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ABSTRACT

Climate Policy and Developing Countries*

We suggest a development-compatible refunding system designed to mitigate climate change. Industrial countries pay an initial fee into a global fund. Each country chooses its national carbon tax. Part of the global fund is refunded to developing and industrial countries, in proportion to the relative emission reductions they achieve. Countries receive refunds net of tax revenues. We show that such a scheme can simultaneously achieve efficient emission reductions and equity objectives, as developing countries abate voluntarily, do not have to pay an initial fee, are net receivers of funds, and are net beneficiaries. Moreover, we explore the potential of simple refunding schemes that do not claim tax revenues and only rely on initial fees paid by industrial countries.

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1 Introduction

Developing countries in Latin America, Asia and Africa are exceptionally burdened by climate change. First, they will be affected by 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 the next decade.

As industrial countries have caused the bulk of current man-made greenhouse gas concentrations and as emission reductions in developing countries would further aggravate poverty, many argue that industrial countries alone should bear the cost of mitigating climate change. While this fairness argument is at the heart of the negotiations for an international agreement following the Kyoto Protocol, it is unclear how efficiency and fairness considerations in the mitigation of climate change can be combined in such a way that they do not conflict with each other. The policy debate and the major issues on current global climate change policy are discussed e.g. in Bosetti et al. (2009), Karp and Zhao (2009), Whalley and Walsh (2009), Chatterji and Ghosal (2009) and in Sinn (2008). A fundamental question is the participation of developing countries.

Moreover, greenhouse gases travel around the world, so mitigation of climate change is a global public good. Accordingly, achieving both efficiency and fairness objectives in climate policy is difficult. In this paper we propose a simple scheme that can incorporate efficiency and fairness objectives into 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. Their emission tax revenues are payable to the 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 for each country is proportional to the relative emission reductions it achieves. Countries receive refunds minus tax revenues. If that amount is negative, countries have to clear their debts.
- 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 the equity and efficiency objectives of climate policy, thus serving as a base for designing an international treaty. We consider a model with a representative industrial and a representative developing country. The developing country has equal or higher marginal damage from greenhouse gas emissions compared to the industrial country, but has equal or lower marginal abatement costs. Both countries join 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 allowing for the increase or decrease of 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 efficiency and equity objectives under a variety of circumstances. Regarding efficiency objectives, the DCR induces both the industrial and the developing country to set abatement levels that are socially optimal. The reason is as follows: A sufficiently high initial fee from the industrial country motivates both countries to set taxes at the socially optimal level as one additional tax dollar and associated emission reduction generates more dollars in refunds. This property stems from the refunding formula as a marginal increase of the tax rate by one country and the associated emission reduction will increase the refunding share for this country at the expense of the other country. When both countries set taxes at the socially optimal level, no country will want to deviate as it would suffer a high marginal decline in refunds. These refunding losses (and the higher marginal damages) outweigh high marginal abatement costs.

Regarding equity objectives, the developing country does not have to pay an initial fee and abates voluntarily. In addition, the refunds to the developing country can be increased by varying the weighting factors in the refunding formula. In particular, choosing an appropriate weighting factor will make the developing country a net receiver of funds. Moreover, as a rule, the developing country is better off than it would be when an international treaty fails and each country decides independently how much to abate.[1] Moreover, we outline the circumstances for which both the industrial and the developing country are better of under a DCR.

We also explore the potential of a simple refunding scheme that renounces claiming tax revenues 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 marginal 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. In Section 4 we calculate the social optimum and the decentralized solution as benchmark cases. In Section 5 we introduce the development-compatible refunding scheme and characterize its properties. Special cases are discussed in Section 6. In Section 7 we consider a simple refunding scheme that does not claim tax revenues. In Section 8 we address extensions to many countries and different policy instruments, and we discuss critical features of our scheme. Section 9 concludes.

2 Relation to the Literature

Our analysis starts from the observation that most economists working on climate policy argue that current generations need to reduce emissions which, in turn, requires a reduction in current consumption. The assessment of whether and how much climate policies requires sacrifice has attracted a lot of attention. Leading contributions such as Stern (2006), Nordhaus (2007), Karp (2005), Fujii and Karp (2008), Rezai et al. (2009), Hoel and Sterner (2007), Tol (2008), and Weitzman (2009) develop different perspectives and identify the pitfalls when such assessments are made. In our paper we assume that the current generation around the globe collectively would like to reduce emissions to some degree. The problem is that nations would like to free ride on abatement efforts by other countries and developing countries need to be compensated for the abatement sacrifices.

It is well known that achieving significant emission reductions through Kyoto-style agreements with emission targets is a very difficult undertaking. As a consequence,

[1] As argued by Spence (2009), it is essential that developing countries get compensated for their abatement efforts in a global agreement as otherwise their growth prospects would be seriously delayed which, in turn, would make it impossible to reach such an agreement in the first place.

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. More recently, Gersbach (2005) and Gersbach and Winkler (2007) have proposed and discussed a global refunding system in which all countries are treated equally. All countries have to pay an initial fee and they all will receive the same refund. The authors show that, if countries are identical, such a scheme will achieve the social global optimum. In this paper we propose a development-compatible refunding scheme in which only industrial countries have to pay an initial fee. Our refunding formula is such that efficient abatement levels are achieved in industrial and in developing countries even if developing countries do not have to pay initial fees, suffer higher marginal damages from climate change and have lower marginal abatement costs.

Using game-theoretic models, a considerable body of research has examined the formation of international environmental agreements. This literature mainly focuses on the circumstances fostering the building of coalitions through multilateral agreements. Such agreements must be self-enforcing, since there is no supranational authority to ensure compliance (for a recent contribution, see the important article by Asheim et al. 2006). The literature reaches two main conclusions: It is unlikely that a grand coalition will be formed, and if it is, 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. Our approach complements this literature by suggesting a refunding scheme that balances the efficiency and equity objectives of a mitigation of climate change.

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 $(i, j \in \{I, D\})$.

The emissions of country i are assumed to equal some "business as usual" emissions $\bar{e}$

minus emission abatement a^i:[2]

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

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

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

We assume that countries use emission taxes as a policy instrument. As developing countries provide the best opportunities for low-cost emission reductions, we assume $\phi^I \leq \phi^D$.[4] Each country i individually sets per-unit emission taxes τ^i. Cost minimizing behavior by the representative firm implies that marginal abatement costs will 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 instantaneously accumulate the stock of greenhouse gases s:

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

Note that for ease of presentation we assume that the initial stock is zero.[5]

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

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

[2] For simplicity, we assume that $\bar{e}^I = \bar{e}^D = \bar{e}$. This assumption reflects the fact that both industrial and developing countries contribute a significant share to global greenhouse-gas emission.

