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## Enforcement and cost-effectiveness of international environmental agreements: The role of side-payments

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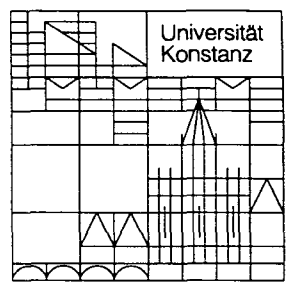
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**Sonderforschungsbereich 178**  
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Carsten Schmidt

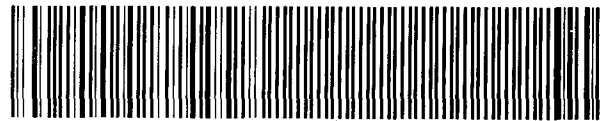
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**Enforcement and Cost-effectiveness of  
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**- The Role of Side-Payments**

**Carsten Schmidt**

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# Enforcement and Cost-effectiveness of International Environmental Agreements – the role of side-payments

Carsten Schmidt\*

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## Abstract:

The paper explores the prospects for international environmental cooperation in a context of limited enforcement, if we allow for side-payments between countries and sequential moves in the implementation of the agreement. The framework of the analysis is a static model of heterogenous countries formulated in terms of costs and benefits of emission abatements. Taking the noncooperative Nash equilibrium as starting-point for negotiations, a mechanism is analysed that uses self-financed transfers as an instrument to create and enforce an international environmental agreement. Two kinds of side-payments are considered: transfers that are self-financed but otherwise unrestricted, and transfers that are restricted to compensations for cost-effectiveness of abatements. Numerical simulations for the different scenarios considered illustrate the gains from cooperation that can be achieved with this mechanism.

JEL classification: D61, D62, H77, Q20, Q28

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# 1 Introduction

The recent creation of international institutions to manage global environmental resources as the *Global Environmental Facility* or the *Montreal Protocol Multilateral Fund* demonstrates that cooperative solutions for international environmental problems which make use of international side-payments not only may be attractive from a theoretic point of view but that they are in fact used. The ongoing negotiations on an international convention to reduce potentially harmful greenhouse gas emissions, for example, raise the question which role transfers could play for such an agreement.

For an international environmental agreement (IEA) to be successful, it has to take into account the key features of transboundary pollution problems. In the context of an IEA where – to a certain extent – side-payments are included as an instrument, especially two characteristics of international environmental policy are important: one fundamental aspect consists in the nonexistence of a higher authority which could force the contracting parties to fulfill their obligations. It is therefore appropriate either to analyse the incentives to manage global environmental resources unilaterally or to concentrate on international cooperative solutions that are self-enforcing. Another crucial aspect is the fact that the countries involved in most cases are considerably different from each other with respect to many characteristics, as e.g. their environmental preferences, economic prosperity, endowments with (natural) resources or technologies available for environmental protection. These heterogeneities may give rise to cost-inefficiencies if environmental policies are not coordinated. Hence, an IEA should not only try to internalize transboundary environmental externalities, it should also aim at cost-effectiveness of abatement efforts.

Combining the aspects of enforcement and cost-effectiveness in international environmental agreements, the paper explores the prospects for cooperative solutions, if we allow for transfers that are paid conditionally on cooperative behavior between countries and sequential moves in the implementation of the agreement. Two kinds of side-payments are considered: transfers that are self-financed but otherwise unrestricted, and transfers that are restricted to compensations for cost-effectiveness of abatements. The latter mirrors the professed purpose of transfers in many IEAs as e.g. the mandate of the Global Environmental Facility or the concept of ‘joint implementation’ within the Framework Convention on Climate Change.

The present analysis builds on contributions about the enforcement-problem and the role of side-payments in international environmental cooperation. In contrast to completely self-enforcing contracts as e.g. in Barrett (1994) or

Finus/Rundshagen (1997) where no additional instruments are available. we consider as in Carraro/Siniscalco (1993) a situation with limited commitment. where self-financed transfers are used as an instrument to bring about stable cooperation. However, in this paper we analyse the case of heterogenous countries. By means of a static, fully specified model as in Barrett (1994) it is shown that the heterogeneity of the countries involved is favourable to the welfare gains attainable through an IEA, especially if transfers are restricted to compensations for cost-effectiveness of the agreement<sup>1</sup>.

The paper is organized as follows: In section 2 we describe the basic two-countries, two-goods model that is formulated in terms of abatement costs and benefits. We use an empirically plausible specification of the model and derive the noncooperative Nash equilibrium as well as the full cooperative (globally first best) allocation. In section 3, a mechanism using side-payments and sequential moves in the implementation of the agreement is described. The gains from cooperation are derived that can be achieved under two alternative kinds of self-financed transfers. The results for different parameter scenarios are illustrated with the help of numerical simulations in section 3 for the case of two and in section 4 for the case of three countries. Section 5 concludes with a summary and possible implications for international environmental policy.

## 2 Costs and benefits of emission reductions

Consider a world of two countries  $A$  and  $B$  whose governments decide upon reductions of emissions that constitute a (pure) common public bad. Then national abatements  $q_k$  add up to

$$Q = q_A + q_B . \tag{1}$$

By considering a one-shot game of complete information and abstracting from general equilibrium effects (like e.g. changes in the terms of trade through environmental policy), the decision problem of a government reduces to balancing national benefits against costs of national abatement efforts. The public good-character of abatements

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<sup>1</sup>Contributions that model heterogenous countries in a dynamic framework are e.g. Finus/Rundshagen (1997) and Kverndokk (1994). Another field of related literature deals with the concept of 'joint implementation' under the Framework Convention on Climate Change. For an overview see Pearce (1994) and for an empirically oriented work e.g. Jackson (1995). The welfare losses of uniform emission reductions in an IEA with heterogenous countries are analysed in Endres (1993) and Hoel (1992).

implies that national benefits depend on aggregate abatement quantities, whereas national abatement costs only depend on a country's own contribution. Net abatement benefits  $\pi$  of country  $k$  thus are

$$\pi_k = B_k(Q) - C_k(q_k) , \quad k = A, B . \quad (2)$$

In order to be able to make any quantitative statements the cost and benefit schedules of  $CO_2$  abatements have to be specified by a plausible functional form. We use a slightly modified version of the specification Barrett (1994) suggests. It allows to consider in a very general way different scenarios of heterogeneity of the countries involved.

Starting with abatement costs, we assume linearly increasing marginal costs of abatements as a reasonable approximation at least over a certain range of abatement quantities<sup>2</sup>. The marginal abatement cost schedule of country  $k$  is

$$C'_k = c_k q_k \quad , \quad c_k > 0 \quad (3)$$

where  $c_k$  is a country-specific exogenous parameter that determines the slope of the marginal cost function for country  $k$ . It comprises simultaneously different reasons that make marginal abatement costs differ between countries. Such reasons are e.g. different substitution possibilities (for energy production) and types of abatement technology available, and the impact of a country's base-year emission level on marginal abatement costs<sup>3</sup>. A less expensive abatement technology or a higher base-year emission level *ceteris paribus* implies a lower value of  $c_k$ .

