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A fair mechanism for efficient reduction of global CO_2-emissions

by

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Abstract

Because of the public good character of global emissions it is difficult to implement reduction targets as formulated at Toronto or Rio. This paper presents a simple mechanism for inducing efficient contributions to the reductions of emissions as a non-cooperative equilibrium. The world is partitioned into groups of countries, and then each country is taxed or subsidised according to its relative performance in the group. We estimate abatement cost- and benefit functions for 135 countries and simulate the mechanism for different groupings of countries. The simulations show that the involved global budget is the smaller the finer the partition and the more equal the countries within a group. Moreover, with such a partition most countries profit from the mechanism so that broad political support may be expected. If groups are composed of unequal countries, then the mechanism leads to a more egalitarian distribution of world income and welfare.

Key words: public goods, efficient private provision, greenhouse gas emissions, global warming

JEL classification: H41, Q28

1. Introduction

The concentration of CO_2 and other greenhouse gas emissions (GHG) in the atmosphere is a global public good, with "good" being used in the technical sense of an economically relevant phenomenon which may be good or bad, or good for some people and bad for others. Reducing this concentration entails private costs for the countries contributing to the reduction but is consumed by all countries. International policy has reacted to this fact by trying to get countries to voluntarily reduce global CO_2 emissions. Several international conferences were organized to achieve agreement on a concerted reduction scheme for GHG emissions. The World Conference on the Changing Atmosphere in Toronto in 1988 called for a 20 percent CO_2 emissions reductions by the year 2005 as compared to 1988 levels. Moreover, 160 countries signed the Climate Convention at the UN Conference on Environment and Development held in Rio in the year 1992. However, this convention did not include legally binding targets but rather expressed the countries' intention to reduce GHG emissions to 1990 levels. Looking at the relevant emissions data it does not come as a surprise that only very few countries comply with the agreed levels of reduction. Due to the free riding phenomenon a solution of the global emissions problem requires a global government endowed with both the power and the will to enforce the agreed reduction policies.

However, the idea to establish a global government planning and executing an optimal policy for the reduction of global emissions has its drawbacks. On the one side, we know that in practice the willingness of individual countries to give money and power to a central bureaucracy is low. On the other side, we know from economic theory that an efficient public provision of a public good would require a government which is not only benevolent but also fully informed about preferences and costs. Since countries have a strategic interest when reporting their evaluations to a central authority, one cannot expect that a global government would have full information for an efficient global emission policy. We conclude from this that for practical and theoretical reasons a meaningful policy proposal for an efficient global reduction of emissions must get by with a central authority that requires only little information.

Modern economic theory has suggested to design mechanisms for implementing the efficient provision of a public good in a decentralized way (see Clarke [1971], Groves [1973], Groves and Ledyard [1977], Green and Laffont [1977], or, more recently, Varian [1994a, b]). It is the purpose of the present study to show that this can be a successful route for dealing with the global warming emissions problem. It is obvious that such an approach has only a chance to be realized in practice if it is based on a mechanism that fulfills the following two requirements: First, the mechanism must be simple enough so that laymen understand how it works. Second, it must be possible to account for fairness or equity aspects between countries.[1] In this paper we consider a simple mechanism proposed by Falkinger [forthcoming][2] and show how it could be successfully applied for achieving an efficient level of global CO_2 emissions by private reduction contributions of the individual countries. The idea is that reductions of emissions are offered by competitive emittents all over the world and the countries' governments decide about their demand for emissions reductions, given the following tax-subsidy scheme: Each country sends its bill about the demanded emissions reductions to the central authority. This bill is compared with the average bill of other countries. Then each country gets a subsidy or has to pay a tax which is proportional to the deviation of its own bill from the average of the other countries' bill. As a consequence, the effective price for the reduction of one unit of emissions is lower than its market price and an efficient level of the individual countries' demand for reductions can be induced as a Nash equilibrium.[3] The market price for the reduction of one unit of emissions is determined by the equilibrium between aggregate demand for reduction and the total reductions offered by competitive emittents throughout the world.

The proposed mechanism is very simple and has the following attractive properties: The budget of the central authority is always balanced, since countries with a bill above the average of the others get a subsidy which countries with a bill below average have to pay. Moreover, the choice of the tax-subsidy rate leading to an efficient reduction of global emissions requires no information about the countries' willingness to pay for the reduction of global emissions. Finally, by comparing countries with comparable countries the fundamental principles of equity

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1 As Laffont [1987, p. 567] points out, in any real application of the mechanism literature " … considerations such as simplicity and stability to encourage trust, goodwill and cooperation, will have to be taken into account".

2 An experimental test in the laboratory was provided by Falkinger, Fehr, Gächter and Winter-Ebmer [1995].

3 Subsidies for inducing higher or efficient private contributions to a public good were also considered by Roberts [1987, 1992], Boadway, Pestieau and Wildasin [1989] or Andreoni and Bergstrom [forthcoming]. Apart from other differences they do not contain the idea of comparing an agent's contribution with the mean contribution of comparable agents. See Brunner and Falkinger [1995] for a general characterization of tax-subsidy schemes for the private provision of public goods.

is fulfilled, that unequals should be treated differently whereas equals should be treated according to the same norm. In the presented mechanism the norm is established endogenously through the average behavior of comparable countries. In our view, this equity aspect is important for the political acceptance of the proposal. Since the mechanism in general has redistributional effects, governments will only subscribe to it if the way to achieve efficiency is judged to be fair.[4] However, we do not claim to give an economic analysis of why and how countries agree to establish a global environmental authority. We only want to show that it is possible to solve the information problem of the global authority in an attractive way.

