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How global is the solution to global warming?

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Abstract

This paper presents efficient CO_2 abatement levels for 135 countries and identifies reasons for the absence of worldwide greenhouse gas emission reductions. Based on individual marginal cost and benefit functions for emission abatement, the Pareto-optimal Samuelson solution is compared with the Nash equilibrium. It was found that the Pareto-optimal solution would require status quo world CO_2 emissions to be reduced by 28%, whereas the Nash equilibrium would require 21% emission reductions. Since only 7% of total emission reductions can be attributed to the global public goods effect, the solution to the climate change problem cannot exclusively be seen in overcoming the freerider behavior. Moreover, we show that the probability for the development of international environmental agreements (IEA) is small. This again supports the argument that from an economic perspective, more emphasis should be put on national policy measures rather than to wait for co-ordinated actions to be agreed on at international climate conferences. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Climate change is a very complex global issue to which an acceptable political solution is still pending. Decision making on global warming must take into consideration the unique characteristics of the phenomenon such as large scientific and economic uncertainties, non-linearities and irreversibilities, asymmetric temporal and geographical impacts, time lags between emissions and their physical and economic consequences, different lifetimes of greenhouse gases in the atmosphere and therefore, the need of long planning horizons. Even in this context, a practicable solution is required to combat global climate change and its negative consequences for life on earth. The notion 'practicable solution' requires answers to the following questions: (i) are current global greenhouse gas (GHG) emissions too high or not?; (ii) which countries should reduce their GHGs?; and (iii) by how much should emissions be reduced?

From an economic perspective, climate change can be seen as a global public good (bad) with the potential for freeriding that has prevented individual countries to significantly reduce their CO_2 emissions. A number of international climate change conferences by the United Nations Framework Convention on Climate Change UNFCCC (starting with the 'Earth Summit' in Rio de Janeiro and followed by the so-called COP conferences in Berlin, Geneva, Kyoto, Buenos Aires, Bonn or recently, The Hague) was held to attain agreement on a concerted reduction of greenhouse gases. However, these conferences have not been successful in their attempt to overcome freeriding incentives as regards to a reduction in greenhouse gas emissions. No legally binding targets were agreed on, and the countries only signaled their intention to reduce emissions in the future.[1] On the contrary, worldwide CO_2 emissions are still growing. The 1997 estimate represents a 1.3% increase over 1996, continuing a trend of modest growth since a 1991–1993 decline in global CO_2 emissions (source: Carbon Dioxide Information Analysis Center, US Department of Energy).

The analysis in this paper identifies reasons for the absence of worldwide greenhouse gas emission reductions. Based on empirical data for 135 countries, evidence is provided that apart from the transnational public goods issue, which is usually seen as the major source of policy failure in combating climate change, a national problem exists. It is shown that almost all countries obviously, do not balance their individual marginal cost and benefits of greenhouse gas emission reductions, and fail to meet their individually efficient emission levels. Therefore, in contrast to the mainstream literature on global warming focusing on the global public good dimension, it is shown that the solution cannot solely be found in binding agreements attained at international conferences. Our analysis suggests

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[1] It remains to be seen whether the emission reduction targets agreed upon in Kyoto will be realized. Experiences from COP-conferences in Buenos Aires, Bonn and The Hague do not indicate significant progress in the negotiations. On the contrary, recent suspension of talks in The Hague on making the Kyoto Protocol operational points rather, towards an opposite direction.

rather that substantial emission reductions can be achieved by economically rational abatement strategies on national levels.

This negative assessment of international conferences being held to cope with the global warming dilemma is founded on the following evidence: a global solution would require a global authority endowed with the power and the will to enforce efficient greenhouse gas reduction policies by either imposing command and control measures, or making use of market-based instruments such as environmental taxes or tradable emission permits. However, such a global authority does not exist and therefore, one has to look for alternative options to overcome the public good problem, which is held responsible for the failure of an efficient global warming policy. Given that world conferences on climate issues have not worked well, this paper investigates whether voluntary environmental agreements or coalitions will form at all under the presence of freerider incentives — see for instance Barrett (1994), Carraro and Siniscalco (1993), and Carraro (1997). Assuming alliances with side payments (co-operative coalitions) and without side payments (non-co-operative coalitions), it is shown empirically, that there is only a low potential for stable coalitions to be formed in order to combat global warming.