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

[4] See Morris et al. (2008) and Criqui et al. (1999).

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

where $\beta^I \leq \beta^D$ as developing countries are more affected by damages caused by climate change than industrial countries (IPCC 2007). The parameters $\beta^i,\ i \in \{I, D\}$, represent marginal damages.[6]

Besides the differences in marginal abatement costs and marginal damages, developing countries are associated with low income per capita, and we assume that it is impossible for them to pay an initial fee. This is obvious by the case for the poorest countries in Africa, as such payments would either be impossible to collect or would severely affect the citizens of that country.

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., to minimize the net present value of the total costs of emission abatement and the sum of national damages stemming from greenhouse-gas emissions. Accordingly, 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 $\tau^i \in \left[0, \frac{\bar{e}}{\phi^i}\right],\ i \in \{I, D\}$. Momentarily we focus on interior solutions. We will provide a sufficient condition for the existence of interior solutions at the end of this subsection.

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:

[6] Marginal damages and marginal abatement costs can be expressed in utility or common currency units. Both interpretations can be applied to our model. It might be easiest to think in monetary units as taxes and transfers are usually expressed in units of money.

Proposition 1 (Social optimum)

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

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

(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 $a^{i\star}$ of both countries are given by

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

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

The proof of Proposition 1 is straightforward. Proposition 1 reveals the well-known property of a social optimum: Tax $\tau^\star$ is set at a level at which 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.

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 $a^{I\star}$ is below $\frac{\bar{e}}{2}$ and the abatement level $a^{D\star}$ 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. Assumption 1 also implies that the social optimum is always an interior solution.

Note that Assumption 1 is equivalent to the following condition expressed solely 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 $\tau^i \in \left[0, \frac{\bar{e}}{\phi^i}\right]$.

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 $F^{DS,i}$, and Assumption 1 rules out corner solutions.

The set of 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 indicates the well-known finding 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

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

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

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: In the decentralized solution the developing country has an even higher incentive to increase its carbon emission tax 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 borne by both countries.

5 Development-Compatible Refunding Scheme

We now design a development-compatible refunding scheme (DCR). The scheme works as follows: If it decides to join the DCR, the industrial country is required to pay an initial fee of $f_0^I \geq 0$ into a fund. Members are free to choose national emission taxes τ^i. All countries owe the fund their emission tax revenues. 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. At the end, the country receives or pays the difference between its tax revenues and the amount of money redistributed from the fund.

The parameter α provides the additional flexibility necessary to balance the incentives of the developing and the industrialized country. Specifically, $\alpha < 1$ is needed to induce the industrial country to choose socially optimal taxes if the developing country obtains

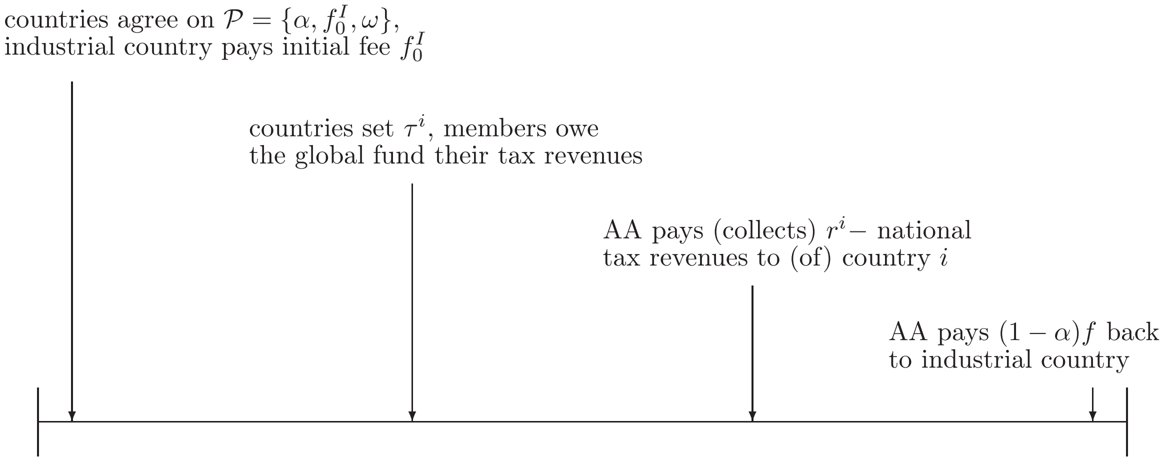

Figure 1: An illustration of the timing of the development-compatible refunding scheme.

very high refunds.[7] The latter may be needed to ensure that the developing countries are net beneficiaries.

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 outset countries sign the DCR, which is managed by an administering agency (AA). Signing the agreement involves

- Payment of an initial fee f_0^I into the fund by the industrial country.
- Tax revenues are liabilities of countries.
- Agreement to a refunding formula with parameters $\{\alpha, \omega\}$ which are explained below. Country i receives refund r^i minus national tax revenues.[8]

[7] An example of parameter constellations for which an efficient DCR fails to exist when $\alpha = 1$ is given by $\beta^I = 0.01$, $\beta^D = 0.5$, $\phi^I = 0.001$, $\phi^D = 0.5$ (calculations are available upon request).

[8] If the difference is negative, country i has to clear its debt.

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 $\omega^i = \tilde{\omega}^i \phi^i$, and DCR denotes the set of countries that joined the refunding system. The formula captures the basic idea behind refunding: The refund a country i receives is proportional to the relative emission reductions it achieves. Varying the weights ω^i ($\omega^i > 0$) makes it possible to heighten or to lower the size of the refund that 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

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

The assets of the fund f before refunds are given by

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

where $f_0^D = 0$.

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

Reciprocal externalities

- Tax externality (D$\leftrightarrow$I): If $\tau^i < \bar{e}/(2\phi^i)$: the higher the tax rate in one country, the higher the taxes this country has to pay into the fund, which represents a positive tax externality.[9] If $\tau^i > \bar{e}/(2\phi^i)$, the tax externality is negative.
- Negative refunding externality (D$\leftrightarrow$I): the higher the abatement in one country, the lower is the refund for the other country, given its tax choice.[10]
- Positive environmental damage externality (D$\leftrightarrow$I): the higher the abatement in one country, the lower is the damage for the other country.