With regard to the specification of national abatement benefits, it seems reasonable to suppose that marginal damages will increase with the level of greenhouse gas emissions, implying positive but decreasing marginal benefits of reducing emissions<sup>4</sup>. We assume therefore linearly decreasing marginal benefits of abatements which can be written as

$$B'_k = b_k(a - Q) \quad , \quad b_k > 0 \quad , \quad Q < a . \quad (4)$$

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<sup>2</sup>See e.g. Nordhaus (1991), p. 929. Assuming that marginal abatement costs increase at an even steeper rate as some of the empirical literature assesses does not change the qualitative results to be reported below.

<sup>3</sup>See Barrett/OECD (1992).

<sup>4</sup>For estimates concerning carbon emissions see Cline (1992a), chapter 4, Cline (1992b), chapter 6 and OECD (1991), chapter 1. Assuming constant marginal abatement benefits as some of the empirical literature suggests does not change the basic results concerning side-payments as enforcement-mechanism.

The parameter  $a$  is the abatement level where marginal benefits would become zero<sup>5</sup> and  $b_k$  is a country-specific parameter that determines the slope of the marginal benefit function. Marginal abatement benefits differ across countries because of e.g. differing valuations of environmental quality, different damages of climate change measured in terms of lost economic income, and different regional impacts of climate change. Integrating marginal benefits and costs, net benefit function (2) is specified to be

$$\pi_k = b_k (a Q - 1/2 Q^2) - c_k/2 q_k^2 \quad b_k > 0, c_k > 0, Q < a, k = A, B. \quad (5)$$

Balancing marginal benefits against costs determines the optimal abatement quantity  $q_k$  of country  $k$ . The way how a country takes into account the abatement activities of the other country (i.e. its assumptions on the other government's behavior) determines which kind of equilibrium will be reached.

## 2.1 Abatements in the noncooperative Nash equilibrium

In this section we discuss the properties of the noncooperative equilibrium when national governments exhibit NASH behaviour<sup>6</sup>. In this case there is an independent maximization of the net benefit function (5) for each country by choosing *nationally* optimal abatement levels given the abatement quantity of the other country. For national abatement quantities to be optimal, marginal benefits  $B'(Q)$  have to be equalized to marginal costs  $C'(q)$ :

$$\partial \pi_k / \partial q_k = b_k (a - Q) - c_k q_k \stackrel{!}{=} 0 \quad \Leftrightarrow \quad b_k (a - Q) = c_k q_k \quad (6)$$

Solving (6) for  $q_k$  gives the 'best response' of country  $k$  for given abatement levels  $\bar{q}$  of the other country:

$$q_A(\bar{q}_B) = \frac{a - \bar{q}_B}{1 + c_A/b_A} \quad (7a)$$

$$q_B(\bar{q}_A) = \frac{a - \bar{q}_A}{1 + c_B/b_B} \quad (7b)$$

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<sup>5</sup>As in Barrett (1994), p.4, we assume  $Q < a$  so that marginal benefits are positive over the relevant range of abatements.

<sup>6</sup>Alternatively, one could consider uneven positions of national governments with regard to their strategic behavior by assuming a Stackelberg game. See Schmidt (1996) for a comparison of the Nash and Stackelberg case with regard to efficiency properties.



The intersection of the reaction curves determines the noncooperative Nash equilibrium  $N^7$ . The equilibrium values  $q_k^N$  of national abatements are

$$q_A^N = \frac{a}{1 + \frac{c_A}{b_A} + \frac{c_A b_B}{b_A c_B}} \quad (8a)$$

$$q_B^N = \frac{a}{1 + \frac{c_B}{b_B} + \frac{c_B b_A}{b_B c_A}} \quad (8b)$$

Substituting these equilibrium quantities into the global net benefit function

$$\Pi = \pi_A + \pi_B = (b_A + b_B) (aQ - 1/2 Q^2) - c_A/2 q_A^2 - c_B/2 q_B^2 \quad (9)$$

gives global net benefits of abatements  $\Pi^N$  under Nash behavior.

## 2.2 Globally efficient abatements

National abatement levels that are *globally* optimal are derived by maximising the sum of net benefits (9) with respect to  $q_A$  and  $q_B$ :

$$\partial\Pi/\partial q_A = (b_A + b_B)(a - q_A - q_B) - c_A q_A \stackrel{!}{=} 0 \quad (10a)$$

$$\partial\Pi/\partial q_B = (b_A + b_B)(a - q_A - q_B) - c_B q_B \stackrel{!}{=} 0 \quad (10b)$$

which yields

$$q_A^* = \frac{a}{1 + \frac{c_A}{b_A + b_B} + \frac{c_A}{c_B}} \quad (11a)$$

$$q_B^* = \frac{a}{1 + \frac{c_B}{b_A + b_B} + \frac{c_B}{c_A}} \quad (11b)$$

The potential welfare gains from full cooperation can be measured by comparing  $\Pi^N$  with global net benefits  $\Pi^*$  of internationally efficient abatements. For this purpose may serve the index  $\Delta \equiv \Pi^N/\Pi^*$  which we can evaluate for different parameter constellations.

Comparing the globally efficient with the noncooperative allocation of abatements illustrates the two sources of inefficiency mentioned above. Not only aggregate abatement is suboptimal ( $Q^N < Q^*$ ), but also its distribution across countries

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<sup>7</sup>This equilibrium is unique because the reaction curves (7) are linear and it is stable, since (by  $b_k > 0$  and  $c_k > 0$ ) the slopes of the curves are less than 1 in absolute value.

generally will be inefficient<sup>8</sup>. Only in the special case of  $b_A = b_B$ , the two ratios  $q_A^*/q_B^* = c_B/c_A$  (from (11) ) and  $q_A^N/q_B^N = (b_A c_B)/(c_A b_B)$  (from (8) ) do coincide, and cost-effectiveness is reached even in the noncooperative equilibrium.

### 3 An enforceable international environmental agreement with side-payments

The globally efficient allocation could be implemented through Coasian' bargaining of the countries involved if complete enforcement were available. This, however, is ruled out here because of the lack of a supranational authority that can force the cooperating agents to fulfill their contractual obligations. In the absence of such a complete institutional framework, agreements not only have to be individually rational, but also incentive-compatible from an ex post-perspective. Therefore, we now set up a mechanism that consists of side-payments and sequential moves of the cooperating parties in order to secure incentive compatibility of the IEA. At first we consider the case where transfers are paid conditionally on cooperative behavior, but are otherwise restricted only by the gains from cooperation a potential donor country could realize through the agreement (i.e. they must be self-financed). Additionally, the model is analysed for the case where transfers are restricted to compensate the potential host country with lower marginal abatement costs for its higher abatement efforts in order to bring about cost-effectiveness of the cooperative abatements.

Assume that the starting-point for negotiating an IEA between countries is the noncooperative Nash equilibrium<sup>9</sup>. As additional institutional structure, we presume that a third party can be constructed (e.g. an international institution as the Global Environmental Facility) where transfers are deposited before they are given to the recipient country. This guarantees that side-payments are always executed according to the terms of the IEA and implies some commitment, although to a very limited extent. We define country  $A$  to be the country with higher abatement net benefits under global efficiency ( $\pi_A^* > \pi_B^*$ ) and hence higher potential gains from cooperation<sup>10</sup>. The sequence of a cooperation game that incorporates side-payments and sequential moves of the acting governments yielding an enforceable IEA then is

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<sup>8</sup>Another way to illustrate this is by comparing the F.O.C. for national optimal behavior  $B'_k = C'_k$  with the modified Samuelson condition for global efficiency  $B'_A + B'_B = C'_A = C'_B$ .

