ with $(K_1^\star, K_2^\star)$, we observe that country 1 benefits from the refunding scheme $\left(K_1^\star < \hat{K}_1\right)$, while country 2 is worse off $\left(K_2^\star > \hat{K}_2\right)$. Anticipating this result, country 2 has no incentive to agree on $\rho^1 = \rho^2 = \frac{1}{2}$ and $\mu = 0$ in the first place.

The underlying reason is that the sum of the costs saved by the refunding scheme over and against to the decentralized solution have to be distributed in a very specific way

[6] In the case of a flow pollutant (i.e., $\gamma = 1$) all endogenous variables take identical values at all times t, so the time horizon T does not matter.

to ensure a permit price level as in the global social optimum. In fact, refunds are low for countries with low abatement cost parameters (i.e., high ϕ_i), while with the decentralized solution these countries can substantially benefit by selling emission permits if they also exhibit low environmental damage parameters (i.e., low β_i). Therefore it may be impossible to agree on $\mu = 0$ and ρ_t^i as given by equation (40) in the first place.

7 Grandfathered Permits

In the following we show that if we allow for some grandfathered emission permits, the refunding scheme can always implement a Pareto improvement compared to the decentralized solution.

7.1 Equilibria with refunding

For $\mu > 0$ the permit price is given by equation (38). In order to implement the global social optimum, we derive the fraction α_t of refunded aggregate revenues by inserting $p_t = p_t^\star = \mathcal{B} \sum_{k=t}^{T} [\delta(1-\gamma)]^{k-t} s_k$ from equation (16) and solving for α_t.

$$\alpha_t = 1 + \frac{\Phi p_t^\star}{\mathcal{E} - 2\Phi p_t^\star} \frac{(n-1)\mu}{1-\mu} > 1 \ , \quad t = 1, \ldots, T \ . \tag{47}$$

As $\mathcal{E} - 2\Phi p_t^\star > 0$ by virtue of Assumption 3, α_t exceeds 1. In other words, the redistribution of the revenues from the emission permits market does not suffice to give adequate incentives to countries to implement the global social optimum. The best the CA can do to implement a permit price as close as possible to the socially optimal permit price $p_t^\star$ in each period is to fully distribute the revenues among the countries by setting $\alpha_t = 1$. By inserting $\alpha_t = 1$ into equations (37) and (38), we obtain $(t = 1, \ldots, T)$

$$\frac{1-\mu}{\Phi}(e^i - \rho_i \mathcal{E}) + \mu \left(p_t + \frac{\epsilon_t^i}{\Phi} \right) + p_t \left[2(1-\mu)\rho_i - \frac{\phi_i}{\Phi} \right] = \beta_i \sum_{k=t}^{T} [\delta(1-\gamma)]^{k-t} s_k \ , \tag{48a}$$

$$p_t = \frac{\mathcal{B}}{1 + (n-1)\mu} \sum_{k=t}^{T} [\delta(1-\gamma)]^{k-t} s_k \ . \tag{48b}$$

Thus the resulting permit price p_t is larger, the smaller the fraction μ of grandfathered permits is. Comparing equation (48b) with the corresponding equations for the social global optimum (16) and the decentralized solution (24), we see that the upper limit is equal to the permit price in the social global optimum $p_t^\star$ achieved for $\mu = 0$ (see the case without grandfathered emissions). The lower limit is reached for $\mu = 1$, where p_t equals the permit price in the decentralized solution $\hat{p}_t$.

To support the permit price p_t given by equation (48b) as the unique subgame perfect Nash equilibrium, condition (36) has to hold. For $\alpha_t = 1$, condition (36) reduces to

$$2(1-\mu)\rho_t^i \geq \frac{\phi_i}{\Phi} - 2\mu \ , \quad i = 1, \ldots, n \ , \quad t = 1, \ldots, T \ . \tag{49}$$