[9] Formally, $\partial f / \partial \tau^i > 0$.

[10] Formally, $\partial \frac{\omega^i \tau^i}{\sum_j \omega^j \tau^j} / \partial \tau^k < 0, \ k \neq i$

Unidirectional externalities

- Positive initial fee externality (I→D): the higher the initial fee paid by the industrial country, the higher is the refund to the developing country.
- Residual refund externality (D→I): If $\tau^D < \bar{e}/(2\phi^D)$, this externality is positive, i.e. the higher the tax of the developing country, the higher is the ultimate residual fund for the industrial country. If $\tau^D > \bar{e}/(2\phi^D)$, this externality is negative.

The idea behind the scheme is to choose the parameters so that the externalities balance and both the developing country and the industrial country will 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*

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

While one can solve for the countries' tax rates, abatement levels and damages for any feasible set of policy parameters $\mathcal{P}$, we directly examine whether one can find a feasible $\mathcal{P}$ that implements the socially optimal solution. For this purpose we define

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 now 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 its total costs

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

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

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

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

To construct a socially optimal $\mathcal{P}$, the policy parameters α, f_0^I and ω have to fulfil the feasibility conditions, and first- and second-order conditions have to hold under the assumption that countries implement the tax goal. This existence problem is dealt with in Appendix A. There, we give a simple sufficient condition for the existence, and we show that non-existence of socially optimal policy schemes can occur when ϕ^I is very small. In such circumstances, the industrial country has very high abatement costs and thus high emissions. Therefore, it has limited incentives to choose the socially optimal tax rate, as it owes the fund high tax revenues while the impact on damages is small. In that case, it may be impossible to induce the industrial country to choose the socially optimal tax rate without distorting the incentives for the developing country.[11]

5.3 Developing Country as Net Receiver

In the next step we examine equity objectives. In particular, we derive conditions under which the developing country is a net receiver of funds, which means that its refunds are higher than or equal to its tax payments. Hence the developing country is a net receiver if

$$\alpha f \frac{\omega^D\tau^D}{\sum_j \omega^j\tau^j} \geq \tau^D(\bar{e} - \phi^D\tau^D) \; . \qquad (28)$$

We obtain one of our main results:

[11]However, even if socially optimal policy parameters do not exist, we show in Appendix A that there are feasible policy parameters that induce the industrial country to set socially optimal taxes and the developing country to abate maximally.

Proposition 3

Suppose there exists a socially optimal policy scheme $\mathcal{P} = \{\alpha, f_0^I, \bar{\omega}^{NR}\}$ *for some* $\omega^{NR} > 0$*. Then, by agreeing on a sufficiently small* $\omega \leq \bar{\omega}^{NR}$*, the countries can always find a socially optimal policy scheme such that the developing country is a net receiver of funds.*

The proof can be found in Appendix B.

Proposition 3 shows that one can align efficiency and equity objectives by choosing a socially optimal policy scheme with a sufficiently small value of ω. This increases the refunding share of the developing country, thus becoming a net receiver of funds. In Section 6.1 we will see that if countries are homogeneous with respect to abatement costs and damages, the developing country is a net receiver under every socially optimal policy scheme.

The initial fee f_0^I tends to infinity and α is strictly smaller than one if ω approaches zero. Hence a socially optimal policy scheme for which the developing country is a net receiver of funds requires a high initial fee to generate a sufficient amount of refunds for the industrial country to preserve their incentives to abate at the socially desirable level.

In the following corollary, we will see that ω does not need to be very small to make the developing country a net receiver.

Corollary 3

Suppose that $\omega^i = \phi^i, i \in \{I, D\}$*, i.e.* $\omega = \phi^I/\phi^D$*. Then, under any socially optimal policy scheme, the developing country is a net receiver of funds.*

The proof can be found in Appendix B.

5.4 Developing and Industrial Country as Net Beneficiary

In the next step we examine socially optimal policy schemes for which the developing country is a net beneficiary of the international treaty with refunding scheme, i.e. it is not worse off with the DCR than with the decentralized solution. This can be expressed formally by

$$F^{DS,D}(\hat{\tau}^D) \geq F^D(\tau^\star) \ . \tag{29}$$

Analogously to Proposition 3, we obtain:

Proposition 4
Suppose there exists a socially optimal policy scheme $\mathcal{P} = \{\alpha, f_0^I, \bar{\omega}^{NB}\}$ *for some* $\bar{\omega}^{NB} > 0$*. Then, by agreeing on a sufficiently small* $\omega \leq \bar{\omega}^{NB}$*, we can always find a socially optimal policy scheme such that the developing country is a net beneficiary of the DCR.*

The proof can be found in Appendix B.

We note that there exist constellations of exogenous model parameters for which a socially optimal policy scheme makes the developing country worse off, compared to the decentralized solution. This occurs when ϕ^I is very small in comparison with ϕ^D, and ω is not low enough.[12] Then the developing country almost bears the entire costs of abatement and receives a small refund. However, this is not a concern, as Proposition 4 implies that the countries can always agree on a sufficiently low value of ω, such that the developing country can be compensated for its large share of abatement costs by maximizing its refunding share.

Note also that the DCR can make both the industrial and the developing country net beneficiaries of the DCR:

Corollary 4
Suppose there exists a socially optimal policy scheme $\mathcal{P} = \{\alpha, f_0^I, \omega\}$ *such that the developing country is not a net beneficiary. Then there exist socially optimal policy schemes that make both the developing and the industrial country better off compared to the decentralized solution.*

The proof can be found in Appendix B. The assumption of Corollary 4 is comparatively weak as the welfare of the developing country can always be lowered by setting ω sufficiently high.

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

[12] For the parameter values $\beta^I = 0.14, \beta^D = 0.15, \phi^I = 1 \cdot 10^{-9}, \phi^D = 1$, the conditions from Lemma 1 in Appendix A represent an upper bound on ω equal to 1.817. Inserting the equilibrium values and the upper bound of ω yields $F^{DS,D}(\hat{\tau}^D) < F^D(\tau^\star)$.

6 Special Cases

6.1 Homogeneous Countries

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

Proposition 5
Suppose $\beta^I = \beta^D = \beta$ and $\phi^I = \phi^D = \phi$. Then there always exists a socially optimal set of policy parameters $\mathcal{P}$. Such policy schemes satisfy $\omega \leq 1$, i.e. $\omega^I \leq \omega^D$. For $\omega^I = \omega^D$ we have $\alpha = 1$.

The proof can be found in Appendix B.