The next section presents the theory. In section 3 we describe our data set and calculate marginal cost and benefit curves for the reduction of CO_2 emissions for 135 countries. We calibrate the curves such that the resulting efficient amount of global emissions reductions coincides with the targets passed at the UN-conference in Rio. This allows us to illustrate the proposed mechanism within a scenario which is accepted on a broad political base. In section 4 we simulate the behavior of the 135 countries under the proposed mechanism and calculate the equilibrium for various partitions of the world into different subgroups of more or less similar countries. Section 5 contains concluding remarks.

2. Theory

After defining the framework we will explain the status quo as the outcome of Nash behavior. From this we derive demand functions for changes of the global emission level and cost functions for changes in the own country's level of emissions. In the further subsections we characterize pareto-optimal allocations, describe our mechanism and demonstrate that the decentralized reduction decisions lead to a globally efficient outcome.

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[4] One may argue that rational agents only participate if they profit from the mechanism. We think that establishing a constitution (be it national or supranational) is a more complex political process, in which the founders not only ask what is in individually profitable but also what is efficient and just.

2.1 Framework

Let $I = \{1, ..., n\}$ be the set of countries. Let welfare of a representative citizen in country $i \in I$ be represented by a quasi-concave utility function

$$U^i(c_i, E) \qquad (1)$$

which is strictly increasing in per-capita income c_i and strictly decreasing in the level of global emissions E. E is the sum of the individual countries' emissions E_i. Normality of c_i and E is assumed.

The emission level E_i of country i is the sum of the emissions caused by i's production sector when producing national income $N_i c_i$. N_i denotes the size of the population in a country. The aggregate relationship between national product and pollution in country i is described by the production function

$$N_i c_i = F_i(E_i), \quad F_i' > 0, F_i'' < 0 \text{ and } i \in I. \qquad (2)$$

2.2 Status quo

The current level of emissions $E^0 = \sum_{i=1}^{n} E_i^0$ results from uncoordinated decisions, where each country i implements through its policy the optimal level of emissions, given the level of emissions of the rest of the world $E_{-i} \equiv \sum_{j \neq i} E_j$.

Thus, we can interpret the status quo $E_1^0, \ldots, E_n^0$ as the Nash equilibrium resulting from the n decision problems[5]

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[5] This corresponds to the standard approach for the analysis of a decentralized equilibrium with private public good provision (see Blume, Bergstrom, Varian [1986] for a systematic presentation). Here countries provide a global bad in a non-cooperative way.

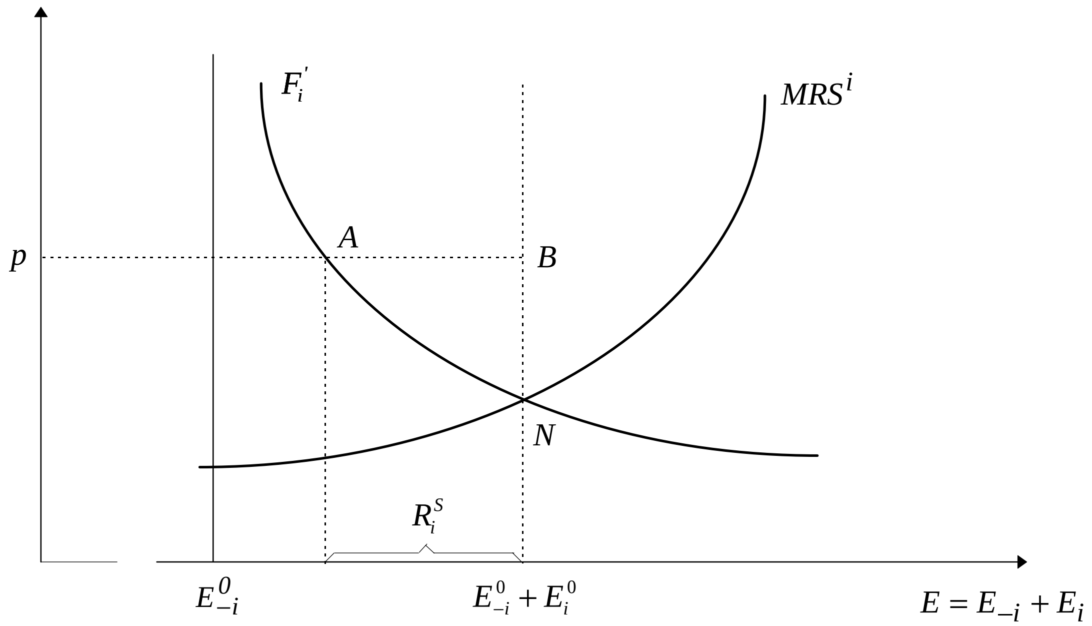
$$\max_{E_i} U^i(c_i, E_i + E_{-i}) \tag{3}$$
s. t. $N_i c_i = F_i(E_i)$.

The corresponding n first-order-conditions characterizing the equilibrium values $E_1^0, \ldots, E_n^0$ are:

$$MRS^i\left[\frac{F_i(E_i^0)}{N_i}, E_i^0 + E_{-i}^0\right] = F_i^{'}(E_i^0), \quad i \in I, \tag{4}$$

with $MRS^i_{c,E}$ denoting the (absolute value of the) marginal rate of substitution $N_i\left|\partial U^i / \partial E\right| / \partial U^i / \partial c_i$ between income and environment, that is, the marginal damage (weighed with the marginal utility of income) in country i caused by an increase in the global level of emissions. Note that by definition each of the N_i citizens is affected by the pollution of the global atmosphere. The right-hand side of equation (4) describes the marginal benefit of the emissions produced in country i for i's income. Figure 1 illustrates this decision problem of country i graphically.

Figure 1: Nash equilibrium in the status quo



2.3 The supply of emissions reductions

According to (2), the cost $z_i(R_i^S)$ of reducing the level of emissions in country i by an amount R_i^S is given by the equation

$$z_i(R_i^S) = F_i(E_i^0) - F_i(E_i^0 - R_i^S). \quad (5)$$

This gives us the marginal cost curve

$$z_i'(R_i^S) = F_i'(E_i^0 - R_i^S). \quad (6)$$

In the decentralized solution of our mechanism the production sectors of the different countries are independent of their government and offer emissions reductions at a competitive world market. The governments of the countries are the purchasers in this market (See section 2.5 for their behavior).