We obtain

Proposition 6 (Refunding with Grandfathered Permits)
For $\alpha_t = 1$ and $\mu \in (0,1)$ and ρ_t^i such that condition (49) and $\epsilon_t^i \geq 0$ hold, there exists a unique subgame perfect Nash equilibrium characterized by the solution of the following system of linear equations ($i = 1, \ldots, n;\ t = 1, \ldots, T$):

$$\tilde{p}_t = \frac{\mathcal{B}\sum_{k=t}^{T}[\delta(1-\gamma)]^{k-t}\left[s_0(1-\gamma)^k + \mathcal{E}\sum_{l=1}^{k}(1-\gamma)^{k-l} - \Phi\sum_{l=1, l\neq t}^{k}(1-\gamma)^{k-l}\tilde{p}_l\right]}{\mu(n-1) + 1 + \mathcal{B}\Phi\sum_{k=t}^{T}\left[\delta(1-\gamma)^2\right]^{k-t}} \ , \tag{50a}$$

$$\tilde{\epsilon}_t^i = \frac{1-\mu}{\mu}\left\{\rho_t^i(\mathcal{E} - 2\Phi\tilde{p}_t) - \left[e^i - \Phi\tilde{p}_t\left(\frac{\phi_i}{\Phi} + \frac{\beta_i}{\mathcal{B}}\right)\right]\right\} + \Phi\tilde{p}_t\left(\frac{\phi_i}{\Phi} + \frac{\beta_i - \bar{\beta}}{\bar{\beta}}\right) \ , \tag{50b}$$

$$\tilde{s}_t = s_0(1-\gamma)^t + \sum_{k=1}^{t}(1-\gamma)^{t-k}(\mathcal{E} - \Phi\tilde{p}_k) \ . \tag{50c}$$

In addition, the following inequalities hold for the permit price $\tilde{p}_t$ and the pollution stock $\tilde{s}_t$:

$$\hat{p}_t < \tilde{p}_t < p_t^\star \ , \quad \frac{\partial \tilde{p}_t}{\partial \mu} < 0 \ , \qquad s^\star < \tilde{s}_t < \hat{s}_t \ , \quad \frac{\partial \tilde{s}_t}{\partial \mu} > 0 \ , \qquad t = 1, \ldots, T \ , \tag{51}$$

where $(p^\star, s^\star)$ and $(\hat{p}, \hat{s})$ denote the outcome in the social global optimum and the decentralized solution respectively, as given by Propositions 1 and 2.

For $\gamma = 1$ we obtain

$$\tilde{p}_t = \frac{n\bar{\beta}\mathcal{E}}{1 + (n-1)\mu + n\bar{\beta}\Phi} \ , \quad \tilde{s}_t = \frac{\mathcal{E}[1 + (n-1)\mu]}{1 + (n-1)\mu + n\bar{\beta}\Phi} \ , \quad t = 1, \ldots, T \ . \tag{52}$$

The proof of Proposition 6 is given in the Appendix.

Proposition 6 says that if a fraction $\mu > 0$ of emission permits is grandfathered, the distribution of the permit market revenues results in permit price levels that are above the corresponding levels in the decentralized solution but below the corresponding levels of the social global optimum. The opposite ranking obtains for the pollution stock. The following corollary shows that Proposition 4 is a special case of Proposition 6.

Corollary 2 (Approximation Result)
For sufficiently small μ, the global social optimum as given by Proposition 1 can be approximated arbitrarily close, if condition (41) as given by Proposition 4 holds for the set of refunding shares

$$\rho_t^i = \frac{e^i - \Phi \tilde{p}_t \left(\frac{\beta_i}{\mathcal{B}} + \frac{\phi_i}{\Phi} \right)}{\mathcal{E} - 2\Phi \tilde{p}_t} \ , \quad i = 1, \ldots, n \ , \quad t = 1, \ldots, T \ . \tag{53}$$

The proof of Corollary 2 is given in the Appendix.

7.2 Pareto improving refunding schemes

While refunding with grandfathered permits can no longer implement the global social optimum, it makes it possible to construct schemes for ensuring that all countries are better off compared to the decentralized solution. The following proposition states our main possibility theorem:

Proposition 7 (Pareto Improvement with Grandfathered Permits)
For any given values of e^i, β_i, ϕ_i and $\alpha_t = 1$, there exist some $\mu \in (0,1)$ and ρ_t^i with $\sum_{i=1}^n \rho_t^i = 1$ such that the resulting outcome $(\tilde{p}_t, \tilde{e}_t, \tilde{s}_t)$ as given by equations (50) is Pareto superior compared to the decentralized solution as given by Proposition 2.