Proposition 5 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 than or equal to 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 degree, i.e. set their taxes to $\tau^I = \tau^D = \tau^\star$. For $\alpha < 1$, the industrial country has higher incentives to tax emissions than 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 in order to increase its refunds.

The following corollary shows that the developing country is a net receiver of funds and a net beneficiary of the DCR for any choice of ω that belongs to a socially optimal policy scheme.

Corollary 5
Suppose $\beta^I = \beta^D = \beta$ and $\phi^I = \phi^D = \phi$. The developing country is a net receiver of funds and a net beneficiary under any socially optimal policy scheme.

The proof can be found in Appendix B.

As the refunding scheme implements the socially optimal emission tax, the developing country benefits in the homogeneous case from the scheme in two ways: It is a net receiver of money and its total costs (abatement costs and damages) are lower than in the decentralized solution.

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 6
Suppose that $\phi^I = \phi^D = \phi$ and $\beta^I = 0 < \beta^D = \beta$. Then there always exists a socially optimal set of policy parameters $\mathcal{P}$. In particular, 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 Appendix B.

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

Corollary 6
Suppose $\phi^I = \phi^D = \phi$ and $\beta^I = 0 < \beta^D = \beta$. Under a socially optimal policy scheme, the developing country is a net receiver of funds if and only if $\omega^I \leq \omega^D$. Moreover, the developing country is a net beneficiary under any socially optimal policy scheme.

The proof of the corollary can be found in Appendix B.

6.3 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 $\alpha = 1$.[13]

[13] 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.

Proposition 7 (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

$$\frac{4\tau(\bar{e} - (\phi^I + \phi^D)\tau)^2(\bar{e} - \phi^D \frac{\beta^I + 2\beta^D}{\beta^I + \beta^D}\tau)}{(\bar{e} - \frac{\beta^I\phi^D + 2\beta^D\phi^D + \beta^D\phi^I}{\beta^I + \beta^D}\tau)(\bar{e} - \frac{\beta^I\phi^D + 2\beta^I\phi^I + \beta^D\phi^I}{\beta^I + \beta^D}\tau)} - \tau(2\bar{e} - (\phi^I + \phi^D)\tau)$$
$$- \frac{2\tau(\bar{e} - (\phi^I + \phi^D)\tau)(\bar{e} - 2\phi^D\tau)}{\bar{e} - \frac{\beta^I\phi^D + 2\beta^I\phi^I + \beta^D\phi^I}{\beta^I + \beta^D}\tau} = 0 \ , \qquad (30)$$

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

The proof can be found in Appendix B. Proposition 7 indicates that it is only possible in knife-edge cases to induce socially optimal abatement levels when no initial fees are paid by the industrial country. An example of 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 from industrial countries help to achieve socially optimal emission abatements and equity objectives.

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 Appendix B. For almost all other constellations of exogenous model parameters, a socially optimal policy scheme $\mathcal{P}$ with $f_0^I = 0$ and $\alpha = 1$ does not exist. Examples are countries with identical abatement costs $\phi^I = \phi^D$ and heterogeneous damages $\beta^I = 0 < \beta^D$.

The interpretation of the property $\omega \geq 1$ in Proposition 7 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 fewer incentives to select the socially optimal tax rates. To counteract these weaker incentives, the industrial country receives a higher share of the fund than the developing country.

7 Refunding Schemes without Tax Revenues

In this section we consider the potential of a refunding scheme that foregoes claiming tax revenues from the member countries.

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

Proposition 8
Under a refunding scheme without drawing on tax revenues, there exists a socially optimal policy scheme $\mathcal{P} = \{\alpha, f_0^I, \omega\}$ if and only if it holds that

$$\frac{\beta^I}{\phi^I} = \frac{\beta^D}{\phi^D} \ . \tag{31}$$

The proof can be found in Appendix B.

The reason why condition (31) has to hold can be identified by investigating the externalities 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. As $\beta^D \geq \beta^I$, the developing country benefits more from abatement by the industrial country. Second, for equal taxes $\tau^I = \tau^D$, the industrial country abates less than the developing country because its abatement costs are higher ($\phi^I \leq \phi^D$). 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 (31). By varying the level of f_0^I and by exploiting the negative refunding externality, the abatement levels of both countries can be raised to socially optimal levels.

Corollary 8
Suppose a socially optimal refunding scheme without claiming tax revenues exists.

(i) Then, the developing country is a net receiver under such a scheme if and only if

$$\omega \leq \frac{2\beta^D\phi^I}{1 + \beta^I\phi^I - \beta^D\phi^D - 2\beta^D\phi^I} \ . \tag{32}$$

(ii) There exists a $\bar{\omega}^{NT} > 0$ such that the developing country is a net beneficiary under such a scheme if and only if $\omega \leq \bar{\omega}^{NT}$.

The proof can be found in Appendix B.

As in Proposition 3 and 4, the developing country will be a net receiver of funds and a net beneficiary if its weight ω^D in the refunding formula is sufficiently large relative to the weight ω^I of the industrial country.

8 Discussion

We have suggested an approach to international negotiations that can solve the compliance and participation problems of developing countries with regard to climate treaties. In this section, we address several concerns as to the applicability of the proposed scheme.

Other policy instruments

While our basic scheme relies on emission taxes, the variant presented in Section 7 that forgoes claiming tax revenues can operate with any policy instrument a country uses to reduce emissions. The reason is that for the refunding scheme in Section 7, only the initial fund and emission abatements matter for refunding. Hence, cap-and-permit trade, command-and-control regulation or emission taxes can be employed by a country, and international coordination of policy instruments is not needed.[14]

Multiple countries

The proposed scheme can be generalized to multiple countries of each type. The refunding formula for a set Ω_I of industrial countries and a set Ω_D of developing countries is given by

$$r^i = \alpha f \frac{\omega^i a^i}{\omega^D \sum\limits_{j \in \Omega_D} a^j + \omega^I \sum\limits_{j \in \Omega_I} a^j} \ , \tag{33}$$

where r^i is the refund to country i, $i \in \{I, D\}$.[15] The following observations show how our results from a two-countries setting generalize to the present setting. As r^i determines the incentive of country i to abate, the more countries involved, the smaller the share an individual country receives from αf. Incentives are restored if αf is increased

[14]Using emission taxes as policy instrument has the advantage that refunding is less vulnerable to cheating as refunds can be based directly on tax rates (see equation (22)). Cheating on tax rates is more difficult than manipulating abatement efforts as tax rates are single numbers in a governmental law.