<sup>9</sup>Hence, we do not consider pre-negotiation strategic behavior.

<sup>10</sup>A sufficient condition for this is that both the marginal abatements benefit and the cost function is steeper for country  $A$ :  $b_A > b_B \wedge c_A > c_B \Rightarrow \pi_A^* > \pi_B^*$ . See Appendix A.1.

as follows:

1. Countries  $A$  and  $B$  negotiate the terms of the IEA with regard to cooperative abatement levels  $q_k^C$  and the transfer  $T$ .
2. Country  $A$  moves first. It raises abatements to the level  $q_A^C$  and deposits the transfer  $T$  agreed-upon in 1.
3. Country  $B$  moves second. It raises its abatements to the cooperative level  $q_B^C$  (or defects and abates  $q_B^D$ ).
4. Country  $B$  receives the side-payment  $T$  if it cooperates (or country  $A$  is refunded if  $B$  defects).

The agreement has to be individually rational for both countries, i.e. it has to guarantee at least the same utility level as in the noncooperative equilibrium<sup>11</sup>. To be stable, it also must be ex post not rewarding (or not possible) for any government to deviate from the agreed measures. For the recipient country incentive compatibility of the IEA is secured if the gain from defecting from the terms of the agreement is not greater than the sanction of the refused side-payment. This sanction is credible because denying the side-payment does not harm the donor country<sup>12</sup>. If the donor country would lose the deposited transfer in case of its own defection, this would not be a sanction to it, since the transfer would have been paid under cooperation anyway<sup>13</sup>. Therefore an additional instrument is needed to secure cooperative behavior of the donor country. It is assumed here that the only possibility for country  $A$  to commit itself to the execution of its obligations from the IEA consists in acting first in the cooperative abatement game. Hence, the sequence of moves described above is voluntarily chosen by the countries and the only way to guarantee incentive compatibility.

The outcome of the negotiations in stage 1 basically depends on two factors: these are the relative bargaining positions of the negotiating governments and the extent to which transfers are available as enforcement-mechanism. Concerning the first factor, we assume here that no country has a systematic advantage in the negotiation process. Then, it seems reasonable to suspect that countries will agree to maximize joint net benefits (9) of abatements. Concerning the availability of transfers, in the following we consider the two scenarios mentioned above.

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<sup>11</sup>It is assumed that if a country is indifferent between cooperating or not, it cooperates.

<sup>12</sup>Moreover, the decision upon it is given to the third party.

<sup>13</sup>In fact, if  $A$  could also defect from paying the transfer, its incentive not to act cooperatively would be even stronger.

### 3.1 Unrestricted self-financed transfers

Taking into account the above considerations, the terms of the IEA agreed-upon in stage 1 have to be the outcome of the following optimisation problem<sup>14</sup>:

$$\max \Pi(q_A^C, q_B^C) \quad \text{s.t.} \quad (12)$$

$$\pi_A(q_A^C, q_B^C) - T \geq \pi_A(q_A^N, q_B^N) \quad (13)$$

$$\pi_B(q_A^C, q_B^C) + T \geq \pi_B(q_A^N, q_B^N) \quad (14)$$

$$\pi_B(q_A^C, q_B^D) - \pi_B(q_A^C, q_B^C) \leq T \quad (15)$$

Transfer  $T$  is defined in terms of net benefits or transferable utility instead of e.g. monetary units or units of a representative private good<sup>15</sup>. Constraints (13) and (14) are the conditions of individual rationality for the two countries to participate in the IEA. Abatements  $q_B^D$  that maximize  $B$ 's net benefits when defecting unilaterally from the agreement we can calculate by substituting  $q_A^C$  into  $B$ 's best response (7b). For the IEA to be enforceable, the gains for  $B$  from defecting have to be smaller than or equal to the transfer  $T$  it receives if and only if it is abating its emissions about  $q_B^C$ . This is captured in constraint (15). For the donor country  $A$ , incentive compatibility is given by the prescription that it executes the IEA before the recipient country  $B$ . If it does so and (15) holds, there is no incentive for  $B$  to defect. And since  $A$  knows this, there is no reason why it should not do the first step in executing the agreement.

In this subsection the upper bound for side-payments which can be used as enforcement-mechanism is determined by the potential gains from cooperation of the donor country (13). The lower bound is given by constraints (14) and (15) for cooperation of  $B$ . Consequently, the participation and incentive compatibility constraints can be written together as

$$\pi_A^C - \pi_A^N \geq T \geq \max[\pi_B^N - \pi_B^C, \pi_B^D - \pi_B^C]. \quad (16)$$

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<sup>14</sup>A more general formulation for (12) would be  $\max(\delta_A \pi_A + \delta_B \pi_B)$ ,  $0 \leq \delta_k \leq 1$ ,  $k = A, B$  where  $\delta_k$  reflects the bargaining power of a government. For the sake of simplicity and as a benchmark, we assume here  $\delta_k = 1$ . The opposite benchmark would be  $\delta_A = 1$ ,  $\delta_B = 0$ . This would be analogous to the Stackelberg case and rule out global efficiency, since then not  $\Pi$  but  $\pi_A$  is maximised.

<sup>15</sup>This transfer-mechanism is different from the classical Kaldor-Hicks compensation principle in two ways: for the IEA to yield incentive compatibility, side-payments not only have to be actually undertaken instead of just being possible, they also have to make the recipient at least as good of as in the situation where it defects unilaterally instead of only making him as least as good of as in the situation without cooperation.

In general, two cases for the solution of the above optimisation problem are possible, depending on whether (16) is binding or not. If not, the globally efficient allocation of abatements (11) is the outcome of the cooperative solution and the gains from environmental cooperation are maximal ( $q_k^C = q_k^*$ ,  $\Pi^C = \Pi^*$ ). If one of the incentive compatibility constraints were binding a second best cooperative solution would be the outcome. However, for the case of only two countries and self-financed, otherwise unrestricted transfers, the full cooperative outcome can always be sustained. In other words, there exist no values of  $b_k$ ,  $c_k$  such that  $\pi_A^* - \pi_A^N < \max[\pi_B^N - \pi_B^*, \pi_B^D - \pi_B^*]$ <sup>16</sup>.

The above result is even true for the case of completely homogenous countries. In this benchmark scenario, it does not matter for global efficiency which country is assigned to be the donor and which to be the recipient of transfers. It does matter, however, for the distribution of gains from environmental cooperation as Table 1 illustrates. The recipient country systematically profits from the fact that it moves last and has to be bribed to stick to the IEA<sup>17</sup>.