Equation (6) means that in a competitive equilibrium an amount $R_i^S = z_i'^{-1}(p)$ of reductions is supplied by the production sector of country i, if the price received for reducing emissions by one unit is p. Summing R_i^S over $i \in I$ and defining $z'^{-1}(p) \equiv \sum_{i=1}^{n} z_i'^{-1}(p)$, we obtain for the total amount $R^S \equiv \sum_{i=1}^{n} R_i^S$ supplied in a competitive world market for reductions the relationship

$$z'(R^S) = p, \quad (7a)$$

where z' denotes the aggregate marginal cost curve with

$$z'(R^S) = F_1'(E_1^0 - R_1^S) = \; \ldots \; = F_n'(E_n^0 - R_n^S). \quad (7b)$$

In Figure 1 *i*'s supply curve of reductions is represented by the differences between the vertical line through the current level of emissions E_i^0 and the F_i'-curve. If at the world market a price *p* is paid per unit of reduction, the production sector of country *i* offers an amount AB. By adding up these differences we obtain the global marginal cost or supply curve *z'*.

2.4 Pareto-optimal reductions of global emissions

The efficient level of global reductions R^* is obtained by solving the planning program:

$$\max_{\substack{c_1,\dots,c_n \\ R_1^S,\dots,R_n^S}} U^i(c_i, E^0 - R^S)$$

$$\text{s.t.} \quad U^j(c_j, E^0 - R) \geq \overline{U}^j, \; j \neq i$$

$$\sum_{i=1}^{n} N_i c_i - \sum_{i=1}^{n} F_i(E_i^0 - R_i^S) \leq 0 .$$

This gives us the Samuelson [1954] rule for efficient allocation of the public good "reduction of emissions":

$$\sum_{i=1}^{n} MRS^i(c_i, E^0 - R^*) = z'(R^*) \text{ with } R^* = \sum_{i=1}^{n} R_i^S \qquad (8)$$

and

$$z'(R^*) = F_1'(E_i^0 - R_i^S) = \dots = F_n'(E_n^0 - R_n^S). \qquad (9)$$

2.5 A fair and efficient mechanism for a decentralized reduction of global emissions

A decentralized reduction of global emissions means that each country *i*'s government determines in a non-cooperative way its demand for the reduction R_i^D of global emissions, given the sum of reductions $R_{-i}^D \equiv \sum_{j \neq i} R_j^D$ demanded by the governments of the other countries.

For equalizing marginal cost, which is implied by production efficiency condition (9), we must allow a country to purchase reductions somewhere in the world, at the price determined by the aggregate supply curve (7). That means, the production sector of a country offers the reduction of emissions R_i^S at a competitive world market, and the government of the country purchases the reductions R_i^D on this market. Whereas in general $R_i^S \neq R_i^D$, in the aggregate the market clearing condition

$$\sum_{i=1}^{n} R_i^S = \sum_{i=1}^{n} R_i^D \; (\equiv R) \tag{10}$$

must be fulfilled.

In order to achieve efficiency on the basis of non-cooperative decisions, we propose the following mechanism: First, according to the principle that unequals should be treated differently (vertical equity), we partition the set of countries I into subgroups of comparable countries $I_1, ..., I_m$ with $|I_k| \geq 2,\ k = 1, ..., m$ and $\bigcup_{k=1}^{m} I_k = I$. ($|I_k|$ denotes the number of countries in I_k). Second, according to the principle that equals should be treated equally (horizontal equity), we impose on each country a group-specific norm reduction. Since we are aiming at a decentralized solution, this group norm cannot be chosen by an exogenous authority. Therefore, we let the norm be determined by the mean reductions demanded by the other countries of the group. Formally, we impose on all countries $i \in I_k,\ k = 1, ..., m,$ a tax-subsidy scheme

$$\varphi^i = \beta(R)\left(\frac{1}{|I_k - 1|} R^D_{I_k - \{i\}} - R_i^D\right) \tag{11}$$

where $R^D_{I_k-\{i\}} \equiv \sum_{j \in I_k - \{i\}} R_j^D$ and $\beta(R) > 0$. $\beta(R)$ is a factor of proportionality depending on the aggregate level of reductions R. The specific function $\beta(R)$ which leads to efficiency will be determined below.

Incentive scheme (11) means that each country announces the purchased amount of reductions R_i^D to a central authority. Countries purchasing less than the average of the other countries of the same group have to pay a tax to the central authority, whereas countries which purchase more than the average get a subsidy. It is important to note that the budget of the mechanism designer is always balanced. For any vector R_1^D, ..., R_n^D, we have[6]

$$\sum_{i=1}^{n} \varphi_i = 0 . \tag{12}$$

The budget constraint of a country i with domestic production F_i, whose firms sell R_i^S units of reductions at the world market and whose government purchases R_i^D units of reductions, is then

$$c_i N_i = F_i(E_i^0 - R_i^S) + pR_i^S - pR_i^D - \varphi^i , \tag{13}$$

where p is the world market price determined by (7).

The non-cooperative equilibrium demand R_1^D, ..., R_n^D under the proposed mechanism is determined by solving for each country i the problem:[7]

$$\max_{c_i , R_i^D} U^i (c_i , E^0 - R_i^D - R_{-i}^D) \tag{14}$$

s. t. (11) and (13),

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6 Rearranging the order of summation gives $\sum_{i \in I_k} \sum_{j \in I_k - \{i\}} R_j^D = (|I_k| - 1) \sum_{i \in I_k} R_i^D$. Using this when summing (11), one gets (12).