The contents of the paper is as follows: Section 2 contains a description of the data set and the calculation of individual marginal cost and benefit functions for the reduction of greenhouse gas emissions for 135 countries. In Section 3, efficient greenhouse gas emissions are presented for both individual countries and several world regions, and show how sensitive the results are to changes in key simulation parameters. Furthermore, it is demonstrated from an economic point of view, that the global climate change problem can be split into a national and a transnational component. Section 4 discusses voluntary environmental agreements and the potential of forming sustainable coalitions to arrive at efficient emission reduction levels. Concluding remarks in Section 5 finish the paper.

2. Data, marginal cost and benefit functions

The empirical analysis in this paper is based on anthropogenic greenhouse gas emissions (World Resources Institute, 1994). These data comprise annual emissions of carbon dioxide (E_i for country i) for $n = 135$ countries.[2] The proportion of emissions contributing to the atmospheric stock is given with $\rho = 0.64$ (Nordhaus, 1994). Moreover, the greenhouse gas concentration in the atmosphere C measured in ppm (parts per million)[3] was converted into weight units to make it comparable with the flow of annual GHG emission.[4] For the calculation of the CO_2 concentration decay rate δ, the IPCC (1996b) estimation of 120 years for the average lifetime of a carbon dioxide particle in the atmosphere was used. Assuming a linear

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[2] We have not considered data for methane, chlorofluorocarbons (CFCs), and nitrous oxide. Therefore, the emissions in this analysis account for 80% of total global warming (Nordhaus, 1991).

[3] Greenhouse gas concentration data were taken from Solow (1992).

[4] For technical details see Falkinger et al. (1996), p. 316f.

Table 1
$2 \times CO_2$ — damages in different world regions (% of GDP)

European Union (EU)	1.4
USA	1.3
OECD America (without USA)	1.5
OECD Europe (without EU)	1.3
OECD Pacific	2.8
Eastern Europe — former USSR	0.7
Central Asia	5.2
South and southeast Asia	8.6
Africa	8.7
Latin America	4.3
Middle East	4.1

decline of the GHG concentration, a decay rate of $\delta = 0.833\%$ was calculated. It should be noticed that the share of anthropogenic CO_2 emissions ρ covers the short-term storages of GHG emissions by the uptake into vegetation and the surface layer of the oceans, which occurs over a few years. In contrast to the short-term deposition, the decay rate δ represents the rate of CO_2 transfer from atmosphere to other reservoirs under which the deep ocean water is the most important one.[5] Finally, empirical figures were assumed for real GDP and emission growth rates q_i and s_i, respectively, the discount rate r, and the length of the simulation period m. Real GDP growth rates were taken from the World Resources Institute (1994), and Oliveira-Martins et al. (1992) provide data for regional emission growth rates, which were applied to the countries in the respective region. To make our analysis comparable to the existing literature, a finite number of 200 years was chosen for m reflecting an average figure of other comparable studies (Cline, 1992; Nordhaus, 1991; or Nordhaus and Yang, 1996), and 4% was assumed for the discount rate r. The effects of changing key parameters are discussed in Section 3.5 (Sensitivity analysis).

2.1. The data on benefits and costs of emission abatement

Monetary estimates for the *economic damage* of global warming (equivalent to the benefits of abatement) presented in the literature are based on market transactions reflecting price and quantity changes caused by CO_2 emissions and on estimations of non-market damages. Fankhauser (1995) and Tol (1995) present the most comprehensive table of global warming damage estimates associated with the $2 \times CO_2$ benchmark warming for several world regions.[6] In case of overlapping

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[5] The values for parameters ρ and δ are standard assumptions to depict the carbon life cycle in economic models (see for instance, Nordhaus, 1994; or Kolstad, 1996). For more technical details on the global carbon cycle and the anthropogenic carbon budget, see the IPCC report (IPCC, 1996b).

[6] The $2 \times CO_2$ benchmark scenario means twice the pre-industrial CO_2 concentration level in the atmosphere, which is expected to occur by the year 2060 (Pearce et al., 1996).

regions, the higher damage figure from the two sources was taken to minimize the risk of underestimating global warming damages. Finally, the figures in Table 1 were obtained. These damage estimates — expressed as GDP percentages — were applied to the countries being located in the relevant world regions and individual monetary damage values for all 135 nations under the $2 \times CO_2$ scenario, have been calculated.