[15]Classification of countries into the groups Ω_I and Ω_D is given for the majority of countries, but is less clear for the group of emerging countries. A GDP per capita threshold can serve as classification criterion. A tight definition of industrial countries would classify emerging countries as developing countries.

accordingly. This occurs automatically when tax revenues are collected and if one half of the countries is industrialized and the sum of initial fees thus increases accordingly. If only a few industrial countries are present, the initial fees per country would have to increase to sustain socially optimal incentives to abate.

The presence of multiple industrial countries, however, raises concerns about their willingness to pay initial fees, which we will address next.

Participation of industrial countries

As reducing greenhouse gases is a global public good, the development-compatible refunding scheme does not eliminate the incentives of an industrial country to free-ride on other industrial countries' initial fee payments. However, it relocates the problem to one time and place, i.e. in the payment of the initial fees. With more than one country, this requires coordination. The common procedure to achieve such coordination among a smaller group of countries, say twenty larger industrial countries, must make each country pivotal for success. The problem can be described by the following two-stage game:

Stage 1	a.)	Signing of the treaty and payment of initial fees.
	b.)	The treaty becomes effective if all industrial countries sign it. Otherwise it is cancelled.[16]
Stage 2	Abatement decision.	

It is straightforward to see that there exists a unique subgame perfect equilibrium in which all countries sign and the industrial countries pay initial fees.

Participation of developing countries

As developing countries participate voluntarily, special efforts to induce them to participate are not necessary. However, the opposite problem may occur. There may be instances where the dictator of a developing country achieves emission reductions by means that should not allow to claim refunds. For example, a dictator may ruin the economy of his country, thereby reducing emissions. Granting refunds in such circumstances would perpetuate poverty. Hence, it may be required that developing countries loose their right to claim refunds, or may not be admitted to the refunding system at all if they pursue such a strategy.

Frictions in implementation

We have assumed that in developing and industrial countries, emission reductions can

[16] If countries have already paid initial fees, those would be returned.

be verified without any costs. However, measuring the emission reductions achieved by a country is a non-trivial task in practice. Countries have incentives to report higher emission abatement than what they actually achieved. Therefore the agency administering the refunds must be equipped with a review board that is able to monitor these reductions properly.

9 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. The development-compatible refunding system still requires coordination among industrial countries to pay the initial fees into the global fund. It would appear, however, that such coordination is a substantially smaller problem than world-scale negotiations in the style of the Kyoto Protocol.

Notation

Throughout Appendix A and Appendix B we work with the following abbreviations:

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

Appendix A Existence

Appendix A deals with the existence of a socially optimal policy scheme $\mathcal{P} = \{\alpha, f_0^I, \omega\}$. It is organized as follows: In the next section we derive the conditions for which α, f_0^I and ω are socially optimal, and we analyze how those conditions can hold simultaneously. Section A.2 provides a simple sufficient condition that always ensures existence, while Section A.3 presents a counterexample where existence fails. In Section A.4 we propose a solution to the case when non-existence occurs. We show that there are feasible policy parameters that induce the industrial country to implement the socially optimal tax rate and the developing country to choose maximal abatement.

A.1 General Conditions for Existence

Socially optimal policy parameters α, f_0^I and ω have to satisfy the feasibility conditions of Definition 1, first- and second-order conditions. This is summed up in the following lemma:

Lemma 1 (Conditions for socially optimal $\mathcal{P}$)
The set of policy parameters $\mathcal{P}$ is socially optimal if and only if ω satisfies

$$\text{(i)} \qquad 0 < \omega \leq \frac{\bar{e} - \frac{\beta^D\phi^I + 2\beta^I\phi^I + \beta^I\phi^D}{B}\tau}{\bar{e} - A\tau} \ , \tag{A.1}$$

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

$$\begin{aligned}\text{(iii)} \qquad & \phi^D(-1 + \beta^D\phi^D + \frac{\bar{e} - A\tau}{\bar{e} - P\tau}) + 2(\bar{e} - \phi^D\frac{\beta^I + 2\beta^D}{B}\tau)\frac{1}{(\omega+1)\tau} \\ & - \frac{(\bar{e} - A\tau)(\bar{e} - 2\phi^D\tau)}{(\bar{e} - P\tau)\tau} > 0 \ .\end{aligned} \tag{A.3}$$

Proof:

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

$$\alpha = \frac{(\omega+1)\,(\bar{e}-A\tau)}{2(\bar{e}-P\tau)}\ , \tag{A.4}$$

$$\begin{aligned} f_0^I = & \frac{2(\omega+1)\tau(\bar{e}-\phi^D\frac{\beta^I+2\beta^D}{B}\tau)(\bar{e}-P\tau)}{\omega(\bar{e}-A\tau)} \\ & -\frac{(\omega+1)\tau(\bar{e}-2\phi^D\tau)}{\omega} - \tau(2\bar{e}-P\tau)\ . \end{aligned} \tag{A.5}$$

Note that Assumption 1 guarantees that α and f_0^I are well defined, as $\bar{e}-P\tau \geq \bar{e}-A\tau > 0$ and hence the denominators occurring in the expressions for α and f_0^I are always non-zero.

According to Definition 1, the policy parameters α and f_0^I have to satisfy

$$\begin{aligned} \alpha &\in [0,1]\ , \\ f_0^I &\geq 0\ . \end{aligned}$$

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

Condition $\alpha \leq 1$ applied to (A.4) and rearranging terms, together with the feasibility condition $\omega > 0$, leads to (i). Condition $f_0^I \geq 0$ applied to (A.5) and rearranging terms leads to (ii).

Now we derive the second-order conditions ensuring that the solution obtained 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

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

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

□

Now we turn to the question whether the conditions on ω, given in Lemma 1, can be satisfied simultaneously. Condition (i) can always be satisfied by positive values of ω, as Assumption 1 implies that the upper bound on ω given in (A.1) is positive. Also (ii) can always be satisfied: Condition (A.2) is equivalent to

$$
\begin{aligned}
&\omega\left\{2(\bar{e}-\phi^D\frac{\beta^I+2\beta^D}{B}\tau) - \frac{(\bar{e}-A\tau)(\bar{e}-2\phi^D\tau)}{\bar{e}-P\tau} - \frac{(\bar{e}-A\tau)(2\bar{e}-P\tau)}{\bar{e}-P\tau}\right\} \\
&\geq \frac{(\bar{e}-A\tau)(\bar{e}-2\phi^D\tau)}{\bar{e}-P\tau} - 2(\bar{e}-\phi^D\frac{\beta^I+2\beta^D}{B}\tau) . \qquad (A.6)
\end{aligned}
$$

If the right-hand side of (A.6) is positive then the term in curly brackets on the left-hand side is negative. Hence, condition (A.2) can be satisfied for positive values of ω

if and only if the right-hand side of (A.6) is negative. But this holds always true as

$$\bar{e} - 2\phi^D\tau - 2\underbrace{\frac{\bar{e} - P\tau}{\bar{e} - A\tau}}_{\geq 1}(\bar{e} - \phi^D\frac{\beta^I + 2\beta^D}{B}\tau) \quad \leq \quad -\bar{e} + \underbrace{\frac{2\beta^D\phi^D}{B}}_{<A}\tau \quad < \quad -\bar{e} + A\tau \ ,$$

and $-\bar{e} + A\tau < 0$ because of Assumption 1.