7 We omit the non-negativity constraint $c_i \geq 0$ since it never binds in the empirical analysis. We do not impose $R_i^D \geq 0$ (see Kirchsteiger and Puppe [1996] for the problems which may arise from this non-negativity constraint). $R_i^D < 0$ means that the government of country i announces to the central authority that it allows to its production sector an increase in emissions above E_i^0 by an amount $|R_i^D|$. As a consequence, country i has to pay a rather high tax according to (11) but at the same time it earns $p|R_i^D|$, since the production sector can sell reductions of $|R_i^D|$ units of emissions, in addition to R_i^S.

where $R_{-i}^D \equiv \sum_{j \neq i} R_i^D$. While the reduction supplying firms are price takers, the reduction purchasing governments play a non-cooperative game and anticipate the impact of their decisions on the world market. That means they take into account that according to (10) and (7a) and (7b) p and R_i^S in constraint (13) are functions of aggregate demand $R_i^D + R_{-i}^D$.

Using (7a), (7b), (10) and (11) in (13) and substituting c_i into (14), we obtain the first-order-conditions for R_i^D, *i = 1, ..., n*:[8]

$$MRS^i = z''(R)(R_i^D - R_i^S) + z'(R) + \beta'(R)\left(\frac{1}{|I_k|-1} R_{I_k-\{i\}}^D - R_i^D\right) - \beta(R). \qquad (15)$$

Summing these equations, we get (use (10) and (12))

$$\sum_{i=1}^{n} MRS^i = n(z'(R) - \beta(R)). \qquad (16)$$

Comparison with (8) shows that this coincides with the condition for an efficient reduction of global emissions if we choose[9]

$$\beta(R) = \left(1 - \frac{1}{n}\right) z'(R). \qquad (17)$$

Thus, the efficient reduction of global emissions can be decentralized by using tax-subsidy scheme (13) with $\beta(R)$ chosen as defined by (17).[10] Moreover, (13) is fair in the sense that it fulfills the generally accepted principles of horizontal and vertical equity.

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8 Note that, according to (7a) and (10), $p=z'(R)$ and $\partial p / \partial R_i^D = z''(R)$ the effect of R_i^D on R_i^S cancels out because of $p=F_i'$ (see (7a,b)).

9 This generalizes the results about efficient subsidy rates in Boadway, Pestieau, Wildasin [1989], Roberts [1992], or Falkinger [forthcoming] for the case of nonconstant marginal cost ($z''(R) \neq 0$) of the considered public good.

3. Data and the estimation of marginal cost and benefit functions

Simulating the behavior of countries under the proposed mechanism requires the estimation of marginal cost and benefit curves for the reduction of greenhouse gas (GHG) emissions. Apart from the discussion of the natural scientific basis for the calculation of anthropogenic GHG emissions this section comprises the estimation and calibration of cost and benefit functions of greenhouse gas abatement for 135 countries.

3.1 Calculation of emission levels and the global stock of emissions

Emissions data of the most important anthropogenic GHG (carbon dioxide (CO_2), methane, and chlorofluorocarbons (CFCs)) are provided by the World Resources Institute for 135 countries (World Resources Institute [1990], [1994]).[11] However, only a fraction of total GHG emissions remains in the atmosphere. This is partly explained by reabsorption into the ocean, partly it remains unexplained. Approximately 1.6 Gigatons (Gt) carbon are missing in the annual concentration balance as compared to the emissions balance (Cline [1991], p. 905). Moreover, emissions remaining in the atmosphere and therefore contributing to the greenhouse effect are distinguished by their different global warming potential (GWP) indicating the intensity of radiation impacts of greenhouse gases in relation to CO_2 (see Table 1). Using both GWP numbers and the percentage of emissions remaining in the atmosphere we expressed all greenhouse gas emissions in terms of CO_2 equivalent trace gases, the typical benchmark for global warming analysis (see Table 2).

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[10] Note that with $m = 1$ and $|I_k| = |I| = n$ equations (15) would reduce to $MRS^i = \frac{1}{n} z''(R) \sum_{i=1}^{n} R_i^D + z'(R) - \beta(R) - z''(R_i^S)$, if $ß(R)$ is chosen according to (17). Thus, without any partition the individual R_i^D are not determined so that (17) does not lead to a unique Nash equilibrium. So $m > 1$ is essential for the working of the mechanism.

[11] We have no data on nitrous oxides. Therefore, the emissions considered in this analysis account approximately for 91 percent of total global warming (Nordhaus [1991]).

Table 1: Greenhouse gas emissions (Source: Bauer [1993])

	Percentage of emissions remaining in the atmosphere	**Global warming potential relative to CO_2**
CO_2	43	1
Methane	17	58
CFCs	100	5098

Since these CO_2 equivalents (FLOWS) are measured in tons we converted GHG concentrations in the atmosphere (STOCK) from ppm (parts per million) into weight units (Gt). This was done by multiplying the ppm concentration of each greenhouse gas by its molecular weight relative to air and by the atmosperic mass of $2.92*10^{18}$ kg. In doing this we were able to calculate the change in atmospheric greenhouse gas concentration caused by annual emissions of anthropogenic CO_2 -equivalent trace gases.

Table 2: GHG concentrations in the atmosphere (Source: Solow [1991], own calculations)*

	preindustrial level (C_{pr})	**present level (C_p)**	**$2xCO_2^+$**
CO_2	280 ppm 2242.13 Gt	354 ppm 2834.69 Gt	560 ppm 4484.26 Gt
Methane	0.8 ppm 135.50 Gt	1.7 ppm 287.94 Gt	1.6 ppm 271.10 Gt
CFCs	0 ppm 0 Gt	0.76 ppm 92.87 Gt	0 ppm 0 Gt
Total	2377.6 Gt	3215.5 Gt	4755.3 Gt

* All Gt in CO_2-equivalents.