The proof of Proposition 7 is given in the Appendix.

Proposition 7 states that as long as Assumptions 1–3 hold it is always possible to implement an outcome that is Pareto superior to the decentralized solution via the refunding scheme, no matter how heterogeneous countries are.

The intuition for this result is as follows: Auctioning of permits and refunding of revenues incurs less aggregate total costs measured as the sum of aggregate abatement costs and aggregate environmental damages. By choosing an appropriate set of refunding shares ρ_t^i one can ensure that all countries benefit from this cost reduction. Finally, allowing for a certain amount of grandfathered permits we can assure that countries will not issue more permits than business-as-usual emissions and that the scheme will induce a subgame perfect equilibrium.

To illustrate how a Pareto improvement can be engineered, we again consider the example discussed in Section 6.2, for which the social global optimum could not be implemented as a Pareto improvement. Using equation (50b) we obtain the total costs of country i

$$\tilde{K}_i = \frac{\beta_i}{2}\tilde{s}^2 + \frac{\phi_i}{2}\tilde{p}^2 + \Phi\tilde{p}^2\left(\frac{\beta_i\frac{1+(n-1)\mu}{n} - \bar{\beta}\left[\rho^i(1-\mu)+\mu\right]}{\bar{\beta}}\right) , \quad i = 1, 2 , \tag{54}$$

where $(\tilde{p}, \tilde{s})$ are given by equation (52). To ensure that country 2 is not worse off in comparison with the decentralized solution, we set $\hat{K}_2 - \tilde{K}_2 = 0$ and solve for ρ^2

$$\rho^2 = \frac{5 - \mu + 2\mathcal{B}\Phi(3 + \mathcal{B}\Phi)}{2(2 + \mathcal{B}\Phi)^2} . \tag{55}$$

Setting $\rho^1 = 1 - \rho^2$ and taking into account that Assumption 3 implies $\mathcal{B}\Phi \in (0, 1)$, we can verify that condition (49) holds for all $\mu \in (0, 1)$. In addition, we derive for $\tilde{\epsilon}^i$

$$\tilde{\epsilon}^1 = \frac{\left[4\mathcal{B}\Phi\mu + (1+\mu)\mathcal{B}^2\Phi^2 - (1-\mu)^2\right]\mathcal{E}}{2\mu(2+\mathcal{B}\Phi)^2} , \tag{56a}$$

$$\tilde{\epsilon}^2 = \frac{(1-\mu)(1+\mu-\mathcal{B}\Phi)\left[(1+\mathcal{B}\Phi)^2 - \mu\right]\mathcal{E}}{2\mu(1+\mu+\mathcal{B}\Phi)(2+\mathcal{B}\Phi)^2} . \tag{56b}$$

We observe that $\tilde{\epsilon}^2 > 0$ for all $\mu \in (0, 1)$. We seek the minimal $\mu \in (0, 1)$ for which $\tilde{\epsilon}^1 \geq 0$ and derive

$$\mu = \frac{1}{2}\left(2 + 4\mathcal{B}\Phi + \mathcal{B}^2\Phi^2 - \sqrt{\mathcal{B}\Phi\left\{16 + \mathcal{B}\Phi\left[24 + \mathcal{B}\Phi\left(8 + \mathcal{B}\Phi\right)\right]\right\}}\right) . \tag{57}$$

μ is a decreasing function of $\mathcal{B}\Phi$ with $\mu = 0$ for $\mathcal{B}\Phi = 1$ and $\mu = 1$ for $\mathcal{B}\Phi = 0$. Hence we can choose a suitable value of μ to ensure that both countries are better off.

Table 1 gives the results for different values of $\mathcal{B}\Phi$. The decentralized solution $(\hat{p}, \hat{s})$ and the Pareto superior solution with refunding $(\tilde{p}, \tilde{s})$ are given as percentages of the corresponding values in the global social optimum. $\Delta\hat{K}$ and $\Delta\tilde{K}$ measure the relative increase in total cost compared to the global social optimum. μ, ρ^1 and ρ^2 are the characteristic parameters of the refunding system.