<b>Table 1: Self-financed unrestricted transfers / homogenous countries</b>					
$a = 1000, \quad b_A = 1, \quad b_B = 1, \quad c_A = 100, \quad c_B = 100$					
$q_A^N = 9.8$	$q_B^N = 9.8$	$Q^N = 19.6$	$\pi_A^N = 14609$	$\pi_B^N = 14609$	$\Delta^N = 0.76$
$q_A^C = 19.2$	$q_B^C = 19.2$	$Q^C = 38.4$	$\pi_A^C - T = 14653$	$\pi_B^C + T = 23807$	$\Delta^C = 1$
$q_A^* = 19.2$	$q_B^* = 19.2$	$Q^* = 38.4$	$\pi_A^* = 19230$	$\pi_B^* = 19230$	$T = 4577$

When the countries are heterogenous, global efficiency can be reached as long as the country with higher potential gains from cooperation is the donor country. We have assumed country  $A$  to be this country ( $b_A > b_B \wedge c_A > c_B \Rightarrow \pi_A^* > \pi_B^*$ ), hence the prescription in the cooperation game to let  $A$  be the donor. Both countries will agree in stage 1 on this rule, if it is not attractive for any of them to change roles, i.e. as long as

$$\pi_A^* - T_{AB} \geq \pi_A^+ + T_{BA} \quad (17a)$$

$$\pi_B^* + T_{AB} \geq \pi_B^+ - T_{BA} \quad (17b)$$

where  $T_{AB}$  ( $T_{BA}$ ) is a transfer from  $A$  to  $B$  ( $B$  to  $A$ ) and  $\pi_k^+$  the pay-off of the cooperative solution with transfers from  $B$  to  $A$ . As numerical simulations show,

<sup>16</sup>The analytical proof is given in appendix A.2.

<sup>17</sup>However, this distributional effect is compensated in the case of heterogenous countries to some extent by the rule that the country with higher potential gains from cooperation is to be the donor.

(17) holds for both countries if  $\pi_A^* > \pi_B^*$ <sup>18</sup>.

Table 2: Self-financed unrestricted transfers from A to B / heterogenous countries					
$a = 1000, b_A = 1, b_B = 1, c_A = 100, c_B = 10$					
$q_A^N = 9.0$	$q_B^N = 90.1$	$Q^N = 99.1$	$\pi_A^N = 90130$	$\pi_B^N = 53607$	$\Delta^N = 0.79$
$q_A^C = 16.4$	$q_B^C = 163.9$	$Q^C = 180.3$	$\pi_A^C - T_{AB} = 120092$	$\pi_B^C + T_{AB} = 60235$	$\Delta^C = 1$
$q_A^* = 16.4$	$q_B^* = 163.9$	$Q^* = 180.3$	$\pi_A^* = 150631$	$\pi_B^* = 29696$	$T_{AB} = 30539$

Table 3 illustrates the inverse case to the above rule, where parameter values are as in Table 2, but B is the donor and A the recipient of transfers. It is inferior not only with regard to global net benefits ( $\Delta^C$ ), but also to national pay-offs of *both* countries.

Table 3: Self-financed unrestricted transfers from B to A / heterogenous countries					
$a = 1000, b_A = 1, b_B = 1, c_A = 100, c_B = 10$					
$q_A^N = 9.0$	$q_B^N = 90.1$	$Q^N = 99.1$	$\pi_A^N = 90130$	$\pi_B^N = 53607$	$\Delta^N = 0.79$
$q_A^C = 17.3$	$q_B^C = 115.5$	$Q^C = 132.8$	$\pi_A^C + T_{BA} = 112667$	$\pi_B^C - T_{BA} = 53607$	$\Delta^C = 0.92$
$q_A^* = 16.4$	$q_B^* = 163.9$	$Q^* = 180.3$	$\pi_A^* = 150631$	$\pi_B^* = 29696$	$T_{BA} = 3723$

### 3.2 Compensations for cost-effectiveness of abatements

Transfers between countries that cooperate on environmental policy may be restricted to compensations for higher, cost-effective abatements of countries with relatively low marginal abatement costs, as it is laid down e.g. in the mandate of the Global Environmental Facility and its concept to compensate only for *incremental costs*. Such transfers can be used not only as compensation for higher abatement costs induced by a cost-effective redistribution of national abatement efforts, but also as an instrument to enforce an IEA about increasing aggregate abatements. We can think of such an agreement as determining at first jointly an optimal increase of abatements by equal percentages, resulting in intermediate cooperative quantities  $q_k^P$ , and then redistributing them in a cost-effective way towards  $q_k^C$  that minimizes aggregate abatement costs, leaving the global amount of cooperative abatements unchanged<sup>19</sup>.

<sup>18</sup>Even if one of the constraints (17) would not hold, the countries could still agree on this rule by an additional ‘second order’ compensation so that it holds at least with equality. This is always possible, since  $\Pi^* > \Pi^+$ .

<sup>19</sup>This may be seen as a rule of fairness and follows the pragmatic approach in many environmental negotiations. It is also necessary to separate in some way the negotiations on mitigating free-riding and on cost-effectiveness. The rule determines the amount of transfers paid to the

In addition to equations (12-15), in this case the optimisation problem also has to take into account that transfers are restricted to compensate low-cost country  $B$  for its incremental abatement costs

$$T^{CE} = C_B(q_B^C) - C_B(q_B^P) \quad (18)$$

and that the cooperative abatements are cost-effective ( $q_A^C/q_B^C = q_A^*/q_B^* = c_B/c_A$ ). To determine the hypothetical abatement quantities  $q_B^P$ , we use the fact that national abatements which are increased in equal proportions are distributed as in the Nash equilibrium ( $q_A^P/q_B^P = q_A^N/q_B^N = b_A c_B/b_B c_A$ ). Since those quantities are redistributed cost-effectively, the level of aggregate abatements remains unchanged ( $Q^P = Q^C$ ). Using the above relationships, we have

$$T^{CE} = \frac{c_B}{2} \left[ 1 - \frac{(1 + \frac{c_B}{c_A})^2}{(1 + \frac{b_A c_B}{b_B c_A})^2} \right] q_B^2. \quad (19)$$

The problem of finding the optimal terms of the IEA that can be sustained under this enforcement-mechanism essentially is about increasing abatements in equal proportions to the level where as much transnational spill-overs of abatements as possible are internalized, at the same time taking into account that the compensation country  $B$  receives has to be high enough to make it rewarding for  $B$  to cooperate. It turns out that either no cooperative solution at all, only a second-best one or as in the case of self-financed unrestricted transfers the full cooperative solution can be enforced with transfers restricted in the described manner, depending on the parameter values of the model. Figure 1 summarizes the results of numerical simulations for different parameter combinations<sup>20</sup>.

