Climate Policy and Development*

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Abstract

We design a development-compatible refunding system to mitigate climate change. Industrial countries pay an initial fee into a global fund. Each country chooses its national carbon tax and taxes are collected in the global fund. Part of the global fund is refunded to the developing and to the industrial countries, in proportion to the relative emission reductions they achieve. The remaining fraction is paid back to industrial countries. We show that a such a scheme can simultaneously achieve globally efficient emission reductions and equity objectives as developing countries abate voluntarily and do not have to pay an initial fee. Moreover, we explore the potential of simple refunding schemes that renounces collecting taxes and only rely on initial fees paid by industrial countries.

Keywords: climate change mitigation, refunding scheme, international agreements, developing countries

JEL: H23, Q54, H41, O10, O13

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1 Introduction

Developing countries are exceptionally burdened by climate change. First, developing countries in Latin America, Asia and in Africa have to fear the most severe damages when temperatures in the atmosphere rise. Second, developing countries currently provide the greatest opportunities for low-cost emission reductions and they are likely to account for more than one-half of greenhouse gas emissions in one decade.

As industrial countries have caused the bulk of man-made current greenhouse gas concentrations and as emission reductions in developing countries would further aggravate poverty, many argue that industrial countries should bear the costs of mitigating climate change. While this fairness argument is at the heart of negotiations for an international agreement following the Kyoto Protocol, it is unclear how efficiency and fairness considerations in mitigating climate change can be combined in such a way that they do not conflict with each other.

As greenhouse gases travel around the world and thus mitigating climate change is a global public good, there is no simple mechanism promising to achieve efficiency and fairness objectives. In this paper, we propose a simple scheme that can incorporate efficiency and fairness objectives in the mitigation of climate change. The scheme works as follows:

- Industrial countries pay an initial fee into a global fund.
- Countries decide on their emission taxes. Tax revenues are collected in a global fund.
- A fraction of the fund is redistributed to the participating countries according to a sharing rule. The sharing rule specifies that the refund a country receives is proportional to the relative emission reductions it achieves.
- The remaining fraction of the global fund is paid back to industrial countries.

Such a refunding scheme is called "development-compatible refunding" (henceforth called DCR), as developing countries do not have to pay an initial fee and abatement by developing countries is voluntary.

We explore whether a DCR can simultaneously achieve equity and efficiency objectives of climate policy and thus could qualify as a blueprint for an international treaty.

We consider a model with a representative industrial and a representative developing country. The developing country has an equal or higher marginal damage from greenhouse gas emissions compared to the industrial country, but has equal or lower marginal abatement costs. Both countries enter into a development-compatible refunding scheme. Each country receives refunds in proportion to the relative emission reductions it has achieved. The relative shares may be varied by a weighting factor that allows to increase or decrease the relative refunding claims of the developing and the industrial country. The fraction of the fund that is not distributed among the countries is paid back to the industrial country.

Our main insight is that a suitably designed DCR can achieve equity and efficiency objectives under a variety of circumstances. In fact, the DCR induces both the industrial and developing country to set abatement levels that are socially optimal. The developing country does not have to pay an initial fee and abates voluntarily. It is better off than it would be in the decentralized solution where an international treaty fails. Moreover, if developing and industrial countries are similar with respect to damages and abatement costs, the developing country is a net receiver of funds.

We also explore the potential of a simple refunding scheme that renounces tax collection from countries. In this simple scheme, refunds are solely financed by initial fees. Such a simple refunding scheme yields socially optimal abatement levels if the relationship between marginal damages and abatement costs are similar across countries.

The paper is organized as follows. In the next section, we relate our analysis to the literature. In Section 3, we present the model. We calculate the social optimum and the decentralized solution as benchmark cases in Section 4. In Section 5, we introduce the development-compatible refunding scheme and characterize its properties. Special cases are discussed in Section 6. In Section 4, we consider a simple refunding scheme without tax collection, and Section 8 concludes.

2 Relation to the Literature

It is well-known that there is much difficulty in achieving significant emission reductions through the Kyoto Protocol in the countries that have agreed to binding targets. As effective compliance to reach the targets is lacking and emissions increase sharply in non-participating economies such as China and India, the need to move forward to a new treaty appears to be urgent. 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. In this paper we consider 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 reductions they achieve within a given period. We design such a global refunding scheme and explore its potential for mitigating climate change.

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

Recently, Gersbach (2005) and Gersbach and Winkler (2007) have proposed and examined a global refunding system in which all countries are treated equally. All countries have to pay an initial fee and all countries receive the same refund. They show that if countries are identical, such a scheme achieves the social global optimum. In this paper we define a development-compatible refunding scheme in which only industrial countries have to pay an initial fee. We develop a refunding formula such that efficient abatement levels are achieved in industrial and in developing countries even if developing countries suffer higher marginal damages from climate change and have lower marginal abatement costs.

3 The Model

We consider a world consisting of two countries, an industrial country I and a developing country D. They are characterized by an emission function E, an abatement cost function C and damages. Throughout the paper countries are indexed by i and j ($i, j \in \{I, D\}$).

Emissions of country i are assumed to equal some "business as usual" emissions $\bar{e}$ minus emission abatement a^i:[1]

$$E^i(a^i) = \bar{e} - a^i \ , \quad \text{with} \quad a^i \in [0, \bar{e}] \ , \quad i \in \{I, D\} \ . \tag{1}$$

We assume these emissions are caused by a representative firm in each country which faces convex abatement costs:[2]

$$C^i(a^i) = \frac{1}{2\phi^i} \left(a^i\right)^2 \ , \quad \text{with} \quad \phi^i > 0 \ , \quad i \in \{I, D\} \ . \tag{2}$$

We assume that countries use emission taxes as policy instrument. As developing countries provide the best opportunities for low-cost emission reductions, we assume $\phi^I \leq \phi^D$. Each country i individually sets per unit emission taxes τ^i. Cost minimizing behavior of the representative firm implies that marginal abatement costs equal the emission tax:

$$\tau^i = \frac{a^i}{\phi^i} \ , \quad \text{with} \quad \tau^i \in \left[0, \frac{\bar{e}}{\phi^i}\right] \ , \quad i \in \{I, D\} \ . \tag{3}$$

Thus, both emissions E^i and abatement costs C^i of country i can be expressed in terms of the emission taxes τ^i:

$$E^i(\tau^i) = \bar{e} - \phi^i \tau^i \ , \quad \text{with} \quad i \in \{I, D\} \ , \tag{4}$$

$$C^i(\tau^i) = \frac{\phi^i}{2} \left(\tau^i\right)^2 \ , \quad \text{with} \quad i \in \{I, D\} \ . \tag{5}$$

The sum of the emissions of both countries accumulate the stock of greenhouse gases, s, instantaneously:

$$s = \sum_{j \in \{I,D\}} E^j(\tau^j) \ . \tag{6}$$

[1] Note that we assume that $\bar{e}^I = \bar{e}^D = \bar{e}$ as both industrial and developing countries contribute a significant share to global emissions of greenhouse gases.

[2] This is a standard short cut to capture aggregate abatement costs in country i (see, e.g., Falk and Mendelsohn 1993).

Note that, for ease of presentation, it is assumed that the initial stock is zero.[3]

The damage caused by the stock of greenhouse gases is given by:

$$\frac{\beta^i}{2} s^2 \ , \quad \text{with} \quad \beta^i > 0 \ , \quad i \in \{I, D\} \ , \tag{7}$$

where $\beta^I \leq \beta^D$ as developing countries are more affected by damages caused by the climate change than the industrial countries (IPCC 2007).

4 Social Optimum and Decentralization

We first characterize the social optimum and the decentralized solution. The social optimum is the efficiency goal of an international agreement. The decentralized solution is the outcome that prevails if no agreement is achieved.

4.1 Social Optimum

Consider a social planner seeking to maximize total welfare, i.e., seeking to minimize the net present value of the total costs of emission abatement and the sum of national damages stemming from greenhouse gas emissions. Hence, the social planner wants to minimize

$$F^{SO}(\tau^I, \tau^D) := \sum_{j \in \{I,D\}} \frac{\phi^j}{2} (\tau^j)^2 + \frac{\beta^j}{2} s^2 \ , \tag{8}$$

with respect to τ^I and τ^D, subject to equation (6), and $\tau^i \geq 0, \ i \in \{I, D\}$.