Condition (A.3) is equivalent to

$$\omega\left\{\phi^D\tau(-1 + \beta^D\phi^D + \frac{\bar{e} - A\tau}{\bar{e} - P\tau}) - \frac{(\bar{e} - A\tau)(\bar{e} - 2\phi^D\tau)}{\bar{e} - P\tau}\right\} \tag{A.7}$$

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

We again observe that the term in curly brackets on the left-hand side is negative if the right-hand side of (A.7) is positive. Hence, we can find a $\omega > 0$ that satisfies condition (A.3) if and only if the right-hand side of (A.7) is negative.

These considerations are summed up in the following lemma:

Lemma 2

A socially optimal policy scheme $\mathcal{P}$ exists if and only if the following conditions hold:

$$\frac{(\bar{e} - A\tau)(\bar{e} - 2\phi^D\tau)}{\bar{e} - P\tau} - 2(\bar{e} - \phi^D\frac{\beta^I + 2\beta^D}{B}\tau) - \phi^D\tau(-1 + \beta^D\phi^D + \frac{\bar{e} - A\tau}{\bar{e} - P\tau}) < 0 \ . \tag{A.8}$$

Closer investigation of the inequalities (A.6) and (A.7) also reveals that if one of them is satisfied for some value $\bar{\omega} > 0$, the same condition is satisfied for all $\omega \in (0, \bar{\omega}]$. This yields

Fact 1

Conditions (A.1), (A.2), and (A.3) impose an upper bound on ω. The lower bound is equal to zero.

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 the developing country to abate insufficiently relative to the industrial country, so it is impossible to induce it to choose the socially optimal abatement levels in equation (12) and (13).

A.2 A Sufficient Condition

A simple sufficient condition for the existence is ϕ^I being close enough to ϕ^D:

Lemma 3

Suppose that ϕ^I is sufficiently close to ϕ^D. Then there always exists a socially optimal policy scheme $\mathcal{P} = \{\alpha, f_0^I, \omega\}$.

Proof:

As we have seen in Lemma 2, a socially optimal policy scheme exists if and only if the condition on the model parameters, (A.8), is satisfied. Inserting $\phi^I = \phi^D = \phi$ into (A.8) as we consider the case of ϕ^I being not too small compared to ϕ^D yields

$$-\bar{e} + 2\phi\tau - \phi\tau(\beta^D\phi + \frac{\bar{e} - A\tau}{\bar{e} - 2\phi\tau}) < 0 \ .$$

This holds by Assumption 1, hence existence is ensured in the case of $\phi^I = \phi^D = \phi$. By continuity, the existence of a socially optimal policy scheme is also guaranteed when ϕ^I is slightly decreased.

□

A.3 A Counterexample

Non-existence of socially optimal policy schemes can occur when ϕ^I is very small. An example is $\phi^D = 1, \phi^I = 10^{-6}, \beta^D = 0.25, \beta^I = 0.2$. For these parameter values, (A.8) from Lemma 2 is not satisfied, and hence, the second-order condition for the minimization problem of the developing country cannot be fulfilled for any feasible set of policy parameters $\mathcal{P}$.

A.4 Corner Solution

Even if the second-order condition of the developing country fails, we can find feasible policy parameters α, f_0^I and ω such that the industrial country implements the socially optimal tax rate $\tau^\star$ and the developing country abates maximally, i.e. sets the corner solution $\frac{\bar{e}}{\phi^D}$:

Lemma 4

There always exists a feasible set of policy parameters $\mathcal{P} = \{\alpha, f_0^I, \omega\}$ such that countries implement $\tau^I = \tau^\star$, $\tau^D = \frac{\bar{e}}{\phi^D}$ under the DCR. It is given by α and ω close to zero, and f_0^I correspondingly large.

Proof:

The countries implement $\tau^I = \tau^\star$, $\tau^D = \frac{\bar{e}}{\phi^D}$ if, evaluated at $\tau^I = \tau^\star$, $\tau^D = \frac{\bar{e}}{\phi^D}$,

$$\frac{\partial F^I}{\partial \tau^I} = 0 \ , \quad \frac{\partial^2 F^I}{(\partial \tau^I)^2} > 0 \ , \quad \frac{\partial F^D}{\partial \tau^D} \leq 0$$

hold. Solving $\frac{\partial F^I}{\partial \tau^I} = 0$ for f_0^I yields

$$f_0^I = \frac{\omega\tau^I + \tau^D}{\alpha\omega\tau^D} \left\{ \frac{\beta^D\phi^I}{B}\tau^I + \alpha(\bar{e} - 2\phi^I\tau^I)\frac{\tau^D}{\omega\tau^I + \tau^D} - \alpha\tau^I(\bar{e} - \phi^I\tau^I)\frac{\omega\tau^D}{(\omega\tau^I + \tau^D)^2} \right\}$$

which is positive for ω close to zero and arbitrary $\alpha \in [0, 1]$. Evaluating $\frac{\partial F^D}{\partial \tau^D}$ at $\tau^I = \tau^\star$, $\tau^D = \frac{\bar{e}}{\phi^D}$, we obtain

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

which is non-positive if α is close to zero. Now we consider $\frac{\partial^2 F^I}{(\partial \tau^I)^2}$:

$$\begin{aligned} \frac{\partial^2 F^I}{(\partial \tau^I)^2} &= \phi^I(1 + \beta^I\phi^I) + 2\alpha\phi^I\frac{\tau^D}{\omega\tau^I + \tau^D} - 2\alpha(\bar{e} - 2\phi^I\tau^I)\frac{\omega\tau^D}{(\omega\tau^I + \tau^D)^2} \\ &\quad + 2\alpha f\frac{\omega^2\tau^D}{(\omega\tau^I + \tau^D)^3} \ , \end{aligned}$$

which is positive for α being close to zero. Hence by setting α and ω close to zero, we can find a feasible albeit large f_0^I such that the countries will implement $\tau^I = \tau^\star$, $\tau^D = \frac{\bar{e}}{\phi^D}$.