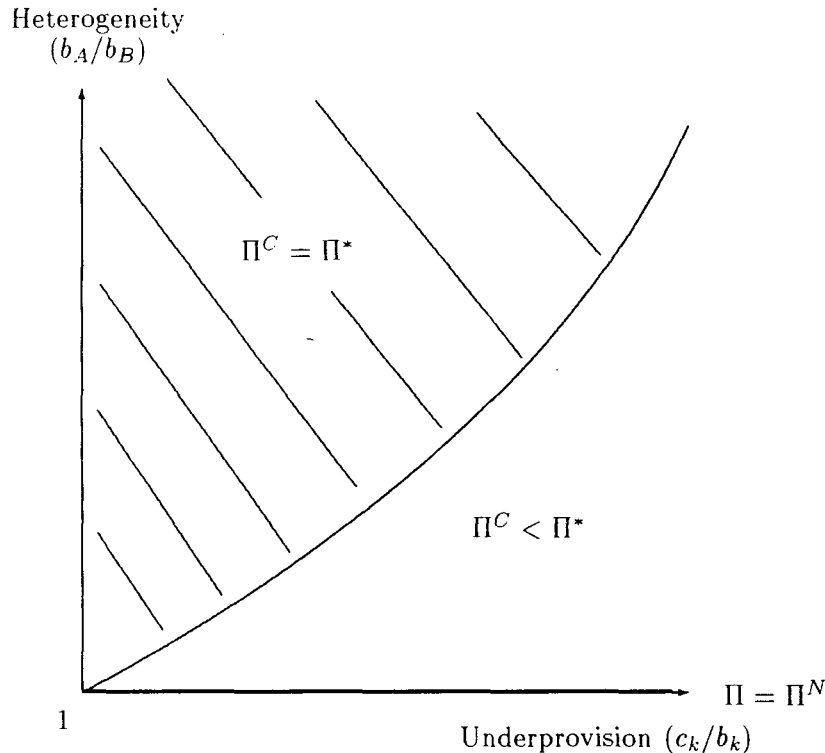
It illustrates that the gains from stable environmental cooperation using compensations for cost-effectiveness depend on two factors depicted on the axes: on the one hand, the outcome depends on how severe the incentives of free-riding on other countries abatements and the resulting welfare losses from underprovision with abatement efforts are. This can be measured by the ratio ( $c_k/b_k$ ). If e.g. the benefits of abatements grow at a much steeper rate than their costs, the latter play only a minor role in the abatement decision and underprovision is not much of a problem. On the other hand, we see from (19) that the transfer is ceteris paribus the higher, the more asymmetric the countries are with respect to benefit parameters ( $\partial T^{CE}/\partial(b_A/b_B) > 0$ ), measured by the ratio  $b_A/b_B$ .

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low-cost country and thereby influences the results reported below.

<sup>20</sup>The Kuhn-Tucker conditions for optimal abatement quantities are derived in appendix A.2.

**Fig. 1: Enforceable IEAs by compensations for cost-effectiveness**



In the benchmark case of completely homogenous countries marginal abatement costs do not differ in the Nash equilibrium, no gains can be made from cost-effectiveness of cooperative abatements and thus, the former cannot be used as enforcement-mechanism for the IEA. The same result we have in scenarios where the countries are heterogenous, but in a way that does not influence the cost-effectiveness of noncooperative abatements. This is the case if we observe different abatement cost schedules ( $c_A \neq c_B$ ), but identical marginal abatement benefits ( $b_A = b_B \Leftrightarrow B'_A = B'_B$ ). The latter implies that there are as for completely homogenous countries no cost-inefficiencies in the Nash equilibrium, although cost parameters  $c_k$  differ across countries<sup>21</sup>.

If there is only moderate asymmetry and marginal abatement costs differ only a little across countries, compensations for cost-effectiveness may be sufficient only

<sup>21</sup>This is due to the fact that national governments equalize marginal abatement benefits and costs when determining nationally optimal noncooperative abatement quantities. A higher value of  $c_k$  in  $A$  is compensated by lower abatements  $q_A^N$ . It can also be seen by comparing the distribution of efficient abatements  $q_A^*/q_B^* = c_B/c_A$  with the distribution of abatements in the Nash equilibrium  $q_A^N/q_B^N = (b_A c_B)/(b_B c_A)$ .



to enforce a second-best IEA ( $\Pi^C < \Pi^*$ ). In this case both countries increase their abatements and the potential gains of recipient country  $B$  from defecting constitute the constraint (15) that restricts the terms of the agreement. Nevertheless, substantial gains from cooperation may still be attainable (Table 4).

$a = 1000, \quad b_A = 1.2, \quad b_B = 1, \quad c_A = 100, \quad c_B = 100$					
$q_A^N = 11.7$	$q_B^N = 9.8$	$Q^N = 21.5$	$\pi_A^N = 18660$	$\pi_B^N = 16508$	$\Delta^N = 0.76$
$q_A^C = 16.6$	$q_B^C = 16.6$	$Q^C = 33.3$	$\pi_A^C - T^{CE} = 23020$	$\pi_B^C + T^{CE} = 21279$	$\Delta^C = 0.96$
$q_A^* = 21.1$	$q_B^* = 21.1$	$Q^* = 42.2$	$\pi_A^* = 27305$	$\pi_B^D = 21279$	$T^{CE} = 2399$

If both the heterogeneity and the potential gains from cooperation are substantial, the agreement results in a reduction of  $A$ 's and a sharp increase in  $B$ 's abatements. Then, again, only a second-best solution is the outcome because constraint (14) may be binding. This can be seen from (19) because the transfer is ceteris paribus the higher, the higher the value of  $c_B$  and the higher cooperative abatements are ( $\partial T^{CE}/\partial q_B = c_B [\dots] q_B > 0$ ). However, transfers for cost-effective abatements increase at a lower rate than marginal abatement costs of  $B$  ( $\partial C_B/\partial q_B = c_B q_B$ ). Thus, globally efficient abatement quantities could make  $B$  worse off than in the Nash equilibrium and defecting would not be profitable, given that high-cost country  $A$  reduced its abatements (Table 5).

$a = 1000, \quad b_A = 1, \quad b_B = 0.1, \quad c_A = 100, \quad c_B = 10$					
$q_A^N = 9.8$	$q_B^N = 9.8$	$Q^N = 19.6$	$\pi_A^N = 14609$	$\pi_B^N = 1461$	$\Delta^N = 0.27$
$q_A^C = 5.2$	$q_B^C = 52.1$	$Q^C = 57.3$	$\pi_A^C - T^{CE} = 44847$	$\pi_B^C + T^{CE} = 1461$	$\Delta^C = 0.78$
$q_A^* = 9.8$	$q_B^* = 98.1$	$Q^* = 107.9$	$\pi_A^* = 97299$	$\pi_B^D = 1009$	$T^{CE} = 9468$

Finally, if countries are sufficiently heterogeneous and initial inefficiencies are not too large, the full cooperative solution can be enforced ( $\Pi^C = \Pi^*$ ). Table 6 gives a numerical example for cases where country  $B$ 's abatement benefits are (close to) zero. This mirrors the scenario where only one country is interested in environmental cooperation. The other country then will participate only if it receives a compensation that is high enough to make it at least indifferent with the Nash equilibrium. Since there exist no incentives for  $B$  to free ride on higher abatements of  $A$  after implementation of stage 2, the increase in net benefits that can be achieved by  $B$ 's defection is equal to its reduction of abatement costs. Since  $B$  gets compensated for higher costs if it cooperates, the full cooperative solution can always (regardless of the values of  $b_A$  and  $c_k$ ) be enforced.