If we insert (6) into F^{SO}, the first-order conditions for an optimal solution are

$$\frac{\partial F^{SO}}{\partial \tau^i} = \phi^i \left(\tau^i - (\beta^I + \beta^D) s \right) \quad = \quad 0 \ , \quad i \in \{I, D\} \, . \tag{9}$$

Due to the strict convexity of F^{SO} these necessary conditions are also sufficient for a unique solution. Equation (9) reveals that both countries set the same emission taxes τ in the social optimum. These are given by the following proposition:

Proposition 1 (Social optimum)

(i) The optimal emission tax $\tau^\star$ for both countries equals

$$\tau^\star = \frac{2\bar{e}(\beta^I + \beta^D)}{1 + (\beta^I + \beta^D)(\phi^I + \phi^D)} \ . \tag{10}$$

[3] Adding an initial stock $s_0 \neq 0$ would not qualitatively affect our results.

(ii) The optimal stock $s^\star$ is given by

$$s^\star = \frac{2\bar{e}}{1+(\beta^I+\beta^D)(\phi^I+\phi^D)} = \frac{\tau^\star}{(\beta^I+\beta^D)} \ . \tag{11}$$

(iii) The abatements a^i of both countries are given by

$$a^I = \frac{2\bar{e}(\beta^I+\beta^D)\phi^I}{1+(\beta^I+\beta^D)(\phi^I+\phi^D)} = \phi^I\tau^\star \ , \tag{12}$$

$$a^D = \frac{2\bar{e}(\beta^I+\beta^D)\phi^D}{1+(\beta^I+\beta^D)(\phi^I+\phi^D)} = \phi^D\tau^\star \ . \tag{13}$$

The proof of Proposition 1 is straightforward. Proposition 1 reveals the well-known property of a social optimum: The tax $\tau^\star$ is set at a level at which aggregate marginal costs of abatement equal aggregate marginal damages from the greenhouse gas stock. Both countries face the same tax. The developing country abates more and benefits more from aggregate abatement efforts.

To simplify the analysis we assume for the remainder of the paper

Assumption 1:

$$\bar{e} - \frac{\beta^D\phi^I + 2\beta^D\phi^D + \beta^I\phi^D}{\beta^I+\beta^D}\tau^\star > 0 \ . \tag{14}$$

The assumption implies that in the social optimum the abatement level a^I is below $\frac{\bar{e}}{2}$ and the abatement level a^D is below $\frac{2}{3}\bar{e}$. Hence we focus on circumstances for which socially desirable emission reductions are below 50% in industrial countries and below 66.7% in developing countries. For $\beta^I = \beta^D$ and $\phi^I = \phi^D$ Assumption 1 simplifies to $\bar{e} - 2a^D = \bar{e} - 2a^I > 0$.

Note that Assumption 1 is equivalent to the following condition solely expressed in terms of the exogenous parameters of the model:

$$1 + \beta^I\phi^I > \beta^D\phi^I + 3\beta^D\phi^D + \beta^I\phi^D \ .$$

4.2 Decentralized Solution

Next we examine a decentralized system where the government in each country seeks to minimize its own costs and damages. We look for Nash equilibria when countries simultaneously choose their emission taxes. Given the choice of the other country, country i minimizes

$$F^{DS,i}(\tau^i) := \frac{\phi^i}{2}(\tau^i)^2 + \frac{\beta^i}{2}s^2 \tag{15}$$

with respect to τ^i and subject to equation (6), and $\tau^i \geq 0$.

If we insert (6) into $F^{DS,i}$, we obtain the first-order condition

$$\frac{\partial F^{DS,i}}{\partial \tau^i} = \phi^i \left(\tau^i - \beta^i s\right) = 0 \ . \tag{16}$$

Analogously to Section 4.1, this necessary condition is also sufficient for a unique solution due to the strict convexity of $F^{DS,i}$.

The set of the necessary and sufficient conditions (16) for both countries $i \in \{I, D\}$ determines the Nash equilibrium. Solving for the tax rates yields

Proposition 2 (Decentralized solution)
There exists a unique Nash equilibrium characterized by $\hat{\tau}^i$ for each country $i \in \{I, D\}$:

$$\hat{\tau}^i = \frac{2\bar{e}\beta^i}{1 + \beta^I\phi^I + \beta^D\phi^D} \ . \tag{17}$$

This yields the following equilibrium stock $\hat{s}$:

$$\hat{s} = \frac{2\bar{e}}{1 + \beta^I\phi^I + \beta^D\phi^D} \ . \tag{18}$$

The proof of Proposition 2 is straightforward. Proposition 2 implies

Corollary 1
We have

$$\hat{s} - s^\star = 2\bar{e}\frac{\beta^I\phi^D + \beta^D\phi^I}{(1 + \beta^I\phi^I + \beta^D\phi^D)(1 + (\beta^I + \beta^D)(\phi^I + \phi^D))} > 0 \ . \tag{19}$$

Proposition 2 reveals the well-known result that decentralized decisions on contributions to the public good "emission reduction" lead to underprovision. Abating emissions in one country creates a positive externality for the other country as it reduces damages in all countries. In a decentralized solution, countries are not compensated for these externalities.

It is also useful to compare tax rates in the social optimum and in the decentralized solution:

Corollary 2

We have

$$\hat{\tau}^I \;<\; \tau^\star \textit{ for all } 0 < \beta^I \le \beta^D,\; 0 < \phi^I \le \phi^D \;, \tag{20}$$

$$\hat{\tau}^D \;<\; \tau^\star \quad \Leftrightarrow \quad \beta^I + (\beta^I)^2\phi^I > (\beta^D)^2\phi^I \;. \tag{21}$$

We note that $\hat{\tau}^D$ may exceed $\tau^\star$ when β^I is small relative to β^D. The intuition for this result is quite clear: the developing country has an even higher incentive to increase its carbon emission tax in the decentralized solution because it suffers high damages and the industrial country chooses little abatement which, in turn, induces the developing country to choose high emission taxes. In the social optimum, however, the costs of abatement are born by both countries.

5 Development-Compatible Refunding Scheme

We now design a development-compatible refunding scheme (DCR). The scheme works as follows: The industrial country is required to pay an initial fee of $f_0^I \ge 0$ into a fund if it decides to join the DCR. Members are free to choose national emission taxes τ^i. The emission tax revenues of all countries are also collected in this fund. A fraction $\alpha \in [0, 1]$ of the fund is reimbursed to the participating countries in proportion to the relative emission reductions they have achieved, whereas the remaining fraction $(1-\alpha)$ of the fund's assets is paid back to the industrial country if it is a DCR member.

In the following, we analyze the potential of a DCR to mitigate climate change. We explain the rules and the timing of payments and refunds in detail and derive conditions under which member countries of the DCR implement socially optimal taxes.

5.1 Rules and Timing of the DCR

The timing of the DCR is illustrated in Figure 1. At the beginning countries sign the DCR which is managed by an administering agency (AA). Signing the agreement involves

- Payment of an initial fee f_0^I of the industrial country into the fund.
- Collection of taxes in the fund.

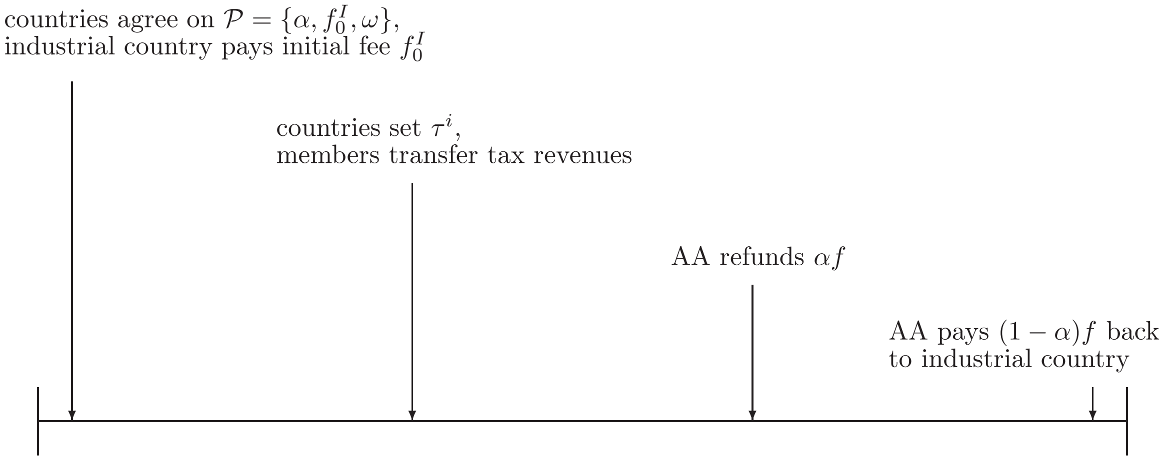

Figure 1: An illustration of the timing of the development-compatible refunding scheme.