□

Lemma 4 implies that even if it is impossible to implement the socially optimal solution $\tau^I = \tau^D = \tau^\star$ under the DCR, the scheme can still induce the countries to abate emissions considerably. This is achieved by setting ω small, which increases the developing country's share of refunds to an extent such that the developing country has an incentive to abate maximally, and by setting α small so that the industrial country benefits from a large leftover in the fund.

Appendix B Proofs

Proof of Proposition 3

If both countries choose the socially optimal tax rate $\tau^I = \tau^D = \tau$, the developing country is a net receiver if and only if

$$\alpha f \frac{1}{\omega + 1} \geq \tau(\bar{e} - \phi^D \tau) \ . \tag{B.1}$$

Inserting α and f_0^I as given in (A.4) and (A.5), respectively, into (B.1) yields

$$\frac{(\omega+1)\tau}{\omega} \left\{ (\bar{e} - \phi^D \frac{\beta^I + 2\beta^D}{B}\tau) - \frac{(\bar{e} - 2\phi^D\tau)(\bar{e} - A\tau)}{2(\bar{e} - P\tau)} \right\} \geq \tau(\bar{e} - \phi^D \tau) \ .$$

By construction of a socially optimal policy scheme, the term in curly brackets on the left-hand side is positive. Furthermore, the term $(\omega + 1)/\omega$ tends to infinity if ω tends to zero. The right-hand side of inequality (B.1) is independent of ω. Thus inequality (B.1) is satisfied if ω is sufficiently small.

From Fact 1, we know that there exist socially optimal policy schemes for all $\omega \in (0, \bar{\omega}^{NR})$ if there exists an optimal policy scheme associated with some $\bar{\omega}^{NR}$. Hence, if there exists a socially optimal scheme, we can always find one for which the developing country is a net receiver. □

Proof of Corollary 3

The developing country is a net receiver if and only if

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

Assuming equal weights in the refunding formula and inserting the tax goal, α and f_0^I as given in (A.4) and (A.5), respectively, this is equivalent to

$$\frac{(1 + \beta^I \phi^I - \beta^I \phi^D - 3\beta^D \phi^D - \beta^D \phi^I)(\phi^D - \phi^I)}{(1 - BP)(1 + BP)} \geq 0 \ .$$

This holds true for all parameters $\phi^I, \phi^D, \beta^I, \beta^D$ that fulfill Assumption 1. Hence, for a refunding formula with equal weights, the developing country is a net receiver for any socially optimal policy scheme. □

Proof of Proposition 4

The developing country is a net beneficiary if and only if

$$\frac{\phi^D}{2}((\hat{\tau}^D)^2 - (\tau^\star)^2) + \frac{\beta^D}{2}((\hat{s})^2 - (s^\star)^2) - \tau^\star(\bar{e} - \phi^D \tau^\star) + \alpha f \frac{1}{\omega + 1} \geq 0 \ . \tag{B.2}$$

We proceed as in the proof of Proposition 3. With the exception of the last term on the left-hand side of (B.2), all terms are independent of ω. If we insert α and f_0^I as given in (A.4) and (A.5), respectively, the last term tends to infinity if ω approaches zero. Hence, for a $\omega > 0$ small enough, inequality (B.2) is satisfied. As the existence of a socially optimal policy scheme with $\bar{\omega}^{NB} > 0$ implies the existence of such a scheme for all $\omega \in (0, \bar{\omega}^{NB})$, we can always find one for which the developing country is a net beneficiary. $\square$

Proof of Corollary 4

Note first that the socially optimal tax rate minimizes total abatement costs and damages. Second, total costs under socially optimal refunding yield the same minimal total abatement costs and damages as monetary flows will net to zero. Third, from Proposition 4 we know that by decreasing ω we can always obtain $F^{DS,D}(\hat{\tau}^D) = F^D(\tau^\star)$ and thus $F^{DS,I}(\hat{\tau}^I) > F^I(\tau^\star)$. As country-specific total costs are continuous in ω, lowering ω slightly will make both countries better off, which completes the proof. $\square$

Proof of Proposition 5

For homogeneous countries $\beta^I = \beta^D = \beta,\ \phi^I = \phi^D = \phi$, the parameters α and f_0^I as given in (A.4) and (A.5), respectively, 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 $\omega \leq 1$ (imposing $\omega > 0$). 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 $\alpha = 1$. $\square$

Proof of Corollary 5

Consider homogeneous countries $\beta^I = \beta^D = \beta,\ \phi^I = \phi^D = \phi$. The developing country is a net receiver if and only if

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

Inserting the tax goal $\tau^I = \tau^D = \tau$ and the policy parameters α and f_0^I derived in the proof of Proposition 5 yields

$$(\bar{e} - \phi\tau)\tau \frac{1-\omega}{2\omega} \geq 0 \ . \tag{B.3}$$

As a socially optimal policy scheme satisfies $\omega \leq 1$ (see Proposition 5), (B.3) holds.

The developing country is a net beneficiary if and only if

$$\frac{\phi}{2}((\hat{\tau}^D)^2 - (\tau^\star)^2) + \frac{\beta}{2}((\hat{s})^2 - (s^\star)^2) - \tau^\star(\bar{e} - \phi\tau^\star) + \alpha f \frac{1}{\omega+1} \geq 0 \ . \tag{B.4}$$

The sum of the first two terms in (B.4) is non-negative, as countries are homogeneous and thus the social optimum minimizes both the sum and each country's total costs. The last two terms simplify to

$$\frac{1-\omega}{2\omega}\tau(\bar{e} - \phi\tau) \ .$$

Again, as $\omega \leq 1$, (B.4) holds. □

Proof of Proposition 6

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 as given in (A.4) and (A.5), respectively, change to

$$\alpha = \frac{(\omega+1)(\bar{e} - 3\phi\tau)}{2(\bar{e} - 2\phi\tau)} \ , \tag{B.5}$$

$$f_0^I = \frac{\tau(\omega+1)(\bar{e} - \phi\tau)(\bar{e} - 2\phi\tau)}{\omega(\bar{e} - 3\phi\tau)} - 2\tau(\bar{e} - \phi\tau) \ . \tag{B.6}$$

Assumption 1 simplifies to $\beta\phi < \frac{1}{4}$.