$^+$ The $2xCO_2$ scenario implicitely assumes that the composition of different GHG remains constant.

Table 2 shows atmospheric GHG concentrations in ppm and Gt for the present, the preindustrial level, and the benchmark scenario of twice the preindustrial CO_2 concentration ($2xCO_2$).

3.2 The damage of global warming or the benefits of greenhouse gas abatement

Several authors have been presenting monetary values for the economic damage caused by global warming in different regions. These calculations are either based on price and quantity changes in market transactions (Tol [1994], Cline [1992], Titus [1992], Nordhaus [1991]) or reflect non-market damages such as losses in the eco-system or increased mortality (Fankhauser [1995], Pearce et al. [1994]).

It seems natural that these damage assessments have been heavily criticised, with the criticism primarily focusing on the “subjective“ valuation of non-market impacts. Moreover, damage estimates are incomplete in the sense that some categories have been neglected altogether while other valuations only partially reflect potential welfare losses caused by global warming. Most authors are aware of the fact that the empirical figures found are far from being exact and recommend allowing for an error range of plus/minus 50 percent (Fankhauser [1995], p. 54).

Table 3: Monetary 2xCO_2 damage in different world regions[12] *(Source: Fankhauser [1995]; Tol [1994])*

	Fankhauser (1994)		**Tol (1994)**	
	bn US$	**%GDP**	**bn US$**	**%GDP**
European Union	63.6	1.4		
United States	61.0	1.3		
Other OECD	55.9	1.4		
OECD America			74.2	1.5
OECD Europe			56.5	1.3
OECD Pacific			59.0	2.8
Total OECD	180.5	1.3	189.5	1.6
Eastern Europe/Former USSR	18.2	0.7	-7.9	-0.3
Centrally Planned Asia	16.7	4.7	18.0	5.2
South and South East Asia			53.5	8.6
Africa			30.3	8.7
Latin America			31.0	4.3
Middle East			1.3	4.1
Total Non-OECD			126.2	2.7
World	269.6	1.4	315.7	1.9

[12] For a detailed description of the damages and the estimation techniques used, see also Pearce et al. [1994].

The most comprehensive table of the difference between the present damage level and the damage occurring with the 2xCO_2 benchmark warming was put together by Fankhauser [1995] and Tol [1994] for different world regions. Their estimations form the basis for our empirical analysis (see Table 3). By applying these damage valuations, expressed in GDP percentages, to the countries being located in the respective world regions we calculated monetary damage values for all countries. In accordance with a risk-avers data selection we chose the higher percentage whenever we had two damage estimates available such as in the case of Eastern Europe and China.

For each country we assume a quadratic global warming damage function

$$D_i(C) = a_0^i + a_1^i C^2 \tag{18}$$

associating different levels of greenhouse gas concentrations C in the atmosphere to the resulting damage D_i. Since we have data available about present and preindustrial GHG concentration levels (C_p and C_{pr}, respectively), and we know the damage estimates associated with the benchmark global warming (2xCO_2) as compared to the present concentration level for every country i, the individual parameters of this function can be calculated as follows. First, we assume the preindustrial global warming damage for any country i to be zero ($D_i(C_{pr})=0$). Second, we know the difference $D_i(2xCO_2)$ - $D_i(C_p)$ from Table 3. Using this in (18) we get a_0^i, a_1^i and the marginal damage function D_i' for each country:

$$a_1^i = \frac{D_i(2xCO_2) - D_i(C_p)}{C_{2xCO_2}^2 - C_p^2}, \qquad a_0^i = -a_1^i C_{pr}^2 \tag{19}$$

and

$$MRS^i = D_i'(C) = 2a_1^i C \tag{20}$$

3.3 Economic costs of greenhouse gas abatement

Economists have been interested in global warming analysis for quite some time. However, the early interest has been more in whether a greenhouse problem existed rather than in evaluating the costs of emission abatement. The situation changed in the aftermath of the Toronto Conference in 1988 when the number of abatement cost models increased rapidly. There exist greenhouse gas abatement models for almost every OECD country today (Fankhauser [1994, p. 95]). These models are, in general, classified into bottom-up and top-down models. Technology-oriented bottom-up models concentrate on the availability of energy supply technologies and thereby derive abatement cost curves with available technologies ordered by their costs of abatement. Empirical studies based on this approach report small or even zero costs of reducing GHG emissions. Top-down models represent an economic approach treating energy as one production input and focusing on changes in relative prices due to the imposition of policy measures such as the introduction of a carbon tax. These models are rather pessimistic and predict considerably higher abatement costs especially for substantial emission cuts.

The most comprehensive computable general equilibrium (CGE) carbon abatement model available is the GREEN model developed at the OECD. Because of the comprehensiveness we used the data from this model as the empirical basis for our cost functions. It includes twelve regional submodels linked through trade flows and eleven economic sectors (for more details, see Burniaux et al. [1992]).[13] Using the GREEN model Oliveira-Martins et al. [1992] present the following economic costs due to a one, two, and three percentage point reduction of the growth of GHG emissions relative to the business-as-usual scenario (E_i^0) without any environmental policy measure. Following Oliveira-Martins et al. [1992, p. 11] business-as-usual means a growth rate of annual CO_2 emissions of 2 percent.