Greenhouse gas abatement models that estimate the costs of emission reductions are available for almost all OECD countries. Technology-oriented bottom up models focusing on the availability of energy supply technologies, report small economic costs of emission reductions. On the contrary, top down models treat energy as an input factor and concentrate on the impacts of changes in relative prices associated with the introduction of environmental policy measures such as the imposition of carbon taxes. These top down models predict considerably higher abatement cost as compared to bottom up models. In our analysis, we rely on the OECD GREEN model, the most comprehensive computable general equilibrium top down model. This model (Oliveira-Martins et al., 1992) presents economic cost for a 1, 2 and 3%-point reduction of the growth of GHG emissions for different points of time in the future, as compared to the status quo called 'business as usual scenario' (BAU) in the absence of any policy measure. To provide an impression of the order of magnitude, such data for the year 2000 are presented in Table 2. However, in the sensitivity analysis in Section 3.5, greenhouse gas abatement cost based on the Global 2100 model from Manne/Richels (Manne, 1992) have been used as well.

2.2. Marginal benefit and cost functions in an intertemporal context

Identifying the optimal amount of emissions requires the calculation of marginal benefit and cost functions. In the given context, optimality can either be based on

Table 2
Cost of a 1, 2 and 3%-point reduction of the emission growth rate (% of GDP)

	−1% (k_i^I)	−2% (k_i^{II})	−3% (k_i^{III})
USA	0.1	0.3	0.7
Japan	0.1	0.2	0.5
European Union	0.1	0.3	0.9
OECD	0.0	0.2	0.6
OPEC	0.8	2.2	4.3
China	0.1	0.3	0.7
former USSR	0.1	0.3	0.7
India	0.0	0.2	0.4
Central and Eastern Europe	−0.1	0.0	0.5
Dynamic Asian Economies	0.1	0.4	0.9
Brazil	0.1	0.4	0.9
Rest	0.1	0.3	0.7

the choice of the optimal amount of emissions at a particular starting point $E(0)_i$ or on the optimal emission growth rate over time s_i. The calculation of an optimal emission growth rate s_i is appropriate from an environmental policy perspective making gradual adjustments to optimality possible. However, for simplicity reasons, we treat the emission growth rate as exogenous and calculate the optimal level of emissions at the starting point 0 (= 1991, which is termed the present). The country i's GHG emissions at time t in the future can be written as $E(t)_i = E(0)_i \times e^{s_i t}$ with $E(0)_i$ representing country i's emission level at starting point 0.

The greenhouse gas concentration level in the atmosphere can be calculated with the following differential equation: $\frac{\partial C(t)}{\partial t} = \sum_{i=1}^{n} \rho \times E(0)_i \times e^{s_i t} - \delta \times (C(t) - C_{\text{pre}})$. According to this equation of motion, the change in the greenhouse gas concentration is equal to the sum of the share of the worldwide greenhouse gas emissions getting into the atmosphere minus the natural decay of the concentration level above the pre-industrial amount of greenhouse gases in the atmosphere C_{pre}. Solving this differential equation gives us the greenhouse gas concentration at time t

$$C(t) = \sum_{i=1}^{n} \frac{\rho \times E(0)_i \times e^{t(s_i+\delta)}}{\delta + s_i} + C_{\text{pre}} + \frac{Z}{e^{\delta t}}$$

whereby the constant Z can be determined with today's concentration level ($C(0) = C_{\text{today}}$).

It is assumed that each country's loss (environmental damage) in percentage of GDP units $L(t)_i$ at a given point in time t, depends on the level of concentration in a quadratic way with parameters a_i and b_i: $L(t)_i = a_i + b_i\ C(t)^2$. No empirical evidence exists on the appropriate functional form of the damage function. Therefore, we have chosen a quadratic function as the simplest way to get a linear marginal damage curve. The parameters are calculated by using the 2 × CO_2 scenario with the corresponding damage (compare Section 2.1) and zero damage in the pre-industrial era. The partial derivative of the discounted sum of all global warming damages from present ($t = 0$) to the end of the simulation period m with respect to $E(0)_i$ is

$$D_i' = \frac{\partial \int_{t=0}^{m} \left(a_i + b_i \times (C(t))^2\right) \times e^{-rt} \mathrm{d}t}{\partial E(0)_i}$$

with r denoting the discount rate. Therefore, a linear marginal damage function is obtained (= benefits of abatement) for any country i

$$D_i'(E(0)_i, E(0)_{-i}) = \alpha_i + \sum_{j=1}^{n} \beta_{ij} \times E(0)_j.$$

Whereas the parameters α_i and β_{ij} represent extensive algebraic terms $E(0)_{-i}$ denotes the set of starting point (present) emission levels of the rest of the world.