- Agreement to a refunding formula with parameters $\{\alpha, \omega\}$.

For the refund r^i a member country i receives, we assume the following refunding rule:

$$r^i = \alpha f \frac{\tilde{\omega}^i a^i}{\sum_{j \in DCR} \tilde{\omega}^j a^j} = \alpha f \frac{\omega^i \tau^i}{\sum_{j \in DCR} \omega^j \tau^j} \ , \quad i \in DCR \ , \tag{22}$$

where we have set $\omega^i = \tilde{\omega}^i \phi^i$. The formula captures the basic idea of refunding: the refund a country i receives is proportional to the relative emission reductions it achieves. Varying the weights ω^i ($\omega^i > 0$) allows to strengthen or to weaken the size of the refund country i obtains if it chooses a particular tax level τ^i and corresponding abatement $a^i = \tau^i \phi^i$. Since only the ratio of the weights ω^i matters, we set $\omega := \omega^I / \omega^D$ and thus

$$\begin{aligned} r^I &= \alpha f \frac{\omega}{\omega + \frac{\tau^D}{\tau^I}} \ , \\ r^D &= \alpha f \frac{\frac{\tau^D}{\tau^I}}{\omega + \frac{\tau^D}{\tau^I}} = \alpha f \frac{\tau^D}{\tau^I \omega + \tau^D} \ . \end{aligned}$$

The assets of the fund f before refunds are made are given by

$$f = \sum_{j \in DCR} \left(f_0^j + \tau^j (\bar{e} - \phi^j \tau^j) \right) \ , \tag{23}$$

where $f_0^D = 0$.

The global warming coupled with the refunding scheme introduces reciprocal and unidirectional externalities:

Reciprocal externalities

- Positive tax externality (D→I, I→D): the higher the abatement of one country, the higher are the taxes it has to pay into the fund and the higher is the refund for the other country.

- Negative refunding externality (D→I, I→D): the higher the abatement of one country, the lower is the refund for the other country, given its tax choice.

- Positive environmental damage externality (D→I, I→D): the higher the abatement of one country, the lower is the damage for the other country.

Unidirectional externalities

- Positive initial fee externality (I→D): the higher the initial fee of the industrial country, the higher is the refund to the developing country.

- Positive residual refund externality (D→I): the higher the tax of the developing country, the higher is the residual fund at the end for the industrial country.

The idea of the scheme is to choose the parameters such that the externalities balance and both the developing country and the industrial country choose socially optimal taxes.

Throughout the remaining section, we assume that both countries join the DCR. We can summarize the treaty by the policy parameters

$$\mathcal{P} := \{f_0^I, \alpha, \omega\} \ , \tag{24}$$

as $\mathcal{P}$ fully determines the monetary flows that will occur. Now we define

Definition 1 (Feasible $\mathcal{P}$)
The set of policy parameters $\mathcal{P} = \{\alpha, f_0^I, \omega\}$ is called feasible *if*

$$\alpha \in [0,1], \quad f_0^I \geq 0, \quad \textit{and} \ \ \omega > 0 \ .$$

When countries choose a particular $\mathcal{P}$ they seek to implement the socially optimal tax:

Definition 2 (Tax goal of DCR)
The DCR's tax goal *is given by the socially optimal tax rate (10), i.e. by*

$$\tau^I = \tau^D = \tau^\star = \frac{2\bar{e}(\beta^I + \beta^D)}{1 + (\beta^I + \beta^D)(\phi^I + \phi^D)} \ . \tag{25}$$

We can then define

Definition 3 (Socially optimal $\mathcal{P}$)
A given set of policy parameters $\mathcal{P}$ is called socially optimal *if it is feasible and the DCR members implement the tax goal under this $\mathcal{P}$.*

5.2 General Characterization

We examine whether it is possible to find feasible policy parameters $\mathcal{P}$ for which the countries implement the tax goal. The industrial country I minimizes

$$F^I(\tau^I) := \frac{\phi^I}{2}(\tau^I)^2 + \frac{\beta^I}{2}s^2 + \tau^I(\bar{e} - \phi^I\tau^I) - \alpha f \frac{\omega^I\tau^I}{\sum_j \omega^j\tau^j} + f_0^I - (1-\alpha)f \tag{26}$$

with respect to τ^I, subject to equation (6) and $\tau^I \geq 0$, given the policy parameters $\mathcal{P}$ and the choices of the other country. The developing country D minimizes

$$F^D(\tau^D) := \frac{\phi^D}{2}(\tau^D)^2 + \frac{\beta^D}{2}s^2 + \tau^D(\bar{e} - \phi^D\tau^D) - \alpha f \frac{\omega^D\tau^D}{\sum_j \omega^j\tau^j} \tag{27}$$

with respect to τ^D, subject to equation (6) and $\tau^D \geq 0$.

Lemma 1
If the DCR members implement the tax goal $\tau^\star$, the policy parameters α and f_0^I in $\mathcal{P}$ have to satisfy

$$\alpha = \frac{(\omega+1)\left(\bar{e} - \frac{\beta^D\phi^I + 2\beta^D\phi^D + \beta^I\phi^D}{\beta^I+\beta^D}\tau^\star\right)}{2(\bar{e} - (\phi^I + \phi^D)\tau^\star)}, \tag{28}$$

$$f_0^I = \frac{2(\omega+1)\tau^\star(\bar{e} - \phi^D\frac{\beta^I+2\beta^D}{\beta^I+\beta^D}\tau^\star)(\bar{e} - (\phi^I+\phi^D)\tau^\star)}{\omega(\bar{e} - \frac{\beta^D\phi^I+2\beta^D\phi^D+\beta^I\phi^D}{\beta^I+\beta^D}\tau^\star)} - \frac{(\omega+1)\tau^\star(\bar{e} - 2\phi^D\tau^\star)}{\omega} - \tau^\star(2\bar{e} - (\phi^I+\phi^D)\tau^\star)\ . \tag{29}$$

The proof can be found in the appendix. To construct a socially optimal $\mathcal{P}$, the parameters have to fulfill the feasibility conditions, Lemma 1 and second-order conditions. The next lemma characterizes these conditions for the existence of a socially optimal policy scheme $\mathcal{P}$:

Lemma 2 (Conditions for socially optimal $\mathcal{P}$)
The set of policy parameters $\mathcal{P}$ is socially optimal if and only if ω satisfies

$$(i) \qquad 0 < \omega \leq \frac{\bar{e} - \frac{\beta^D\phi^I + 2\beta^I\phi^I + \beta^I\phi^D}{\beta^I + \beta^D}\tau}{\bar{e} - \frac{\beta^D\phi^I + 2\beta^D\phi^D + \beta^I\phi^D}{\beta^I + \beta^D}\tau} \ , \tag{30}$$

$$(ii) \qquad \frac{2(\omega+1)(\bar{e} - \phi^D\frac{\beta^I + 2\beta^D}{\beta^I + \beta^D}\tau)(\bar{e} - (\phi^I + \phi^D)\tau)}{\omega(\bar{e} - \frac{\beta^D\phi^I + 2\beta^D\phi^D + \beta^I\phi^D}{\beta^I + \beta^D}\tau)} - \frac{(\omega+1)(\bar{e} - 2\phi^D\tau)}{\omega}$$
$$-(2\bar{e} - (\phi^I + \phi^D)\tau) \geq 0 \ , \tag{31}$$

$$(iii) \qquad \phi^D(-1 + \beta^D\phi^D + \frac{\bar{e} - \frac{\beta^D\phi^I + 2\beta^D\phi^D + \beta^I\phi^D}{\beta^I + \beta^D}\tau}{\bar{e} - (\phi^I + \phi^D)\tau}) + 2(\bar{e} - \phi^D\frac{\beta^I + 2\beta^D}{\beta^I + \beta^D}\tau)\frac{1}{(\omega+1)\tau}$$
$$-\frac{(\bar{e} - \frac{\beta^D\phi^I + 2\beta^D\phi^D + \beta^I\phi^D}{\beta^I + \beta^D}\tau)(\bar{e} - 2\phi^D\tau)}{(\bar{e} - (\phi^I + \phi^D)\tau)\tau} > 0 \ , \tag{32}$$

where $\tau = \tau^\star$.

The proof can be found in the appendix. A closer investigation of the conditions (30), (31) and (32) reveals the following fact.

Fact 1
Conditions (30), (31) and (32) impose an upper bound on ω and a lower bound that is equal to zero.

The proof of the fact is given in the appendix.

The intuition why a DCR imposes an upper bound on ω runs as follows: a very high level of ω and thus a large value of ω^I relative to ω^D would induce that the developing country abates too little relative to the industrial country and thus it is impossible to induce that the socially optimal abatement levels in equation (12) and (13) are chosen.