$\mathcal{B}\Phi$	$(\hat{p}, \hat{s})$	$\Delta\hat{K}$	$(\tilde{p}, \tilde{s})$	$\Delta\tilde{K}$	μ	ρ^1	ρ^2
0.1	(52.4,104.8)	2.27	(67.7,103.2)	1.04	52.5	42.2	57.8
0.25	(55.6,111.1)	4.94	(78.4,105.4)	1.17	34.5	38.0	62.0
0.5	(60.0,120.0)	8.0	(89.0,105.5)	0.60	18.5	33.5	66.5
0.75	(63.6,127.3)	9.92	(95.6,103.3)	0.14	8.0	30.3	69.7
0.9	(65.5,131.0)	10.7	(98.5,101.4)	0.02	3.0	28.7	71.3

Table 1: Numerical values for the decentralized solution and the refunding scheme for different values of $\mathcal{B}\Phi$ as percentages of the corresponding values in the social global optimum.

8 Discussion

Within the formal representation of our model we have shown that an international permit market with refunding can implement a Pareto superior solution compared to a standard international permit market. Our formal results rest on a number of assumptions, some of which we shall discuss in the following.

First, we have assumed a central agency that decides on the fraction of auction revenues α_t refunded to member countries. As we have seen, in each period the permit price is as close as possible to the permit price in the global social optimum if $\alpha_t = 1$. Thus it is possible to set $\alpha_t = 1$ in the initial step when governments negotiate the parameters of the refunding scheme. This leaves the CA with the purely administrative task of ensuring the successful operation of the international permit market. Denying any decision-making power to the CA will prevent member countries from continuously trying to influence the CA's decision on α_t.

Second, with respect to participation we have assumed a standard international permit market without refunding as the status-quo scenario. However, as the EU emission trading scheme is the first – and so far the only – international permit market for greenhouse gas emissions, the status-quo scenario outside the EU is a decentralized solution where each country reduces greenhouse gas emissions on a purely national scale, e.g., by levying emission taxes. Such a decentralized solution falls short of a standard international emission permit market as efficiency gains cannot be utilized when countries exhibit different marginal abatement costs. Thus enacting a permit market scheme with refunding in this case yields even larger Pareto improvements.

Although we consider Pareto superiority a minimum requirement for member countries to agree on an international trading scheme with refunding, it is not necessarily sufficient. Equity considerations may play a crucial role in the negotiation of international agreements. Although the discussion of the political economy of international agreements lies beyond the scope of this paper, we note that a possible tension does exist between efficiency and equity. On standard emission permit markets, countries with low environmental damages are net sellers of emission permits. In the trading scheme with refunding, these countries have to receive above-average refunds to compensate them for their lost permit revenues. Thus, to implement Pareto improvements, countries with low environmental damages receive high refunds, while countries that suffer strongly from climate change receive fewer refunds.

Third, unlike most of the game-theoretical literature on international environmental agreements, we have not imposed the property of no-exit. The underlying reason is that our model is inspired by the EU emission trading scheme. Within a supranational authority such as the EU, the unilateral exit of individual countries is hampered, as the EU has the power to force countries to participate in the scheme.

For international permit markets with refunding that extend to countries outside the EU, there are two possible types of exit. First, a country may decide not to participate in the refunding scheme but to trade permits on the permit market. This exit option can be avoided by restricting access to the emission permit market to members of the refunding scheme. Second, a country may decide not to participate in the refunding scheme and to restrict environmental policy to its own jurisdiction, thereby benefiting from the emission reductions of the member countries of the refunding scheme. Such individual defection may be advantageous for countries with high abatement costs. In order to avoid this type of exit, one might levy entry fees increasing the level of the fund so that countries lose larger claims on refunds if they exit.[7]

Numerous extensions deserve further scrutiny. For instance, it might be useful to explore the potential and limits of a refunding scheme where governments can only agree on formal equality, i.e., each country obtains the same fraction of auction revenues. This might be particularly relevant when local abatement costs or local environmental damages are the private information of member countries. Moreover, it might be useful to consider a scenario where countries negotiate that only a fraction of auction revenues will be refunded in order to build up a fund that can be used for preventive measures

[7] Gersbach and Winkler (2007) taking up a suggestion made by Gersbach (2005) show how exit can be avoided with entry fees when countries levy emission taxes.

lowering environmental damages in particular countries.