Table 6: Compensations for cost-effectiveness					
$a = 1000, b_A = 1, b_B \rightarrow 0, c_A = 10, c_B = 10$					
$q_A^N = 90.9$	$q_B^N = 0$	$Q^N = 90.9$	$\pi_A^N = 45454$	$\pi_B^N = 0$	$\Delta^N = 0.55$
$q_A^C = 83.3$	$q_B^C = 83.3$	$Q^C = 166.67$	$\pi_A^C - T^{CE} = 83333$	$\pi_B^C + T^{CE} = 0$	$\Delta^C = 1$
$q_A^* = 83.3$	$q_B^* = 83.3$	$Q^* = 166.67$	$\pi_A^* = 118055$	$\pi_B^* = -34722$	$T^{CE} = 34722$

## 4 The case of more than two countries

It would be tempting to interpret the two-country-case from above as a model of two groups of countries as e.g. a coalition of industrialized countries jointly undertaking side-payments to a group of developing countries. This, however, would neglect the incentives for strategic behavior *within* coalitions. If non-cooperative behavior of one country does not lead necessarily to a total breakdown of an IEA as in the case of only two players, the free-rider problem is manifest not only in the incentive to defect from an agreement, but also in the incentive to abstain from an IEA whilst a sub-group of the countries involved cooperates. Hence, in many cases partial cooperation of a sub-group of governments will emerge (Finus/Rundshagen, 1997) which gives rise to an additional coordination problem (Carraro/Siniscalco, 1993, p.322)<sup>22</sup>. •

To investigate the additional problems that arise in a multiple-country context, in this section the transfer-mechanism is applied to the simplest scenario of more than two countries. This is the case of three countries. We illustrate how the results change due to this modification by numerical examples for each of the two transfer-mechanisms described in section 3.

### 4.1 Unrestricted self-financed transfers

Consider three countries  $A, B, C$  involved in an international environmental problem. In addition to the decision as described in section 3, each government now also decides about joining the IEA or abstaining from it, given the other two governments cooperate. The participation decision is captured in the pay-off matrix of Tables 7 to 9, where P stands for ‘participation’ and O for ‘staying outside’ the agreement. The numbers in brackets indicate the pay-offs of the individual countries ( $\pi_A, \pi_B, \pi_C$ ) and the number in square brackets is the index of global efficiency [ $\Delta = \Pi/\Pi^*$ ]. NC stands for the noncooperative Nash equilibrium, the other cases

<sup>22</sup>In addition, even if a ‘grand coalition’ comprising all the countries involved emerges, there still has to be solved the problem of ‘burden sharing’. This is especially relevant when side-payments are given jointly by a group of donors.

describe cooperative solutions where a transfer is paid from the country(ies) on the left of the arrow to the country(ies) on the right<sup>23</sup>. The results for case of homogeneous countries are exemplified in Table 7. Comparing the pay-offs of each country for

<b>Table 7: Participation Decision / Unrestricted transfers</b>				
$a = 10, \quad b_A = b_B = b_C = 1, \quad c_A = c_B = c_C = 10$				
		country B		
		P	O	
country A	P	country C	O	
		P	country C	
		O	O	
P	$A \rightarrow B$ and $C$ :	$A \rightarrow B$ :	$A \rightarrow C$ :	
	(17,26,26) [0.98]	(17,20,24) [0.88]	(17,24,20) [0.88]	
	$A$ and $B \rightarrow C$ :			
	(21,21,30) [1.0]			
	$B \rightarrow A$ and $C$ :	$B \rightarrow A$ :		
	(26,17,26) [0.98]	(20,17,24) [0.88]		
	$B$ and $C \rightarrow A$ :			
(30,21,21) [1.0]				
$C \rightarrow A$ and $B$ :		$C \rightarrow A$ :		
(26,26,17) [0.98]		(20,24,17) [0.88]		
$A$ and $C \rightarrow B$ :				
(21,30,21) [1.0]				
O	$B \rightarrow C$ :	NC:	NC:	
	(24,17,20) [0.88]	(17,17,17) [0.74]	(17,17,17) [0.74]	
	$C \rightarrow B$ :			
	(24,20,17) [0.88]		NC:	
			(17,17,17) [0.74]	

the different possible situations, it turns out that the full cooperative solution with participation of all three countries is not an equilibrium. However, it is profitable for each country to cooperate with one other country, given that the third country stays outside. Hence, in this scenario not only partial cooperation emerges, but also there is no unique cooperative equilibrium<sup>24</sup>.

The results may be different for the case of heterogeneous countries. For example, when costs and benefits of abatements are distributed as in the case of two countries ( $b_A > b_B > b_C \wedge c_A > c_B > c_C \Rightarrow \pi_A > \pi_B > \pi_C$ ) and the countries are sufficiently asymmetric (Table 8), the participation of all three countries can be enforced. However, for the full cooperative solution to be incentive compatible, additional transfers are required that solve the coordination problem. In the numerical example of Table 8, this is possible through additional transfers from  $A$  to  $B$  and  $C$

<sup>23</sup>The allocations indicated “—” are dominated and therefore not computed.

<sup>24</sup>In total, six equilibria are possible:  $A \rightarrow B$ ,  $B \rightarrow A$ ,  $A \rightarrow C$ ,  $C \rightarrow A$ ,  $B \rightarrow C$ ,  $C \rightarrow B$ .

Table 8: Participation Decision / Unrestricted transfers							
$a = 10, b_A = 1 > b_B = 0.5 > b_C = 0.1, c_A = 10 > c_B = 5 > c_C = 1$							
		P country B			O		
		P	country C	O	P	country C	O
country A	P	$A \rightarrow B$ and $C$ :	$A \rightarrow B$ :	$A \rightarrow C$ :	NC:		
		(29,23,2) [1.0]	(21,9,3) [0.60]	(26,19,6) [0.95]	(17,9,2) [0.52]		
		$A$ and $B \rightarrow C$ :					
		(41,11,2) [1.0]					
	$B \rightarrow A$ and $C$ :	$B \rightarrow A$ :					
	—	—					
	$B$ and $C \rightarrow A$ :						
	—						
$C \rightarrow A$ and $B$ :		$C \rightarrow A$ :					
—		—					
$A$ and $C \rightarrow B$ :							
(21,14,2) [0.68]							
O	$B \rightarrow C$ :	NC:	NC:	NC:	NC:		
	(32,13,2) [0.86]	(17,9,2) [0.52]	(17,9,2) [0.52]	(17,9,2) [0.52]	(17,9,2) [0.52]		
	$C \rightarrow B$ :						
—							

(-9,+8,+1) or from  $B$  to  $A$  and  $C$  (+3,-4,+1). In Table 8, both the solution where  $A$  is the only donor as well as when  $A$  and  $B$  jointly pay transfers to  $C$  are full cooperative equilibria. Thus, even with such additional transfers there may exist more than one cooperative solution for the ‘grand coalition’. Again, the heterogeneity of the countries involved facilitates cooperation. This is true even if self-financed transfers are not further restricted because in the case of multiple countries the heterogeneity helps to solve the coordination problem.

## 4.2 Compensations for cost-effectiveness of abatements

In case side-payments are restricted to compensations for cost-effectiveness of abatements under the IEA, the coordination problem is the same as described above. Table 9 ( $\pi_A > \pi_B > \pi_C$ ) shows that there is again a potential for the full cooperative solution<sup>25</sup>. However, this would require additional transfers (-4,+3,+1) which have been ruled out here by assumption. Hence, only a coalition two countries will

<sup>25</sup>The allocations indicated “—” do not correspond to the principle of compensating low-cost countries and are therefore ruled out.

cooperate which may still generate substantial gains from cooperation as Table 9 illustrates.