It is not guaranteed that a socially optimal policy scheme exists for an arbitrary parameter set as it is not ensured that the upper bound in Fact 1 is positive. However, we obtain a simple sufficient condition when we assume that β^I is sufficiently small:

Corollary 3
Suppose that $\bar{e} - 3\phi^D\tau^\star > 0$ and that β^I is sufficiently small. Then, there exists always a socially optimal policy scheme $\mathcal{P} = \{\alpha, f_0^I, \omega\}$.

The proof can be found in the appendix.

In the next section, we look at a variety of special cases.

6 Special Cases

6.1 Homogeneous Countries

In this subsection, we assume that countries are symmetric regarding their parameters describing damage and abatement costs, i.e. we assume $\beta^I = \beta^D = \beta$ and $\phi^I = \phi^D = \phi$. Applying Lemma 2, we obtain

Proposition 3
Suppose $\beta^I = \beta^D = \beta$ and $\phi^I = \phi^D = \phi$. Then, there exists a socially optimal set of policy schemes $\mathcal{P}$. Such policy schemes satisfy $\omega^I \leq \omega^D$. For $\omega^I = \omega^D$ we have $\alpha = 1$.

The proof can be found in the appendix.

Proposition 3 implies that a DCR exists when countries are identical regarding damages and abatement costs. Such a scheme requires a refunding rule where the weight of the developing country is larger or equal than that of the industrial country. The intuition for this runs as follows: From an efficiency point of view, both countries should abate to the same amount, i.e. set their taxes to $\tau^I = \tau^D = \tau^\star$. For $\alpha < 1$, the industrial country has higher incentives to tax emissions compared to the developing country as it will receive the residual fund at the end which is larger the larger the tax revenues are. In order to induce the developing country to set the same emission tax if $\alpha < 1$, the weight in the refunding formula has to be higher for the developing country.

Corollary 4
Suppose $\beta^I = \beta^D = \beta$ and $\phi^I = \phi^D = \phi$. The developing country is always net receiver under a socially optimal policy scheme.

The proof can be found in the appendix.

6.2 Identical Abatement Costs and Heterogeneous Damages

In this subsection we assume that the countries display identical abatement costs, i.e. $\phi^I = \phi^D = \phi$, and that damages are extremely unequal, i.e. $\beta^I = 0 < \beta^D = \beta$. We obtain:

Proposition 4
Suppose that $\phi^I = \phi^D = \phi$ and $\beta^I = 0 < \beta^D = \beta$. Then there exists a socially optimal

set of policy schemes $\mathcal{P}$. Such policy schemes satisfy

$$0 < \omega < \frac{4\beta^3\phi^3 + 2\beta^2\phi^2 + 2\beta\phi - 1}{-4\beta^3\phi^3 - 10\beta^2\phi^2 + 6\beta\phi - 1} \ . \tag{33}$$

In particular, the scheme $\mathcal{P} = \{\alpha, f_0^I, 1\}$ with

$$\begin{aligned} \alpha &= \frac{\bar{e} - 3\phi\tau}{\bar{e} - 2\phi\tau} \ , \\ f_0^I &= 2\phi\tau^2 \frac{\bar{e} - \phi\tau}{\bar{e} - 3\phi\tau} \ , \end{aligned}$$

where $\tau = \tau^\star$, is socially optimal.

The proof can be found in the appendix.

In contrast to Subsection 6.1 it is possible to construct socially optimal policy schemes with $\omega = 1$ and $\alpha < 1$.

Corollary 5
Suppose $\phi^I = \phi^D = \phi$ and $\beta^I = 0 < \beta^D = \beta$. The developing country is net receiver under a socially optimal policy scheme if and only if $\omega^I \leq \omega^D$.

The proof of the corollary can be found in the appendix.

6.3 Equal Weights in the Refunding Formula

We now consider a special refunding formula that uses weights $\tilde{\omega}^i = 1$, $i \in \{I, D\}$. The refunding formula then covers the actual relative abatement country i achieves, namely

$$r^i = \alpha f \frac{\phi^i \tau^i}{\sum_j \phi^j \tau^j} \ , \quad i \in \{I, D\} \ . \tag{34}$$

We obtain the following result:

Proposition 5
For the refunding formula (34), there exists a socially optimal set of policy parameters $\mathcal{P} = \{\alpha, f_0^I, \frac{\phi^I}{\phi^D}\}$ if and only if

$$\begin{aligned} &\phi^D \left(\frac{\bar{e} - \frac{\phi^I\beta^D + 2\phi^D\beta^D + \phi^D\beta^I}{\beta^I + \beta^D}\tau}{\bar{e} - (\phi^I + \phi^D)\tau} - 1 \right) + \phi^D\beta^D \left(\frac{2\phi^I}{(\beta^I + \beta^D)(\phi^I + \phi^D)} + \phi^D \right) \\ &+ \frac{\bar{e} - \frac{\phi^I\beta^D + 2\phi^D\beta^D + \phi^D\beta^I}{\beta^I + \beta^D}\tau}{\bar{e} - (\phi^I + \phi^D)\tau} \frac{\phi^D - \phi^I}{(\phi^I + \phi^D)\tau}\bar{e} \quad > \quad 0 \ , \end{aligned} \tag{35}$$

where $\tau = \tau^\star$.

The proof can be found in the appendix.

This special case allows us to provide further simple sufficient conditions for the existence of a socially optimal policy scheme $\mathcal{P}$:

Corollary 6
Suppose a refunding formula with equal weights.

(i) For homogeneous countries $\beta^I = \beta^D$, $\phi^I = \phi^D$, there exists always a socially optimal policy scheme $\mathcal{P}$.

(ii) For countries with identical abatement costs $\phi^I = \phi^D = \phi$ and heterogeneous damages $\beta = 0 < \beta^D = \beta$, there exists always a socially optimal policy scheme $\mathcal{P}$.

6.4 No Initial Fees and Complete Refunding

It is important to stress that the presence of initial fees $f_0^I > 0$ is in general necessary to induce socially optimal abatement levels. We illustrate this fact by considering the case $f_0^I = 0$ and $\alpha = 1$.[4]

Proposition 6 (No initial fees and no residual fund)
Suppose $f_0^I = 0$ and $\alpha = 1$. Then, a socially optimal policy scheme $\mathcal{P}$ exists only if

$$\frac{4\tau(\bar{e} - (\phi^I + \phi^D)\tau)^2(\bar{e} - \phi^D \frac{\beta^I + 2\beta^D}{\beta^I + \beta^D}\tau)}{(\bar{e} - \frac{\beta^I\phi^D + 2\beta^D\phi^D + \beta^D\phi^I}{\beta^I + \beta^D}\tau)(\bar{e} - \frac{\beta^I\phi^D + 2\beta^I\phi^I + \beta^D\phi^I}{\beta^I + \beta^D}\tau)} - \tau(2\bar{e} - (\phi^I + \phi^D)\tau)$$

$$- \frac{2\tau(\bar{e} - (\phi^I + \phi^D)\tau)(\bar{e} - 2\phi^D\tau)}{\bar{e} - \frac{\beta^I\phi^D + 2\beta^I\phi^I + \beta^D\phi^I}{\beta^I + \beta^D}\tau} = 0 \ , \qquad (36)$$

where $\tau = \tau^\star$. Such a policy scheme will always fulfill $\omega \geq 1$.

The proof can be found in the appendix. Proposition 6 indicates that only in knife-edge cases it is possible to induce socially optimal abatement levels when no initial fees are paid by the industrial country. An example for such a knife-edge case is that of identical countries $\phi^I = \phi^D$ and $\beta^I = \beta^D$, shown in the following corollary. Hence, initial fees by industrial countries help to achieve socially optimal emission abatements and equity objectives.

[4] We note that the theoretical case $f_0^I = 0$ and $\alpha < 1$ would imply that the industrial country receives residual funds even if it does not pay an initial fee. As this would be a dramatic violation of a development-compatible refunding scheme, we neglect this case.

Corollary 7

For homogeneous countries $\phi^I = \phi^D = \phi$, $\beta^I = \beta^D = \beta$, there exists a socially optimal policy scheme $\mathcal{P}$ where no initial fees are paid and α is equal to one. It is given by $\mathcal{P} = \{1, 0, 1\}$.