[13] The model regions are USA (The United States), OPEC (Oil and Petrol Exporting Countries), CEEC (Central and Eastern Europe), JAP (Japan), CH (China), DAE (Dynamic Asian Countries), EU (European Union), USSR (Former Soviet Union), BRAZ (Brazil), OECD, IND (India), ROW (Rest of the world)

Table 4: Costs per year of a 1, 2, 3 percentage point reduction of emissions growth relative to business-as-usual E_i^0 measured in percentage of GDP (Source: Oliveira-Martins et al. [1992])

	USA	JAP	EU	OECD	OPEC	CH	USSR	IND	CEEC	DAE	BRAZ	ROW
-1 PP	0.1	0.1	0.1	0.0	0.8	0.1	0.1	0.0	-0.1	0.1	0.1	0.1
-2 PP	0.3	0.2	0.3	0.2	2.2	0.3	0.3	0.2	0.0	0.4	0.4	0.3
-3 PP	0.7	0.5	0.9	0.6	4.3	0.7	0.7	0.4	0.5	0.9	0.9	0.7

Taking these figures as granted we assume the following quadratic cost function for GHG abatement in each country *i:*

$$z_i\left(R_i^S\right) = b_0^i + b_1^i\left(E_i^0 - R_i^S\right) - b_2^i\left(E_i^0 - R_i^S\right)^2 \tag{21}$$

with z_i and R_i^S representing country *i*'s abatement costs and its level of emissions reductions. Taking the first derivative of the cost function we get the following linear marginal cost function

$$z_i^{'}\left(R_i^S\right) = b_1^i - 2b_2^i\left(E_i^0 - R_i^S\right) \tag{22}$$

We estimated the parameters b_1^i and b_2^i assuming zero marginal costs at $R_i^S = 0$ and using the GREEN simulation results by considering R_i^S values equal to a 1, 2, 3 percentage point reduction of emissions growth relative to business-as-usual E_i^0 (see Table 4).

3.4 Calibration

After the estimation of cost and benefit functions we calibrated the original functions such that the actual emission levels can be interpreted as the outcome of Nash behavior (step 1) and the efficient amount of emissions reductions coincides with the targets of the UN conference on Environment and Development held in Rio in the year 1992 (step 2). The first step is based on the assumption of rational government behavior. The second step assumes that the policy makers base their decisions on cost and damage assessments under which the Rio-scenario describes an efficient solution.

Step 1: Estimating the original cost functions we had assumed zero marginal costs at the business-as-usual emission level. In order to interpret these business-as-usual emission levels as the outcome of Nash behavior we have to shift the original cost functions upward because the marginal damages resulting from present concentration plus the business-as-usual emissions are positive and therefore higher than zero. The assumption of Nash behavior, which means that the countries are balancing marginal damages and marginal benefits at the business-as-usual emission levels ($F_i^{'} = z_i^{'}$), implies that the marginal cost function of emission abatement has to be shifted upward such that this cost function intersects with the benefit function at the business-as-usual emission level (see Figure 1). Therefore, we have increased the parameter of the marginal cost function b_1^i by the marginal damage resulting from present concentration plus business as usual emissions $2a_1^i(C_p + \sum_i E_i^0)$.

Step 2: The purpose of the empirical analysis is to illustrate the mechanism in a scenario, which is accepted on a broad political basis. The most recent political target referring to the reduction of greenhouse gas emissions was formulated at the UN Conference on Environment and Development in Rio de Janeiro in 1992. The Climate Convention expressed the aim to reduce GHG emissions to 1990 levels. In our setting stabilizing emissions to 1990 levels is equivalent to reducing the global level of emissions by approximately 2 percent as compared to the business-as-usual scenario. In order to achieve that the efficient amount of global emissions reduction in our data set is equal to this politically formulated emissions reduction target we divided the countries' original marginal cost functions (22) by a proportional factor such that the resulting Samuelson solution (see (8) and (9)) coincides with the politically formulated emissions reduction target.[14] This proposed emissions reduction target of 2 percent below E^0 can be achieved by dividing the countries' original abatement costs through 355.1. The corresponding global emissions reduction in absolute terms amounts to 305.9 million tons of CO_2-equivalents. We call this the Rio-scenario.

[14] It should be noticed that the structure of the original data set remains unchanged. Only the level of abatement costs was reduced.

Starting from the present CO_2 concentration level we simulation results for the proposed mechanism for one subsequent period. Since the data (emissions, abatement costs, gross domestic products, ...) are available on a per year basis and the latest greenhouse gas emissions are published for the year 1991, the following empirical analysis refers to 1992 as the simulation period.

4. Simulation of the mechanism

Simulating the Rio-scenario means to solve a system of 135 equations with the same number of unknowns. The mechanism simulation enables us - based on the marginal cost- and benefit functions estimated in section 3 - to recalculate the efficient reduction levels, the monetary payments among the countries and every country's welfare change through the implementation of the mechanism. Concerning monetary payments one must distinguish between payments for emissions reductions and tax payments imposed by the mechanism. While the former correspond to market transactions, the latter determine the size of the central authority's budget. Of course, the results depend on how the set of 135 countries is partitioned into subgroups (see section 2.5).

4.1 The grouping of the countries

Whereas the physical reductions in the countries, the price of reductions, aggregate net payments and the overall potential for a Pareto improvement remain independent of the chosen partition due to neglected income effects, the grouping of countries changes the emissions reductions demanded by every country, the countries' net welfare positions, the number of countries benefiting from the implementation of the mechanism and the administrative budget of the global authority. Depending on the partition, different points on the Pareto frontier result. Possible partitions can either be based on political considerations or on economic and scientific characteristics. Policy-based partitions may distinguish between different groups by general country characteristics. For example, distinction can be made between industrialized and developing countries or between the so-called "First-", "Second-" and "Third World".

Another possibility is to differentiate by the countries' economic performance (national income) or by their individual greenhouse gas emissions. Apart from the selection criteria on the basis of which the partition is made, the size of the groups may also substantially influence the distributive and budgetary consequences of the mechanism.