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

$$\omega \leq \frac{\bar{e} - \phi\tau}{\bar{e} - 3\phi\tau} \ . \tag{B.7}$$

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

$$\bar{e} - 2\phi\tau - \omega(\bar{e} - 4\phi\tau) \geq 0 \ . \tag{B.8}$$

We only have to examine the case $\bar{e} - 4\phi\tau > 0$, as for $\bar{e} - 4\phi\tau \leq 0$, (B.8) holds. Inequality (B.8) is then equivalent to

$$\omega \leq \frac{\bar{e} - 2\phi\tau}{\bar{e} - 4\phi\tau} \ . \tag{B.9}$$

Comparison of (B.7) and (B.9) reveals that (B.7) 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

$$\begin{aligned} 0 &< \phi^2 \frac{\tau}{\bar{e} - 2\phi\tau} + 2\phi \frac{\omega}{(\omega + 1)} \ , \\ 0 &< -\phi^2 \frac{\tau}{\bar{e} - 2\phi\tau} + \beta\phi^2 - \frac{\bar{e} - 3\phi\tau}{\tau} + \frac{2(\bar{e} - 2\phi\tau)}{(\omega + 1)\tau} =: g(\omega) \ . \end{aligned}$$

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 :

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

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

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

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

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

which is negative for $0 \leq \beta\phi < 1/4$. Due to 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 $g(\omega)$ changes. By setting $g(\omega) = 0$ and solving for ω, we see that it 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 $h(x) = \frac{4x^3+2x^2+2x-1}{-4x^3-10x^2+6x-1}$ is always larger than 1 for $0 < x < \frac{1}{4}$ (recall 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 6

Recall that the developing country is a net receiver if and only if

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

We insert the tax goal $\tau^I = \tau^D = \tau$ and the policy parameters α and f_0^I from Proposition 6, and obtain

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

which is equivalent to $\omega \leq 1$ and hence $\omega^I \leq \omega^D$. This proves the first point.

The developing country is a net beneficiary if and only if

$$\frac{\phi}{2}((\hat{\tau}^D)^2 - (\tau^\star)^2) + \frac{\beta}{2}((\hat{s})^2 - (s^\star)^2) - \tau^\star(\bar{e} - \phi\tau^\star) + \alpha f \frac{1}{\omega + 1} \geq 0 .$$

Inserting the tax rates, α and f_0^I, this inequality is equivalent to

$$\omega(6\beta^2\phi^2 + 3\beta\phi - 1) + (1 + \beta\phi) \geq 0 . \tag{B.10}$$

To evaluate inequality (B.10), we distinguish two cases. Case 1: If $6\beta^2\phi^2 + 3\beta\phi - 1 > 0$, then all terms on the left-hand side of (B.10) are positive and the inequality is fulfilled. Case 2: If $6\beta^2\phi^2 + 3\beta\phi - 1 < 0$, we insert the upper bound of ω from Proposition 6, $\frac{4\beta^3\phi^3+2\beta^2\phi^2+2\beta\phi-1}{-4\beta^3\phi^3-10\beta^2\phi^2+6\beta\phi-1}$, into the left-hand side of (B.10) and obtain

$$\frac{\beta^2\phi^2(24\beta^3\phi^3 + 20\beta^2\phi^2 - 6)}{-4\beta^3\phi^3 - 10\beta^2\phi^2 + 6\beta\phi - 1} ,$$

which is positive as $\beta\phi < 1/4$ from Assumption 1 holds. Thus the left-hand side is positive for all $\omega \in \left(0, \frac{4\beta^3\phi^3+2\beta^2\phi^2+2\beta\phi-1}{-4\beta^3\phi^3-10\beta^2\phi^2+6\beta\phi-1}\right)$ since it is decreasing in ω. This completes the proof. □

Proof of Proposition 7

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 (30). □

Proof of Corollary 7

For homogeneous countries $\beta^I=\beta^D=\beta,\ \phi^I=\phi^D=\phi$, condition (30) 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 5 that for homogeneous countries there always exists 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 8

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

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

is minimized, whereas the developing country minimizes

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

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 only hold simultaneously if

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

This is equation (31).

If condition (31) holds, the first-order conditions above reduce to one equation, from which we can express α in terms of ω and f_0^I :

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

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

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

Inserting the tax goal and α from (B.13), we obtain

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

which holds true for all $\omega > 0$. Hence it is always possible to find socially optimal policy parameters, given that condition (31) is satisfied. $\square$

Proof of Corollary 8

As to part (i), recall that the developing country is a net receiver if and only if

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

For a refunding scheme without tax revenues, according to Proposition 8, αf is equal to $\frac{(\omega+1)^2 \tau^2 \phi^I \beta^D}{\omega B}$. Inserting this expression and rearranging terms yields

$$\omega \left(\bar{e} - \frac{\beta^I \phi^D + \beta^D \phi^D + \beta^D \phi^I}{B} \tau \right) \leq \frac{\beta^D \phi^I}{B} \tau \ .$$

Inserting the tax rates and taking into account Assumption 1 leads to inequality (32).

As to part (ii), the developing country is a net beneficiary if and only if

$$\frac{\phi^D}{2}((\hat{\tau}^D)^2 - (\tau^\star)^2) + \frac{\beta^D}{2}((\hat{s})^2 - (s^\star)^2) - \tau^\star(\bar{e} - \phi\tau^\star) + \alpha f \frac{1}{\omega + 1} \geq 0 \ ,$$

which can be rewritten as

$$\omega \left\{ \frac{\phi^D}{2}((\hat{\tau}^D)^2 - (\tau^\star)^2) + \frac{\beta^D}{2}((\hat{s})^2 - (s^\star)^2) - \tau^\star(\bar{e} - \phi\tau^\star) + \frac{\beta^D \phi^I}{B}(\tau^\star)^2 \right\} \geq -\frac{\beta^D \phi^I}{B}(\tau^\star)^2 \tag{B.14}$$

As the right-hand side of inequality (B.14) is negative, we can always find a $\omega > 0$ that satisfies (B.14). Moreover, tedious algebraic manipulations reveal that the term in curly brackets on the left-hand side is negative.[17] Therefore, (B.14) provides an upper boundary $\bar{\omega}^{NT} > 0$ on ω, such that the developing country is a net beneficiary for all $\omega \leq \bar{\omega}^{NT}$. $\square$

[17] Details are available upon request.

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