The proof can be found in the appendix. For almost all other parameter constellations, a socially optimal policy scheme $\mathcal{P}$ with $f_0^I = 0$ and $\alpha = 1$ does not exist. An example are countries with identical abatement costs $\phi^I = \phi^D$ and heterogeneous damages $\beta^I = 0 < \beta^D$.[5]

The interpretation of the property $\omega \geq 1$ in Proposition 6 is as follows: As $\phi^I \leq \phi^D$, the industrial country abates less than the developing country when taxes are equal and therefore contributes more to the fund. Furthermore, as $\beta^I \leq \beta^D$, the industrial country is less affected by damages caused by higher emissions than the developing country. Hence, the industrial country has less incentives to select the socially optimal tax rates. To counteract these weaker incentives, the industrial country receives a higher share of the fund compared to the developing country.

7 Refunding Schemes without Tax Collection

In this section, we consider the potential of a refunding scheme that renounces collecting taxes from the member countries.

The simplest refunding scheme is when the industrial country pays an initial fee of f_0^I which is then refunded to the countries according to the relative emission abatement they achieve.

Proposition 7

Under a refunding scheme without tax collection, there exists a socially optimal policy scheme $\mathcal{P} = \{\alpha, f_0^I, \omega\}$ if and only if

$$\frac{\beta^I}{\phi^I} = \frac{\beta^D}{\phi^D} \tag{37}$$

holds. Such a scheme satisfies

$$\alpha = \frac{(\omega+1)^2\tau^2}{\omega f_0^I} \frac{\phi^I \beta^D}{\beta^I + \beta^D} \ ,$$

[5]In a similar way one can show that for almost all parameter constellations where a socially optimal policy scheme $\mathcal{P} = \{\alpha, f_0^I, \omega\}$ exists, it is not possible to find a socially optimal policy scheme $\mathcal{P} = \{1, f_0^I, \omega\}$.

where $\tau = \tau^\star$.

The proof can be found in the appendix.

The reason why condition (37) has to hold can be found by investigating the externalities that are at work. We focus on the case $\omega^I = \omega^D$. First, there is the positive environmental damage externality: if one country abates more, the damage for the other country decreases. The developing country benefits more from abatement by the industrial country as $\beta^D \geq \beta^I$. Second, for equal taxes $\tau^I = \tau^D$ the industrial country abates less than the developing country because its abatement costs are higher. These two effects balance each other if the relationship between marginal damages and marginal abatement costs is equal for both countries as given in equation (37). By varying the level of f_0^I and exploiting the negative refunding externality, the abatement levels of both countries can be raised to the socially optimal levels.

8 Conclusion

The successor to the Kyoto Protocol should promote voluntary abatement by developing countries. Our proposal calls for industrial countries to set up a global fund. Competition of industrial and developing countries for refunds yields the socially optimal solution. This feature solves the compliance problem that has weakened the Kyoto Protocol. Moreover, developing countries and in particular China and India would voluntarily join the system as joining actually entails no obligation as they can set the tax rate at zero. The development-compatible refunding system still requires coordination among industrial countries to pay the initial fees into the global fund. It appears that such coordination is a substantially smaller problem than world scale negotiations in the style of the Kyoto Protocol.

Appendix

Throughout the appendix, we work with the following abbreviations:

$$
\begin{aligned}
B &= \beta^I + \beta^D \ , \\
P &= \phi^I + \phi^D \ , \\
A &= \frac{\beta^D P + \phi^D B}{B} \ , \\
\tau &= \tau^\star \ \text{(tax goal)} \ , \\
\omega &= \frac{\omega^I}{\omega^D} \ .
\end{aligned}
$$

Proof of Lemma 1

Optimization of the objective functions F^I and F^D given in (26) and (27), respectively, yields the first-order conditions

$$
\begin{aligned}
\frac{\partial F^I}{\partial \tau^I} &= \bar{e} - \phi^I \tau^I - \beta^I \phi^I s - \alpha(\bar{e} - 2\phi^I \tau^I)\frac{\omega^I \tau^I}{\sum \omega^j \tau^j} - \alpha f \frac{\omega^I \omega^D \tau^D}{(\sum \omega^j \tau^j)^2} \\
&\quad -(1-\alpha)(\bar{e} - 2\phi^I \tau^I) = 0 \ , \\
\frac{\partial F^D}{\partial \tau^D} &= \bar{e} - \phi^D \tau^D - \beta^D \phi^D s - \alpha(\bar{e} - 2\phi^D \tau^D)\frac{\omega^D \tau^D}{\sum \omega^j \tau^j} - \alpha f \frac{\omega^I \omega^D \tau^I}{(\sum \omega^j \tau^j)^2} = 0 \ .
\end{aligned}
$$

Assuming that both countries implement the tax goal, i.e. $\tau^I = \tau^D = \tau$, the first-order conditions are equivalent to

$$
\begin{aligned}
0 &= \bar{e} - \phi^I \tau - \frac{\beta^I \phi^I}{B}\tau - \alpha(\bar{e} - 2\phi^I \tau)\frac{\omega}{\omega+1} - (1-\alpha)(\bar{e} - 2\phi^I \tau) \\
&\quad -\alpha(f_0^I + \tau(2\bar{e} - P\tau))\frac{\omega}{(\omega+1)^2 \tau} \\
0 &= \bar{e} - \phi^D \tau - \frac{\beta^D \phi^D}{B}\tau - \alpha(\bar{e} - 2\phi^D \tau)\frac{1}{\omega+1} \\
&\quad -\alpha(f_0^I + \tau(2\bar{e} - P\tau))\frac{\omega}{(\omega+1)^2 \tau} \ .
\end{aligned}
$$

Solving these for α and f_0^I leads to

$$
\begin{aligned}
\alpha &= \frac{(\omega+1)(\bar{e} - A\tau)}{2(\bar{e} - P\tau)} \ , \\
f_0^I &= \frac{2(\omega+1)\tau(\bar{e} - \phi^D \frac{\beta^I + 2\beta^D}{B}\tau)(\bar{e} - P\tau)}{\omega(\bar{e} - A\tau)} - \frac{(\omega+1)\tau(\bar{e} - 2\phi^D \tau)}{\omega} - \tau(2\bar{e} - P\tau) \ .
\end{aligned}
$$

Note that Assumption 1 guarantees that α and f_0^I are well defined as $\bar{e}-P\tau \geq \bar{e}-A\tau > 0$. □

Proof of Lemma 2

Under tax goal implementation, the policy parameters α and f_0^I are given by

$$\alpha = \frac{(\omega+1)(\bar{e}-A\tau)}{2(\bar{e}-P\tau)} , \tag{A.1}$$

$$f_0^I = \frac{2(\omega+1)\tau(\bar{e}-\phi^D\frac{\beta^I+2\beta^D}{B}\tau)(\bar{e}-P\tau)}{\omega(\bar{e}-A\tau)} - \frac{(\omega+1)\tau(\bar{e}-2\phi^D\tau)}{\omega} - \tau(2\bar{e}-P\tau) , \tag{A.2}$$

see Lemma 1. They have to satisfy

$$\alpha \in [0,1] ,$$
$$f_0^I \geq 0 .$$

Condition $\alpha \geq 0$ is satisfied under Assumption 1.

Condition $\alpha \leq 1$ leads to (i), together with the feasibility condition $\omega > 0$. Condition $f_0^I \geq 0$ leads to (ii).

Now we derive the second-order conditions which ensure that the solution we found from the necessary conditions is indeed a minimum. The second derivatives of the objective functions $F^I(\tau^I)$ and $F^D(\tau^D)$ are

$$\frac{\partial^2 F^I}{(\partial\tau^I)^2} = -\phi^I + \beta^I(\phi^I)^2 + 2\alpha\phi^I\frac{\omega^I\tau^I}{\sum\omega^j\tau^j} - 2\alpha(\bar{e}-2\phi^I\tau^I)\frac{\omega^I\omega^D\tau^D}{(\sum\omega^j\tau^j)^2} + 2\alpha f\frac{(\omega^I)^2\omega^D\tau^D}{(\sum\omega^j\tau^j)^3} + 2(1-\alpha)\phi^I ,$$

$$\frac{\partial^2 F^D}{(\partial\tau^D)^2} = -\phi^D + \beta^D(\phi^D)^2 + 2\alpha\phi^D\frac{\omega^D\tau^D}{\sum\omega^j\tau^j} - 2\alpha(\bar{e}-2\phi^D\tau^D)\frac{\omega^I\omega^D\tau^I}{(\sum\omega^j\tau^j)^2} + 2\alpha f\frac{(\omega^D)^2\omega^I\tau^I}{(\sum\omega^j\tau^j)^3} .$$