The following tables present simulation results using four different partitions. Improper partition 1 means that all 135 countries remain in one single group. Since in the absence of any partition the proposed mechanism breaks down with the efficient $ß^*$ determined by (17) (see footnote 10), simulating this "no partition scenario" requires $ß$ to slightly deviate from its efficient level. Therefore, we changed $ß$ to $ß^*(1+\varepsilon)$, $\varepsilon = 5*10^{-6}$ to guarantee a solution for the Nash equilibrium. Partitions 2 and 3 discriminate between the countries according to their economic well-being expressed in gross domestic product (GDP). Whereas countries characterized by similar income levels are put together into the same group under partition 2, the grouping in partition 3 unites countries with different GDPs[15]. The reason behind these two partitions is to highlight the distributive effects between "poor" and "rich" countries associated with the choice of the country grouping. Both partitions 2 and 3 comprise groups of five countries each. To illustrate the effects of varying the group size, partition 4 consists of just 3 countries each with similar GDPs. Of course, every other partition can be chosen.

4.2 Simulation results

Solving the 135 reaction functions for the Nash equilibrium under the mechanism, we obtain the emissions reductions demanded by each country[16]. In discussing and interpreting our results, we focus on administrative and distributional aspects, respectively. As shown in chapter 2 efficiency is guaranteed by construction of the mechanism for any proper partition.

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[15] We have chosen absolute GDP values as the appropriate criterion for grouping the countries since all available data on abatement costs and damages resulting from CO_2 emissions are expressed in percent of absolute GDP. This means that the country's population size plays no major role for the costs and benefits comprised by the data. An alternative criterion for measuring the similarity of countries would be their emissions levels. However, since emissions are strongly correlated with absolute GDP-levels, one obtains more or less the same grouping of the countries.

[16] It should be noticed that the number of countries with a negative demand for emissions reductions R_i^D varies from 27 to 88 in partitions 1 to 4. A negative demand for reductions means that a country *i* allows to its

As far as physical emissions reductions by the countries are concerned, we found that in the Samuelson solution every country reduces its greenhouse gas emissions as compared to the business-as-usual case, even though no single country reduces emissions to zero at the equilibrium price.

The budget of the global authority

The budget of the global authority consists of tax/subsidy payments φ_i indicating the amount of redistribution through taxes and subsidies levied and paid by the global authority according to scheme (11). To keep the figures easy to survey, Table 5 shows two different aggregation levels. Aggregate taxes and subsidies are provided for different world regions, and for all countries together ignoring any geographical location. Whereas the regional numbers indicate winning and losing regions, total aggregates reflect the budget size of the global authority (total sum of taxes due to the balanced budget of the mechanism) under different partitions.

Table 5: Tax/Subsidy-Payments (in mill. US \$)[17]

	almost efficient	**efficient**		
	Partition 1 (no partition)	**Partition 2** (equal GDP, 5 countries)	**Partition 3** (unequal GDP, 5 countries)	**Partition 4** (equal GDP, 3 countries)
Net Tax/Subsidy Payments per Region: $\sum_i \varphi_i$ **, i** $\in$ **region**				
USA	288226.04	36.18	53.78	8.21
Japan	285525.92	35.41	59.53	7.76
European Union	45555.59	-124.13	53.59	-9.10
Other OECD	-101746.56	-77.67	-19.85	-55.77
Energy exporting LDCs	-277203.41	-16.21	-97.95	4.12
China	465350.47	101.30	84.19	47.25
former USSR	143568.43	-4.73	35.50	-15.97
India	165610.02	39.42	29.33	19.93
Central and Eastern Europe	-80138.05	1.58	9.46	2.89
Dynamic Asian Countries	54126.30	-8.40	34.68	9.81
Brazil	74463.73	13.08	18.89	-18.07
Rest of the world	-1063338.48	4.16	-261.15	-1.05
Budget size of the global authority:				
$\frac{1}{2}\sum_{i=1}^{n}\lvert\varphi_i\rvert$	1934140.88	340.37	702.07	153.11

production sector an emission level of $E_i^0 + \lvert R_i^D \rvert$ instead of E_i^0. Starting from this level, $R_i^S + \lvert R_i^D \rvert$ units of reductions are sold on the competitive world market (see footnote 7).

17 A negative sign means a subsidy.

The figures indicate the flows of money redistributed through the budget of the central authority. The budget size of the global authority is lower if similar countries are summarized in one and the same group as opposed to an arrangement into partitions with very different countries within a group. Whereas overall tax payments add up to 340.7 million US$ under partition 2, this figure runs up to 702 million US$ under partition 3. Moreover, the budget size of the global authority is the lower the smaller the number of countries in a group. This can be seen by comparing partitions 2 and 4. If the number of countries in one group is reduced from five to three, the volume of redistribution through the central budget decreases to 153.4 million US$. Furthermore, the results for partition 1 show that without a proper partition the almost efficient solution is only achieved with very high amounts of taxes and subsidies. Summarizing the results, under administrative aspects a partition into small groups of equal countries is to be recommended, since it implies a minimal global government. For an evaluation of the distributional aspects, however, also total net payments (including the payments corresponding to market transactions) have to be considered as well.

Total net payments

Since under perfect competition the earnings of the country's production sector from selling emissions reductions are offset by the cost of reductions, total income changes associated with the mechanism consist of two types of payments: The expenditures for the demand of emissions reductions (pR_i^D) and the tax/subsidy payment (φ_i) discussed above. The first term reflects market transactions, a country’s purchases of global emissions reductions. The change in the Gini-coefficient based on these figures indicates the direction towards a more equal or unequal income distribution due to the implementation of the mechanism.[18]

Table 6 contains aggregate net payments for different world regions and partitions with the sum of positive and negative net payments reflecting the volume of redistribution. The difference between these two sums is equal to the costs resulting from world-wide emissions reductions pR. It should be noticed that the high tax/subsidy payments under the improper partition are compensated by a very high positive or negative demand for emissions reductions through which the final results are very similar to partitions 2,3 and 4. Thus, the small deviation of the efficient β only results in a deviation from efficient emissions reductions by approximately 0.38 percent. The Gini-coefficients in partitions 2 and 3 show that if countries with different income levels are put together in one group (partition 3) the income distribution becomes more equal (negative change of the Gini coefficient) whereas the opposite is true for partition 2. Similar countries in the partitions tend to make the income distribution more unequal (the Gini coefficient increases). Thus, it follows that one can generate beneficial situations either to industrialized or developing countries depending on the partition. The mechanism designer can choose the direction of redistribution given an efficient allocation in either case.