<b>Table 9: Participation Decision / CE-Compensations</b>					
$a = 10, \quad b_A = 1 > b_B = 0.5 > b_C = 0.1, \quad c_A = 10 > c_B = 5 > c_C = 1$					
		country B		O	
		P	country C	O	
		P	country C	O	
country A	P	$A \rightarrow B$ and $C$ : (18,10,2) [0.57]	$A \rightarrow B$ : (20,9,3) [0.60]	$A \rightarrow C$ : (28,15,2) [0.84]	NC: (17,9,2) [0.52]
		$A \rightarrow B \wedge B \rightarrow C$ : (29,9,2) [1.0]			
		$B \rightarrow A$ and $C$ : —	$B \rightarrow A$ : —		
		$B$ and $C \rightarrow A$ : —			
		$C \rightarrow A$ and $B$ : —		$C \rightarrow A$ : —	
		$A$ and $C \rightarrow B$ : —			
	O	$B \rightarrow C$ : (30,13,2) [0.83]	NC: (17,9,2) [0.52]	NC: (17,9,2) [0.52]	NC: (17,9,2) [0.52]
		$C \rightarrow B$ : —			

## 5 Conclusion

The paper explores the prospects for cooperative environmental policy where limited commitment is available. Within the framework of specific abatement cost and benefit functions and starting negotiations from the noncooperative Nash equilibrium, a model is analysed that uses conditional transfers and sequential moves to reach an enforceable international environmental agreement. Both kinds of side-payments considered prove to be powerful instruments. In the general, the welfare gains that can be achieved with the mechanism considered depend on the target of the negotiations, the availability of side-payments, the costs and benefits of emission reductions and the number of the countries involved. If countries agree to maximize joint net benefits of abatements, the full cooperative solution can always be attained in the two-country-case and substantial gains from cooperation are possible even if transfers are restricted to compensations for cost-effectiveness of abatement efforts and

if more than two countries are involved. In both cases, the prospects for gains from environmental cooperation are the better, the more heterogenous the countries are.

The institutional requirement that is needed to bring the proposed enforcement-mechanism to work in addition to the general availability of side-payments is the existence of a 'third party' that works as intermediary between the donor and the host country. If one stresses the absence of a supranational enforcement-authority as it is done here, the requirement of an intermediary is nevertheless not too strong an assumption. The only competence needed is to collect and distribute the side-payments according to the rules previously determined in the IEA. Any own discretionary power is not necessary. The requirement is even less problematic if the IEA can fall back on an already existing institution that is designed more or less precisely for this purpose, as e.g. the Global Environmental Facility. Of course, one might argue that insurance against non-complying behavior through the deposition of a mortgage could be constructed to enforce any kind of cooperative solution, if only the deposited amounts are high enough. However, this is a fairly stronger requirement than the mechanism to deposit only those transfers which are paid in accordance to the agreement anyway.

An important implication of the analysis undertaken in this paper for international environmental policy is that countries in face or in process of negotiating over an international environmental problem as e.g. 'global warming' should not engage in cost-effectiveness before the IEA is successfully negotiated. Every policy measure that improves the cost-effectiveness even before the implementation of the agreement reduces the cost-savings that can be reached within the agreement itself and which may be used as a mechanism to enforce the latter. From this perspective the concept of 'joint implementation' in the Framework Convention on Climate Change, for example, should be linked (except for limited pilote projects to explore and demonstrate its practicability) closely to the success of the IEA itself.

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## Appendix

### A.1 Sufficient condition for higher potential gains from environmental cooperation

Define the country to have higher potential gains from the IEA whose abatement net benefits in the social optimum are the highest and call it country  $A$ . Then  $\pi_A^* > \pi_B^*$  must hold. Substituting (11) gives

$$\begin{aligned}\pi_A^* - \pi_B^* &= (b_A - b_B)Q^*[2a - Q^*] + c_B q_B^{*2} - c_A q_A^{*2} \\ &= (b_A - b_B)Q^*[2a - Q^*] \\ &\quad + (c_A - c_B) \left[ 1 + \frac{c_A c_B}{(b_A + b_B)^2} \right] + \frac{2(c_A^2 - c_B^2)}{b_A + b_B} + \frac{c_A^3 - c_B^3}{c_A c_B} > 0\end{aligned}$$

The first term is positive for  $b_A > b_B \wedge Q^* < 2a$ , the latter holding because of (4). The other three terms are all positive for  $c_A > c_B$ . Hence,  $b_A > b_B \wedge c_A > c_B \Rightarrow \pi_A^* > \pi_B^*$ .

### A.2 Incentive compatibility of the full cooperative solution in the case of unrestricted self-financed transfers

To prove that the social optimum in the two-country-case can always be attained by self-financed, but otherwise unrestricted transfers, we have to check by use of (16) if there exist values of  $b_k, c_k$  such that  $\pi_A^* - \pi_A^N < \max[\pi_B^N - \pi_B^*, \pi_B^D - \pi_B^*]$ . We have

$$\pi_A^* - \pi_A^N > \pi_B^N - \pi_B^* \Leftrightarrow \Pi^* > \Pi^N$$

This holds always and follows from the presence of externalities. In addition, also  $\pi_A^* - \pi_A^N > \pi_B^D - \pi_B^*$  has to hold. Define

$$\begin{aligned}b &=: b_B, & b_A &=: (1 + \beta)b \\ c &=: c_B, & c_A &=: (1 + \gamma)c\end{aligned}$$

where  $\beta > 0, \gamma > 0$  because of  $b_A \geq b_B, c_A \geq c_B$ , following from the rule that the country with equal or higher potential gains is to be the donor. With the help of this simplification  $\pi_A^* - \pi_A^N > \pi_B^D - \pi_B^*$  can be written as

$$\begin{aligned}(2 + \beta)Q^*[2a - Q^*] - (1 + \gamma)c/b(q_A^{*2} - q_A^{N2}) - c/b(q_B^{*2} - q_B^{D2}) \\ - (1 + \beta)Q^N[2a - Q^N] - Q^D[2a - Q^D] > 0\end{aligned}$$



Substituting (11a) into (7b), this and (11a) into (5), separately inserting (11) and (8) into (5) and rearranging yields

$$\beta[\dots] + \gamma[\dots] + (c/b)^2(1 + c/b) > 0$$

where the two terms in square brackets are both positive<sup>26</sup>. Hence, for nonnegative values of  $\beta$ ,  $\gamma$ ,  $c$  and  $b$  the constraint is never binding and the social optimum the outcome of the IEA.