Using $\tau^I = \tau^D = \tau$ and inserting the expressions for α and f_0^I, the second-order conditions can be written as

$$\begin{aligned}
0 &< \phi^I(1+\beta^I\phi^I - \frac{\bar{e}-A\tau}{\bar{e}-P\tau}) - \frac{(\bar{e}-A\tau)(\bar{e}-2\phi^I\tau)}{\bar{e}-P\tau}\frac{\omega}{(\omega+1)\tau} \\
&\quad +2(\bar{e}-\phi^D\frac{\beta^I+2\beta^D}{B}\tau)\frac{\omega}{(\omega+1)\tau} - \frac{(\bar{e}-A\tau)(\bar{e}-2\phi^D\tau)}{\bar{e}-P\tau}\frac{\omega}{(\omega+1)\tau} , \\
0 &< \phi^D(-1+\beta^D\phi^D + \frac{\bar{e}-A\tau}{\bar{e}-P\tau}) - \frac{(\bar{e}-A\tau)(\bar{e}-2\phi^D\tau)}{\bar{e}-P\tau}\frac{\omega}{(\omega+1)\tau} \\
&\quad +2(\bar{e}-\phi^D\frac{\beta^I+2\beta^D}{B}\tau)\frac{1}{(\omega+1)\tau} - \frac{(\bar{e}-A\tau)(\bar{e}-2\phi^D\tau)}{\bar{e}-P\tau}\frac{1}{(\omega+1)\tau} .
\end{aligned}$$

They further simplify to

$$\begin{aligned}
0 &< \phi^I(1+\beta^I\phi^I - \frac{\bar{e}-A\tau}{\bar{e}-P\tau}) + 2\frac{\beta^D\phi^I}{B}\frac{\omega}{\omega+1} , \\
0 &< \phi^D(-1+\beta^D\phi^D + \frac{\bar{e}-A\tau}{\bar{e}-P\tau}) - \frac{(\bar{e}-A\tau)(\bar{e}-2\phi^D\tau)}{(\bar{e}-P\tau)\tau} \\
&\quad +2(\bar{e}-\phi^D\frac{\beta^I+2\beta^D}{B}\tau)\frac{1}{(\omega+1)\tau} .
\end{aligned}$$

The first inequality always holds because $\bar{e}-A\tau \leq \bar{e}-P\tau$ and Assumption 1. The second inequality is (iii). This completes the proof. □

Proof of Fact 1

Condition (31) in Lemma 2 is equivalent to

$$\begin{aligned}
&\omega\left\{2(\bar{e}-\phi^D\frac{\beta^I+2\beta^D}{B}\tau) - \frac{(\bar{e}-A\tau)(\bar{e}-2\phi^D\tau)}{\bar{e}-P\tau} - \frac{(\bar{e}-A\tau)(2\bar{e}-P\tau)}{\bar{e}-P\tau}\right\} \\
&\geq \frac{(\bar{e}-A\tau)(\bar{e}-2\phi^D\tau)}{\bar{e}-P\tau} - 2(\bar{e}-\phi^D\frac{\beta^I+2\beta^D}{B}\tau) .
\end{aligned}$$

Assuming that the term in curly brackets is positive, we can solve this inequality for ω and get a lower bound on ω. On the other hand, under Assumption 1, the term in curly brackets being positive implies that the term on the right-hand side is negative, so that the lower bound on ω is in fact negative.

A similar consideration of condition (32) reveals that it is equivalent to

$$\begin{aligned}
&\omega\left\{\phi^D\tau(-1+\beta^D\phi^D+\frac{\bar{e}-A\tau}{\bar{e}-P\tau}) - \frac{(\bar{e}-A\tau)(\bar{e}-2\phi^D\tau)}{\bar{e}-P\tau}\right\} \\
&> \frac{(\bar{e}-A\tau)(\bar{e}-2\phi^D\tau)}{\bar{e}-P\tau} - 2(\bar{e}-\phi^D\frac{\beta^I+2\beta^D}{B}\tau) - \phi^D\tau(-1+\beta^D\phi^D+\frac{\bar{e}-A\tau}{\bar{e}-P\tau})
\end{aligned}$$

Assuming that the term in curly brackets is positive, we obtain a lower bound on ω. But again, this assumption also implies that the right-hand side of the inequality above is negative. This yields in fact a negative lower bound on ω.

Hence (ii) and (iii) in Lemma 2 either provide a negative lower bound on ω or an upper bound for which the sign still has to be determined.

Therefore, the largest lower bound on ω is given in (30) and is equal to zero. □

Proof of Corollary 3

If we set $\beta^I = 0$, conditions (i)–(iii) in Lemma 2 simplify to

$$\text{(i)} \qquad 0 < \omega \leq \frac{\bar{e} - \phi^I \tau}{\bar{e} - (\phi^I + 2\phi^D)\tau} \ ,$$

$$\text{(ii)} \qquad \frac{2(\omega+1)(\bar{e} - 2\phi^D\tau)(\bar{e} - P\tau)}{\omega(\bar{e} - (\phi^I + 2\phi^D)\tau)} - \frac{(\omega+1)(\bar{e} - 2\phi^D\tau)}{\omega} - (2\bar{e} - P\tau) \geq 0 \ ,$$

$$\text{(iii)} \qquad \phi^D(-1 + \beta^D\phi^D + \frac{\bar{e} - (\phi^I + 2\phi^D)\tau}{\bar{e} - P\tau}) + 2\frac{\bar{e} - 2\phi^D\tau}{(\omega+1)\tau}$$
$$- \frac{(\bar{e} - (\phi^I + 2\phi^D)\tau)(\bar{e} - 2\phi^D\tau)}{(\bar{e} - P\tau)\tau} > 0 \ .$$

The second inequality in (i) is equivalent to

$$\frac{\omega+1}{\omega} \geq \frac{2(\bar{e} - P\tau)}{\bar{e} - \phi^I\tau} \ , \tag{A.3}$$

and (ii) can be written as

$$\frac{(\omega+1)(\bar{e} - 2\phi^D\tau)}{\omega} \underbrace{\left(\frac{2(\bar{e} - (\phi^I + \phi^D)\tau)}{\bar{e} - (\phi^I + 2\phi^D)\tau} - 1\right)}_{>1} - (2\bar{e} - P\tau) \geq 0 \ .$$

If $\frac{\omega+1}{\omega} \geq \frac{2\bar{e} - P\tau}{\bar{e} - 2\phi^D\tau}$, which is a stronger condition on ω than (A.3) as $\frac{2\bar{e} - P\tau}{\bar{e} - 2\phi^D\tau} > \frac{2(\bar{e} - P\tau)}{\bar{e} - \phi^I\tau}$, the last inequality holds true. We therefore find that for all ω that satisfy

$$\omega \leq \frac{\bar{e} - 2\phi^D\tau}{\bar{e} - (\phi^I - \phi^D)\tau} \ (< 1) \ , \tag{A.4}$$

conditions (i) and (ii) are fulfilled.

Now we consider condition (iii). It can be written as

$$\phi^D(-1 + \frac{\bar{e} - (\phi^I + 2\phi^D)\tau}{\bar{e} - P\tau} + \frac{\bar{e} - 2\phi^D\tau}{\bar{e} - P\tau})$$
$$+2\frac{\bar{e} - 2\phi^D\tau}{(\omega+1)\tau} - \frac{\bar{e} - 2\phi^D\tau}{\tau} + \beta^D(\phi^D)^2 \ > \ 0 \ .$$

Rearranging terms yields

$$\phi^D \frac{\bar{e} - 3\phi^D \tau}{\bar{e} - P\tau} + \frac{\bar{e} - 2\phi^D \tau}{\tau} \left(\frac{2}{\omega + 1} - 1 \right) + \beta^D (\phi^D)^2 > 0 \ .$$

The second term is positive as we saw above that $\omega < 1$, and the first term is positive if we strengthen Assumption 1 to $\bar{e} - 3\phi^D \tau > 0$. Taking everything together, for a suitable choice of the parameters of the model, β^D, ϕ^I and ϕ^D and a sufficiently small β^I, we can find a socially optimal parameter set $\mathcal{P} = \{\alpha, f_0^I, \omega\}$. □

Proof of Proposition 3

For homogeneous countries $\beta^I = \beta^D = \beta,\ \phi^I = \phi^D = \phi$, the parameters α and f_0^I derived in Lemma 1 change to

$$\begin{aligned} \alpha &= \frac{\omega + 1}{2} \ , \\ f_0^I &= \frac{1 - \omega}{\omega} (\bar{e} - \phi\tau)\tau \ . \end{aligned}$$

Since Assumption 1 simplifies to $\bar{e} - 2\phi\tau > 0$ in the case of homogeneous countries, both $\alpha \leq 1$ and $f_0^I \geq 0$ are equivalent to $\omega \leq 1$. The second-order conditions are

$$\begin{aligned} 0 &< \beta\phi^2 + \frac{\omega}{\omega + 1}\phi \ , \\ 0 &< \beta\phi^2 + (\bar{e} - \phi\tau)\frac{1 - \omega}{(\omega + 1)\tau} + \frac{\omega}{\omega + 1}\phi \ . \end{aligned}$$

They are satisfied for any $\omega \leq 1$. Hence, for a refunding rule with $\omega^I \leq \omega^D$, there exist socially optimal parameter sets $\mathcal{P}$.