9 Conclusion

In this paper we have proposed a simple blueprint for an international emission market with refunding that helps to align national and global interests on emission reductions. We have shown that an international permit market with refunding can implement a Pareto superior solution compared to a standard international permit market. Moreover, if the share of grandfathered permits is sufficiently small and countries are sufficiently homogeneous, an arbitrarily close approximation to the socially optimal solution can be achieved.

Appendix

Proof of Proposition 1

By inserting equation (12) into equation (16) we obtain a linear system of T equations (17a) with full rank. Thus there exists a unique solution for the T unknowns $p_t^\star$ $(t = 1, \ldots, T)$. Inserting the resulting $p_t^\star$ into equation (12) yields equation (17b). Equations (18) follow by inserting $\gamma = 1$ into equations (17). □

Proof of Proposition 2

By inserting equation (12) into equation (24) we derive a linear system of T equations (27a) with full rank. Thus there exists a unique solution for the T unknowns $\hat{p}_t$ $(t = 1, \ldots, T)$. Inserting the resulting $\hat{p}_t$ into equation (25) and (12) yields equations (27b) and (27c). Equations (28) follow by inserting $\gamma = 1$ into equations (27). □

Proof of Proposition 3

The Lagrangian (34) is convex if and only if its Hessian is positive semi-definite. A matrix is positive semi-definite if all eigenvalues are non-negative. The Hessian of the Lagrangian (34) is a diagonal matrix, as $\frac{\partial^2 \mathcal{L}}{\partial \epsilon_t^i s_{t'}} = 0$ for all $i = 1, \ldots, n$ and $t, t' = 1, \ldots, T$. Thus the eigenvalues are given by the diagonal elements $\frac{\partial^2 \mathcal{L}}{\partial \left(\epsilon_t^i\right)^2}$ and $\frac{\partial^2 \mathcal{L}}{\partial s_t^2}$. By using equation (9) we calculate

$$\frac{\partial^2 \mathcal{L}}{\partial \left(\epsilon_t^i\right)^2} = \delta^{t-1} \left\{ \frac{2\mu}{\Phi} + \frac{1}{\Phi} \left[2(1-\mu)\rho_t^i \alpha_t - \frac{\phi_i}{\Phi} \right] \right\} , \tag{A.1a}$$

$$\frac{\partial^2 \mathcal{L}}{\partial s_t^2} = \delta^{t-1} \beta_i > 0 \; . \tag{A.1b}$$

The right-hand side of equation (A.1a) is non-negative if and only if condition (36) holds. □

Proof of Proposition 4

For $\alpha_t = 1$ and ρ_t^i given by equation (40), the socially optimal permit prices $p_t^\star$ and pollution stocks $s_t^\star$ as given by Proposition 1 are a candidate for a subgame perfect Nash equilibrium, as they solve the necessary condition (39a). However, if the Lagrangian (34) is jointly convex in all ϵ_t^i and s_t, then equation (39a) is also sufficient for a unique solution. Condition (41) follows directly from condition (36) of Proposition 3 by inserting $\mu = 0$ and $\alpha_t = 1$. □

Proof of Corollary 1

According to equation (40), homogeneous countries imply that $\rho_t^i = \frac{1}{n}$ $(i = 1, \ldots, n;\ t = 1, \ldots, t)$. For this set of ρ_t^i condition (41) holds. $\square$

Proof of Proposition 5

When $\mu = 0$ and all countries are homogeneous, the conditions for Proposition 4 hold, hence the global social optimum is supported as a unique subgame perfect Nash equilibrium. The sum of the total costs of all countries in the global social optimum denoted by $K^\star = \sum_{t=1}^{T} \delta^{t-1} \left[\frac{\Phi}{2}\left(p_t^\star\right)^2 + \frac{\mathcal{B}}{2}\left(s_t^\star\right)^2\right]$ is smaller than the sum of the total costs of all countries in the decentralized solution $\hat{K} = \sum_{t=1}^{T} \delta^{t-1} \left[\frac{\Phi}{2}\hat{p}_t^2 + \frac{\mathcal{B}}{2}\hat{s}_t^2\right]$, as by construction $p^\star$ and $s^\star$ are the unique minimizers of the sum of total costs. As countries are homogeneous, the total costs of all countries are identical and equal $\frac{1}{n}$ of the sum of total costs. $\square$