Table 6: Net Payments (in mill. US $)[19]

	almost efficient	**efficient**		
	Partition 1 (no partition)	**Partition 2** (equal GDP, 5 countries)	**Partition 3** (unequal GDP, 5 countries)	**Partition 4** (equal GDP, 3 countries)
Aggregate Net Payments per Region: $\sum_i \left(pR_i^D + \varphi_i \right)$ **, i** $\in$ **region**				
USA	0.61	16.43	4.55	16.43
Japan	0.61	16.28	7.68	16.28
European Union	6.76	9.24	31.49	9.24
Other OECD	5.53	-0.07	-0.26	-0.07
Energy exporting LDCs	15.99	0.71	-14.26	0.71
China	0.61	26.15	1.44	26.15
former USSR	0.61	8.49	8.82	8.49
India	0.61	9.70	-1.42	9.70
Central and Eastern Europe	4.30	-0.11	18.48	-0.11
Dynamic Asian Countries	2.46	5.42	20.64	5.42
Brazil	0.61	4.70	2.58	4.70
Rest of the world	44.27	-14.25	2.93	-14.25
Sum of positive net payments:				
$\sum_{i=1}^{I} \left(pR_i^D + \varphi_i \right)$ for all $\left(pR_i^D + \varphi_i \right) > 0$	83.0046	125.43	365.23	125.43
Sum of negative net payments:				
$\left\| \sum_{i=1}^{I} \left(pR_i^D + \varphi_i \right) \right\|$ for all $\left(pR_i^D + \varphi_i \right) < 0$	0	42.74	282.54	42.74
Change of the Gini coefficient for the income position in percent:				
	+0.00835	+0.000195	-0.000098	+0.00020

[18] The Gini-coefficient before the implementation of the mechanism is 0.7412.

[19] A negative sign means an inflow.

Welfare Changes

Even though monetary net payments probably represent an important policy-relevant decision criterion, the countries' welfare change including the improvement of the environment is the decisive factor from an economic point of view. Two figures are presented with respect to this welfare issue: the number of countries benefitting from the mechanism implementation and the change of the Gini-coefficient for the countries' welfare positions (Table 7).[20]

Table 7: Welfare changes (in mill. US $)[21]

	inefficient	**efficient**		
	Partition 1 (no partition)	**Partition 2** (equal GDP, 5 countries)	**Partition 3** (unequal GDP, 5 countries)	**Partition 4** (equal GDP, 3 countries)
Welfare Change:				
number of countries with welfare improvement	25	114	48	114
Change of the Gini coefficient for the welfare position in percent	+0.000206	+0.000196	-0.000099	+0.000129

In general, the countries' welfare change including benefits associated with reduced greenhouse gas reductions is very similar to their change in income, a fact that arises from relatively low emissions reductions recommended by the Rio-scenario. To indicate how close a Pareto improvement is achieved we have included the number of countries benefiting from implementing the mechanism design. Partitions 2 and 4 with similar countries provide the highest number of countries with an increase in welfare (114) whereas the implementation is only beneficial for 25 countries under partition 1. In this connection it should be noticed that every efficient partition guarantees a potential Pareto improvement according to the Hicks-Kaldor criterion.

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[20] Welfare means income adjusted for environmental damage caused by greenhouse gas emissions. The Gini-coefficient before the implementation of the mechanism amounts to 0.7426.

[21] A negative sign means a loss.

5. Conclusions

In this study we proposed a simple mechanism for the problem of global warming. We showed that efficient levels of CO_2-emissions can be implemented by this mechanism. Before the decentralized decisions about reductions of emissions are made by the production sectors and governments of the different countries, the world must be partitioned into groups of countries, with countries belonging to the same group being submitted to the same norm, namely the average reduction of emissions financed by the other countries in the group. While the proposed mechanism produced an efficient solution under any grouping of countries, the distribution across countries depend on which countries are put in the same group by the mechanism designer. This leaves room for equity considerations which ultimately have to be decided by international policy conventions. Whether a particular partition of the world is just or not can be discussed either by applying a priori principles like horizontal and vertical equity or by looking at the concrete consequences of the partition. For showing the consequences of different designs we simulated the equilibria under the mechanism for a series of plausible groupings of countries.

For the so-called Rio-scenario - a 2 percent reduction of global emissions results as efficient solution - we calculate administrative and distributional implications under the proposed mechanism for four different partitions of the world. Since efficiency is guaranteed for any proper partition, the interesting questions are how the size of the central administration and the cross-country distribution of the costs of efficient emission abatement vary with the grouping of countries. As far as the budget of the required global authority is concerned, the simulations showed that this budget is the smaller the finer the partition and the more equal the countries put into one and the same group. Regarding distributional effects our simulations showed that the cross-country distribution of incomes as well as of welfare (including the benefits arising from the reduction of global emissions) becomes more equal if countries with different income levels are put together in a group, and it becomes less equal if the world is partitioned into groups of similar countries. The reason for this result is that the mechanism induces efficient reduction levels along with payments from rich to poor countries, if the groups are composed of unequal countries. If, however, efficiency is viewed as the only purpose of international environmental policy, our simulations suggest that the best way to reach this goal is to form small groups of similar countries. Then most countries, namely 114 out of 135, experience an increase in their welfare compared to the status quo, without any further compensation payments (Of course, there is always a potential Pareto improvement since the mechanism induces an efficient allocation with any proper partition). We conclude from this that it should not be impossible to find broad political support for such a mechanism design.

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