For $\omega^I = \omega^D$ and hence $\omega = 1$, we obtain $\alpha = 1$. □

Proof of Corollary 4

Consider homogeneous countries $\beta^I = \beta^D = \beta,\ \phi^I = \phi^D = \phi$. The developing country is net receiver if and only if its payments to the fund are smaller or equal than the refund it gets, i.e. if and only if

$$\tau^D (\bar{e} - \phi\tau^D) \leq \alpha f \frac{\omega^D \tau^D}{\sum_j \omega^j \tau^j} \ .$$

Inserting the tax goal $\tau^I = \tau^D = \tau$ and the policy parameters α and f_0^I derived in the proof of Proposition 3, this condition is equivalent to

$$(\bar{e} - \phi\tau)\tau \frac{1 - \omega}{2\omega} \geq 0 \ . \tag{A.5}$$

As proved in Proposition 3, the policy parameters $\mathcal{P}$ are socially optimal if and only if $\omega \leq 1$, therefore (A.5) holds true and the developing country is net receiver for all socially optimal policy parameters. $\square$

Proof of Proposition 4

Suppose identical abatement costs $\phi^I = \phi^D = \phi$ and heterogeneous damage costs $\beta^I = 0 < \beta^D = \beta$. Then, the parameters α and f_0^I derived in Lemma 1 change to

$$\alpha = \frac{(\omega+1)(\bar{e}-3\phi\tau)}{2(\bar{e}-2\phi\tau)} , \tag{A.6}$$

$$f_0^I = \frac{\tau(\omega+1)(\bar{e}-\phi\tau)(\bar{e}-2\phi\tau)}{\omega(\bar{e}-3\phi\tau)} - 2\tau(\bar{e}-\phi\tau) . \tag{A.7}$$

Assumption 1 simplifies to $\bar{e} - 3\phi\tau > 0$. Since $\tau = \frac{2\bar{e}\beta}{1+2\beta\phi}$, this is equivalent to

$$\beta\phi < \frac{1}{4} .$$

For a socially optimal parameter set $\mathcal{P} = \{\alpha, f_0^I, \omega\}$, $\omega > 0$ has to hold. The condition $\alpha \geq 0$ is satisfied under Assumption 1, and $\alpha \leq 1$ is equivalent to

$$\omega \leq \frac{\bar{e}-\phi\tau}{\bar{e}-3\phi\tau} . \tag{A.8}$$

Moreover, $f_0^I \geq 0$ has to hold. This can be written as

$$\bar{e} - 2\phi\tau - \omega(\bar{e}-4\phi\tau) \geq 0 . \tag{A.9}$$

We only have to examine the case $\bar{e} - 4\phi\tau > 0$, as for $\bar{e} - 4\phi\tau \leq 0$, (A.9) holds. Inequality (A.9) is then equivalent to

$$\omega \leq \frac{\bar{e}-2\phi\tau}{\bar{e}-4\phi\tau} . \tag{A.10}$$

Comparison of (A.8) and (A.10) reveals that (A.8) is the stronger condition.

We now turn to the second-order conditions. For identical abatement costs $\phi^I = \phi^D = \phi$ and heterogeneous damage costs $\beta^I = 0 < \beta^D = \beta$, they can be written as

$$0 < \phi^2 \frac{\tau}{\bar{e}-2\phi\tau} + 2\frac{\omega}{(\omega+1)\tau}\phi\tau ,$$

$$0 < -\phi^2 \frac{\tau}{\bar{e}-2\phi\tau} + \beta\phi^2 - \frac{\bar{e}-3\phi\tau}{\tau} + \frac{2(\bar{e}-2\phi\tau)}{(\omega+1)\tau} =: f(\omega) .$$

The former inequality always holds since $\bar{e} - 2\phi\tau > 0$ and $\omega > 0$. For the latter we calculate the derivative with respect to ω :

$$f'(\omega) = -\frac{2(\bar{e} - 2\phi\tau)}{(1+\omega)^2\tau} < 0 \ .$$

Hence it is strictly monotonically decreasing in ω. Consider $f(\omega)$ evaluated at $\omega = 0$. Using $\tau = \frac{2\bar{e}\beta}{1+2\beta\phi}$, we find

$$f(0) = \frac{-4\beta^3\phi^3 - 2\beta^2\phi^2 - 2\beta\phi + 1}{2\beta(1-2\beta\phi)} \ ,$$

which is positive for $0 \leq \beta\phi < 1/4$. On the other hand, if we evaluate the second derivative at $\omega = \frac{\bar{e}-\phi\tau}{\bar{e}-3\phi\tau}$, we get

$$f\left(\frac{\bar{e} - \phi\tau}{\bar{e} - 3\phi\tau}\right) = -\beta\phi^2\frac{1+2\beta\phi}{1-2\beta\phi} \ ,$$

which is negative for $0 \leq \beta\phi < 1/4$. Due to the strict monotonicity with respect to ω, there exists a unique $\omega \in (0, \frac{\bar{e}-\phi\tau}{\bar{e}-3\phi\tau})$ for which the sign of $f(\omega)$ changes. This is given by

$$\omega = \frac{4\beta^3\phi^3 + 2\beta^2\phi^2 + 2\beta\phi - 1}{-4\beta^3\phi^3 - 10\beta^2\phi^2 + 6\beta\phi - 1} \ .$$

Hence the second-order conditions are satisfied for all ω in the interval

$$\left(0, \ \frac{4\beta^3\phi^3 + 2\beta^2\phi^2 + 2\beta\phi - 1}{-4\beta^3\phi^3 - 10\beta^2\phi^2 + 6\beta\phi - 1}\right) \ .$$

The function $g(x) = \frac{4x^3+2x^2+2x-1}{-4x^3-10x^2+6x-1}$ is always larger than 1 for $0 < x < \frac{1}{4}$ (remind that Assumption 1 is equivalent to $\beta\phi < \frac{1}{4}$). Therefore, there exists a socially optimal policy scheme $\mathcal{P} = \{\alpha, f_0^I, 1\}$, and α and f_0^I simplify in this case to

$$\begin{aligned} \alpha &= \frac{\bar{e} - 3\phi\tau}{\bar{e} - 2\phi\tau} \ , \\ f_0^I &= 2\phi\tau^2\frac{\bar{e} - \phi\tau}{\bar{e} - 3\phi\tau} \ . \end{aligned}$$

This completes the proof. □

Proof of Corollary 5

Remind that the developing country is net receiver if and only if

$$\tau^D(\bar{e} - \phi\tau^D) \leq \alpha f\frac{\omega^D\tau^D}{\sum_j \omega^j\tau^j} \ .$$

Under implementation of the tax goal $\tau^I = \tau^D = \tau$ and the policy parameters α and f_0^I we derived in the proof of Proposition 4 for the case of identical abatement costs $\phi^I = \phi^D = \phi$ and heterogeneous damage costs $\beta^I = 0 < \beta^D = \beta$, this rewrites to

$$\frac{\omega + 1}{2\omega} \geq 1 \ ,$$

which is equivalent to $\omega \leq 1$ and hence $\omega^I \leq \omega^D$. □

Proof of Proposition 5

The special refunding formula (34) uses $\omega^i = \phi^i, \ i \in \{I, D\}$, hence $\omega = \phi^I/\phi^D$. Inserting this into the expressions for α and f_0^I derived in Lemma 1, we obtain

$$\begin{aligned} \alpha &= \frac{P}{2\phi^D} \frac{\bar{e} - A\tau}{\bar{e} - P\tau} \ , \\ f_0^I &= \frac{2\beta^D P\tau^2}{B} \frac{\bar{e} - P\tau}{\bar{e} - A\tau} + \frac{\tau}{\phi^I}((\phi^D - \phi^I)\bar{e} - P\phi^I\tau) \ . \end{aligned}$$

Assumption 1 now implies $\alpha > 0$. Furthermore, because of $\beta^I \leq \beta^D$ and $\phi^I \leq \phi^D$, α is the product of two factors ≤ 1, and hence $\alpha \leq 1$ holds. $f_0^I \geq 0$ is equivalent to

$$\frac{2\beta^D P\tau^2}{B} \frac{\bar{e} - P\tau}{\bar{e} - A\tau} + \frac{\phi^D}{\phi^I} \bar{e}\tau \geq \tau(\bar{e} + P\tau) \ .$$

Again because of $\beta^I \leq \beta^D$ and $\phi^I \leq \phi^D$, we have

$$\underbrace{\frac{2\beta^D}{B}}_{\geq 1} \underbrace{\frac{\bar{e} - P\tau}{\bar{e} - A\tau}}_{\geq 1} P\tau^2 \geq P\tau^2 \quad \text{and} \quad \underbrace{\frac{\phi^D}{\phi^I}}_{\geq 1} \bar{e}\tau \geq \bar{e}\tau \ ,$$

therefore, $f_0^I \geq 0$ holds.