### A.3 Kuhn-Tucker conditions for optimal abatements when transfers are restricted to compensations for cost-effectiveness

The optimisation problem in section 3.2 is

$$\begin{aligned} \max \Pi(q_A^C, q_B^C) \quad \text{s.t.} \\ 0 &\leq \pi_A(q_A^C, q_B^C) - T^{CE} - \pi_A(q_A^N, q_B^N) \\ 0 &\leq \pi_B(q_A^C, q_B^C) + T^{CE} - \pi_B(q_A^N, q_B^N) \\ 0 &\leq \pi_B(q_A^C, q_B^C) + T^{CE} - \pi_B(q_A^C, q_B^D) \\ T^{CE} &= \frac{c_B}{2} \left[ 1 - \frac{(1 + \frac{c_B}{c_A})^2}{(1 + \frac{b_{ACB}}{b_{BCA}})^2} \right] q_B^{C^2} \\ q_B^C &= c_A/c_B q_A^C \end{aligned}$$

The Lagrangian function is

$$L(q_A^C, \lambda_1, \lambda_2, \lambda_3) = \Pi + \lambda_1[\pi_A^C - T^{CE} - \pi_A^N] + \lambda_2[\pi_B^C + T^{CE} - \pi_B^N] + \lambda_3[\pi_B^C + T^{CE} - \pi_B^D]$$

The first order conditions for a maximum of  $\Pi^C$  are

$$\begin{aligned} \partial L / \partial q_A^C &= a(b_A + b_B) + a(c_A/c_B)(b_A + b_B) - (b_A + b_B)q_A^C \\ &\quad - 2(c_A/c_B)(b_A + b_B)q_A^C - (c_A/c_B)^2(b_A + b_B)q_A^C - c_A q_A^C - (c_A^2/c_B)q_A^C \\ &\quad + \lambda_1 a b_A + \lambda_1 a b_A (c_A/c_B) - \lambda_1 (b_A + c_A)q_A^C - 2\lambda_1 b_A (c_A/c_B)q_A^C \\ &\quad - \lambda_1 A (c_A/c_B)^2 \left[ b_A + c_B \left( 1 - \frac{(1 + \frac{c_B}{c_A})^2}{(1 + \frac{b_{ACB}}{b_{BCA}})^2} \right) \right] q_A^C \\ &\quad + \lambda_2 a b_B + \lambda_2 a b_B (c_A/c_B) - \lambda_2 b_B q_A^C - 2\lambda_2 b_B (c_A/c_B)q_A^C \\ &\quad - \lambda_2 (c_A/c_B)^2 \left[ b_B + c_B \left( \frac{(1 + \frac{c_B}{c_A})^2}{(1 + \frac{b_{ACB}}{b_{BCA}})^2} \right) \right] q_A^C \end{aligned} \quad (1)$$

<sup>26</sup>The complete expression is left out here because of lack of space. It is available upon request.

$$\begin{aligned}
& + \lambda_3 ab_B + \lambda_3 ab_B(c_A/c_B) - \lambda_3 b_B q_A^C - 2\lambda_3 b_B(c_A/c_B)q_A^C \\
& - \lambda_3(c_A/c_B)^2 \left[ b_B + c_B \left( \frac{(1 + \frac{c_B}{c_A})^2}{(1 + \frac{b_A c_B}{b_B c_A})^2} \right) \right] q_A^C - \frac{\lambda_3 a c_B}{1 + \frac{c_B}{c_A}} + \frac{\lambda_3 c_B}{1 + \frac{c_B}{c_A}} \leq 0 \\
\partial L / \partial \lambda_1 = & ab_A q_A^C - b_A / 2 q_A^{C^2} - c_A / 2 q_A^{C^2} - ab_A q_A^N + b_A / 2 q_A^{N^2} + c_A / 2 q_A^{N^2} \quad (2) \\
& - \frac{c_A^2}{2c_B} \left[ 1 - \frac{(1 + \frac{c_B}{c_A})^2}{(1 + \frac{b_A c_B}{b_B c_A})^2} \right] q_A^{C^2} \geq 0
\end{aligned}$$

$$\begin{aligned}
\partial L / \partial \lambda_2 = & ab_B q_A^C - b_B / 2 q_A^{C^2} - c_B / 2 q_B^{C^2} - ab_B q_A^N + b_B / 2 q_A^{N^2} \quad (3) \\
& + b_B / 2 q_B^{N^2} + \frac{c_A^2}{2c_B} \left[ 1 - \frac{(1 + \frac{c_B}{c_A})^2}{(1 + \frac{b_A c_B}{b_B c_A})^2} \right] q_A^{C^2} \geq 0
\end{aligned}$$

$$\begin{aligned}
\partial L / \partial \lambda_3 = & ab_B q_A^C + ab_B(c_A/c_B)q_A^C - b_B / 2 q_A^{C^2} - b_B(c_A/c_B)q_A^{C^2} \quad (4) \\
& - 1/2(c_A/c_B)^2 \left[ b_B + c_B \frac{(1 + \frac{c_B}{c_A})^2}{(1 + \frac{b_A c_B}{b_B c_A})^2} \right] q_A^{C^2} \\
& - \frac{a^2 b_B}{2(1 + \frac{c_B}{b_B})} - \frac{a c_B}{1 + \frac{c_B}{b_B}} q_A^C + \frac{c_B}{2(1 + \frac{c_B}{b_B})} q_A^{C^2} \geq 0
\end{aligned}$$

$$0 = q_A^C \partial L / \partial q_A^C \quad (5)$$

$$0 = \lambda_i \partial L / \partial \lambda_i, \quad i = 1, 2, 3 \quad (6)$$

$$q_A^C \geq 0 \quad (7)$$

$$\lambda_i \geq 0, \quad i = 1, 2, 3 \quad (8)$$

The optimal cooperative abatements of country A are for

Case 1:  $\lambda_i = 0, \quad i = 1, 2, 3$

(none of the incentive compatibility constraints is binding)

$$q_A^C = q_A^* = \frac{a}{1 + \frac{c_A}{b_A + b_B} + \frac{c_A}{c_B}}$$

Case 2:  $\lambda_2 > 0, \lambda_i = 0, \quad i = 1, 3$  (constraint (14) is binding)<sup>27</sup>

$$q_A^C = \frac{a + \left( a^2 - (2/b_B) \pi_B^N \left[ 1 + \frac{c_B}{b_B} \left( 1 + \frac{b_A c_B}{b_B c_A} \right)^{-2} \right] \right)^{1/2}}{\left( 1 + \frac{c_A}{c_B} \right) \left[ 1 + \frac{c_B}{b_B} \left( 1 + \frac{b_A c_B}{b_B c_A} \right)^{-2} \right]}$$

Case 3:  $\lambda_3 > 0, \lambda_i = 0, \quad i = 1, 2$  (constraint (15) is binding)

$$q_A^C = \frac{a \left( 1 + \frac{c_A}{c_B} + \frac{c_A}{b_B} + \left[ \left( \frac{c_A}{c_B} + \frac{c_A}{b_B} \right)^2 - \left( \frac{c_A}{c_B} + \frac{c_A}{b_B} \right) - \left( \frac{c_A}{c_B} + \frac{c_A}{b_B} \frac{(1 + \frac{c_B}{c_A})^2}{(1 + \frac{b_A c_B}{b_B c_A})^2} \right) \right]^{1/2} \right)}{1 + 2 \left( \frac{c_A}{c_B} + \frac{c_A}{b_B} \right) + \left( \frac{c_A}{c_B} + \frac{c_A}{b_B} \right) \left( \frac{c_A}{c_B} + \frac{c_A}{b_B} \frac{(1 + \frac{c_B}{c_A})^2}{(1 + \frac{b_A c_B}{b_B c_A})^2} \right)}$$

<sup>27</sup>Numerical simulations show that (13) is never binding, as long as  $\pi_A^* \geq \pi_B^*$ .