Proof of Proposition 6

By inserting equation (12) into equation (48a) we obtain the linear system of T equations (50a) for the T unknowns $\tilde{p}_t$ $(t = 1, \ldots, T)$. Inserting the resulting $\hat{p}_t$ into equation (12) yields equation (50c). From equation (38) and by setting $\alpha_t = 1$ we obtain

$$\beta_i \sum_{k=t}^{T} \left[\delta(1-\gamma)\right]^{k-t} s_k = \frac{\beta_i}{\mathcal{B}} p_t \left[\mu(n+1)+2(1-\mu)-1\right] \ , \tag{A.2}$$

Equation (50b) is derived by inserting (A.2) into equation (48a). The solution determined by equations (50) is a candidate for the Nash equilibrium as it is consistent with the necessary conditions (48a). If, in addition, $\mu \in (0, 1)$ and ρ_t^i are such that condition (49) and $\epsilon_t^i \geq 0$ for all $i = 1, \ldots, n$ and $t = 1, \ldots, T$ hold, the necessary conditions are also sufficient for the unique subgame perfect Nash equilibrium. Conditions (51) directly follow from equation (48b). Equations (52) are derived by inserting $\gamma = 1$ into equations (50). $\square$

Proof of Corollary 2

We insert ρ_t^i from equation (53) into equation (50b) and observe that $\tilde{\epsilon}_t^i \geq 0$ $(i = 1, \ldots, n;\ t = 1, \ldots, T)$ by virtue of Assumption 2. As condition (41) imposes tighter constraints on the magnitude of the refunding shares than condition (49), the requirements for Proposition 6 are fulfilled. We next observe that $\lim_{\mu \to 0} \tilde{p}_t = p_t^\star$. Thus, for sufficiently small μ abatement efforts, emission levels and environmental damages are arbitrarily close to their socially optimal values. To sum up, for sufficiently small μ, the subgame perfect Nash equilibrium as given by Proposition 6 is arbitrarily close to the global social optimum. □

Proof of Proposition 7

Set $\alpha_t = 1$. We claim that for any distribution of ρ_t^i, for which $\sum_{i=1}^n \rho_t^i = 1$ holds, it is possible to find a $\mu \in (0,1)$ for which the the resulting outcome $(\tilde{p}_t, \tilde{\epsilon}_t, \tilde{s}_t)$ as given by equations (50) can be supported as the unique subgame perfect Nash equilibrium. According to Proposition 6, for this to hold we have to satisfy condition (49) and to ensure that all $\epsilon_t^i \geq 0$. We observe that for μ sufficiently close to 1 condition (49) holds for all $i = 1, \ldots, n$ for any distribution of ρ_t^i. Moreover, as $\Phi \tilde{p}_t \left(\frac{\phi_i}{\Phi} + \frac{\beta_i - \bar{\beta}}{\beta} \right) > 0$ by virtue of Assumption 2 also all $\epsilon_t^i \geq 0$ for any distribution of ρ_t^i if μ is sufficiently close to 1. For any $\mu \in (0,1)$ and the corresponding outcome $(\tilde{p}_t, \tilde{\epsilon}_t, \tilde{s}_t)$ the sum of the total costs $\tilde{K} = \sum_{t=1}^T \delta^{t-1} \left[\frac{\Phi}{2} \tilde{p}_t^2 + \frac{\mathcal{B}}{2} \tilde{s}_t^2 \right]$ is smaller than the sum of total costs in the decentralized solution $\hat{K} = \sum_{t=1}^T \delta^{t-1} \left[\frac{\Phi}{2} \hat{p}_t^2 + \frac{\mathcal{B}}{2} \hat{s}_t^2 \right]$. This holds as the total costs are strictly convex in p_t, s_t and exhibit their minimum at $p_t^\star$, $s^\star$, as seen in Section 4. As a consequence, it is always possible to choose the refunding shares ρ_t^i so that nobody is worse off and at least one country is strictly better off than in the decentralized solution. □

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