Before we turn to the second-order conditions, we note that Assumption 1 implies $BP < 1$.

Calculating the second derivatives and inserting $\tau^I = \tau^D = \tau$, α and f_0^I from above yields the second-order conditions

$$\begin{aligned} 0 &< \phi^I \left(1 - \frac{\bar{e} - A\tau}{\bar{e} - P\tau}\right) + (\phi^I)^2 \left(\frac{2\beta^D}{BP} + \beta^I\right) \ , \\ 0 &< \phi^D \left(\frac{\bar{e} - A\tau}{\bar{e} - P\tau} - 1\right) + \phi^D\beta^D \left(\frac{2\phi^I}{BP} + \phi^D\right) + \frac{\bar{e} - A\tau}{\bar{e} - P\tau} \frac{\phi^D - \phi^I}{P\tau} \bar{e} \ . \end{aligned}$$

The former inequality holds because of $0 < \bar{e} - A\tau \leq \bar{e} - P\tau$. The latter inequality is (35). This completes the proof. □

Proof of Corollary 6

For homogeneous countries $\beta^I = \beta^D = \beta,\ \phi^I = \phi^D = \phi$, condition (35) simplifies to

$$\beta\phi\left(\frac{1}{2\beta} + \phi\right) > 0 \ ,$$

which holds true as $\beta, \phi > 0$. Therefore, (35) is always satisfied, which leads to (i).

For countries with identical abatement costs $\phi^I = \phi^D = \phi$ and heterogeneous damages $\beta^I = 0 < \beta^D = \beta$, condition (35) simplifies to

$$\phi\left(\frac{\bar{e} - 3\phi\tau}{\bar{e} - 2\phi\tau} - 1\right) + \phi\beta\left(\frac{1}{\beta} + \phi\right) > 0$$

or

$$\frac{\bar{e} - 3\phi\tau}{\bar{e} - 2\phi\tau} + \beta\phi > 0 \ ,$$

which holds true under Assumption 1. This leads to (ii). □

Proof of Proposition 6

Recall from Lemma 1 that a necessary condition for a socially optimal policy scheme $\mathcal{P}$ is that α and f_0^I fulfill

$$\begin{aligned}
\alpha &= \frac{(\omega + 1)(\bar{e} - A\tau)}{2(\bar{e} - P\tau)} \ , \\
f_0^I &= \frac{2(\omega + 1)\tau(\bar{e} - \phi^D \frac{\beta^I + 2\beta^D}{B}\tau)(\bar{e} - P\tau)}{\omega(\bar{e} - A\tau)} - \frac{(\omega + 1)\tau(\bar{e} - 2\phi^D\tau)}{\omega} \\
&\quad -\tau(2\bar{e} - P\tau) \ .
\end{aligned}$$

Setting α to 1 yields

$$\omega = \frac{\bar{e} - \frac{\beta^I\phi^D + 2\beta^I\phi^I + \beta^D\phi^I}{B}\tau}{\bar{e} - \frac{\beta^I\phi^D + 2\beta^D\phi^D + \beta^D\phi^I}{B}\tau}$$

which is always ≥ 1. Inserting this into the equation for f_0^I and setting it to zero yields condition (36). □

Proof of Corollary 7

For homogeneous countries $\beta^I = \beta^D = \beta,\ \phi^I = \phi^D = \phi$, condition (36) simplifies to

$$\frac{4\tau(\bar{e} - 2\phi\tau)^2(\bar{e} - \frac{3}{2}\phi\tau)}{(\bar{e} - 2\phi\tau)^2} - \frac{2\tau(\bar{e} - 2\phi\tau)^2}{\bar{e} - 2\phi\tau} - 2\tau(\bar{e} - \phi\tau) = 0 \ ,$$

which always holds true. Recall from Proposition 3 that for homogeneous countries, there exists always a socially optimal policy scheme provided that $\omega \leq 1$. Now, if $\alpha = 1$ and $f_0^I = 0$, it follows that $\omega = 1$ since

$$\begin{aligned} \alpha &= \frac{\omega + 1}{2} \ , \\ f_0^I &= \frac{1-\omega}{\omega}(\bar{e} - \phi\tau)\tau \ . \end{aligned}$$

This completes the proof. □

Proof of Proposition 7

The industrial country wants to set its emission tax τ^I such that

$$\frac{\phi^I}{2}(\tau^I)^2 + \frac{\beta^I}{2}s^2 - \alpha f_0^I \frac{\omega^I \tau^I}{\sum_j \omega^j \tau^j} + f_0^I - (1-\alpha) f_0^I \tag{A.11}$$

is minimized, whereas the developing country minimizes

$$\frac{\phi^D}{2}(\tau^D)^2 + \frac{\beta^D}{2}s^2 - \alpha f_0^I \frac{\omega^D \tau^D}{\sum_j \omega^j \tau^j} \tag{A.12}$$

with respect to τ^D. The first-order conditions then are

$$\begin{aligned} 0 &= \phi^I \tau^I - \beta^I \phi^I s - \alpha f_0^I \frac{\omega^I \omega^D \tau^D}{(\sum_j \omega^j \tau^j)^2} \ , \\ 0 &= \phi^D \tau^D - \beta^D \phi^D s - \alpha f_0^I \frac{\omega^I \omega^D \tau^I}{(\sum_j \omega^j \tau^j)^2} \ . \end{aligned}$$

Assuming implementation of the tax goal $\tau^I = \tau^D = \tau$, they simplify to

$$\begin{aligned} 0 &= \phi^I \tau - \frac{\beta^I \phi^I}{B}\tau - \alpha f_0^I \frac{\omega}{(\omega+1)^2 \tau} \ , \\ 0 &= \phi^D \tau - \frac{\beta^D \phi^D}{B}\tau - \alpha f_0^I \frac{\omega}{(\omega+1)^2 \tau} \ . \end{aligned}$$

These two equations can hold simultaneously only if

$$\beta^I \phi^D = \beta^D \phi^I \ .$$

This is equation (37).

If condition (37) holds, the first-order conditions above reduce to one equation, from which we can express α in terms of ω and f_0^I :

$$\alpha = \frac{(\omega+1)^2 \tau^2}{\omega f_0^I} \frac{\beta^D \phi^I}{B} \ . \tag{A.13}$$

We have

$$\begin{aligned}
\alpha > 0 \quad &\Leftarrow \quad \omega,\ f_0^I > 0 \ , \\
\alpha \leq 1 \quad &\Leftrightarrow \quad f_0^I \geq \frac{(\omega+1)^2}{\omega} \frac{\beta^D \phi^I}{B} \tau^2 \ .
\end{aligned}$$

The second-order conditions are

$$\begin{aligned}
\phi^I + \beta^I (\phi^I)^2 + 2\alpha f_0^I \frac{(\omega^I)^2 \omega^D \tau^D}{(\sum_j \omega^j \tau^j)^3} \quad &> \quad 0 \ , \\
\phi^D + \beta^D (\phi^D)^2 + 2\alpha f_0^I \frac{(\omega^D)^2 \omega^I \tau^I}{(\sum_j \omega^j \tau^j)^3} \quad &> \quad 0 \ .
\end{aligned}$$

Inserting the tax goal and α from (A.13), we get

$$\begin{aligned}
\phi^I + \beta^I (\phi^I)^2 + \frac{2\beta^D \phi^I}{B} \frac{\omega}{\omega+1} \quad &> \quad 0 \ , \\
\phi^D + \beta^D (\phi^D)^2 + \frac{2\beta^D \phi^I}{\beta^I + \beta^D} \frac{1}{\omega+1} \quad &> \quad 0 \ ,
\end{aligned}$$

which holds true for all $\omega > 0$. Hence it is always possible to find socially optimal policy parameters, given that condition (37) is satisfied. □

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