In accordance with the damages — marginal damage is expressed as a function of $E(0)_i$ — the cost of reducing emission growth rates as indicated by Oliveira-Martins et al. (1992), are recalculated and equivalently expressed as the economic cost of changing the initial emission level $E(0)_i$. For this purpose, starting point emissions $E(0)_i^I$, $E(0)_i^{II}$ and $E(0)_i^{III}$ are calculated that provide after m periods the same level of emissions as the *actual* business as usual starting point emissions $E(0)_i^{\mathrm{BAU}}$, combined with a reduction in s_i by one, two or three percentage points, respectively.

For that purpose the term $\Omega_i(t)$ was defined as the stock of cumulated emissions in the atmosphere caused by country i during the time period from 0 to t. In the sequel, the change of this stock over time can be written as $\frac{\partial \Omega_i(t)}{\partial t} = \rho \times E(0)_i \times e^{s_i t} - \delta \Omega_i(t)$, the amount of effective actual emissions minus the natural decay of cumulated emissions. For the purpose of calculating a marginal cost curve of emission abatement, it is sufficient to assume a zero stock of cumulated emissions at time 0 [$\Omega_i(0) = 0$]. This initial condition and the equation of motion result in

$$\Omega_i(t) = \frac{\rho \times E(0)_i \times e^{s_i t}}{s_i + \delta} - \frac{\rho \times E(0)_i}{(s_i + \delta) \times e^{\delta t}}.$$

Using this function for the stock of cumulated emissions in the atmosphere, it is possible to calculate the starting point emissions $E(0)_i^I$, $E(0)_i^{II}$ and $E(0)_i^{III}$. As an example, $E(0)_i^{II}$ results from solving the following equation with respect to $E(0)_i^{II}$:

$$\begin{aligned} &\frac{\rho \times E(0)_i^{\mathrm{BAU}} \times e^{(s_i - 0.02)t}}{(s_i - 0.02) + \delta} - \frac{\rho \times E(0)_i^{\mathrm{BAU}}}{((s_i - 0.02) + \delta) e^{\delta t}} \\ &\quad = \frac{\rho \times E(0)_i^{II} \times e^{s_i t}}{s_i + \delta} - \frac{\rho \times E(0)_i^{II}}{(s_i + \delta) e^{\delta t}}. \end{aligned}$$

For each of these different starting point emissions $E(0)_i^I$, $E(0)_i^{II}$ and $E(0)_i^{III}$, the corresponding discounted costs K_i^I, K_i^{II} and K_i^{III} were calculated by using the costs of a 1, 2 or 3 percentage point reduction of the emission growth rate k_i^I, k_i^{II} and k_i^{III} (compare Table 2). For example, K_i^{II} is computed as $\int_{t=0}^{m} y(0)_i \times e^{q_i t} \times k_i^{II} \times e^{-rt} \mathrm{d}t$ with $y(0)_i$ the initial real GDP in country i, q_i the annual GDP growth rate in country i, and r the discount rate.

Given these figures, the marginal cost $\frac{K_i^{III} - K_i^{II}}{E(0)_i^{II} - E(0)_i^{III}}$, $\frac{K_i^{II} - K_i^{I}}{E(0)_i^{I} - E(0)_i^{II}}$ and $\frac{K_i^{I}}{E(0)_i^{\mathrm{RAU}} - E(0)_i^{I}}$ are computed. Based on these points of marginal costs and initial emissions $[E(0)_i^{III}$, $E(0)_i^{II}$ and $E(0)_i^{I}]$, the parameters η_i, γ_i and λ_i of the following quadratic marginal cost function $K_i^{'}$, have been estimated,

$$K_i^{'}(E(0)_i) = \eta_i + \gamma_i \ln(E(0)_i) + \lambda_i(\ln(E(0)_i))^2 \forall\, 0 < E(0)_i < E(0)_i^{\mathrm{BAU}}$$

under the constraint of zero marginal costs of emission abatement at the business as usual emission level $(K_i^{'}[E(0)_i^{\mathrm{BAU}}] = 0)$ and that the marginal cost for emissions below the business as usual level cannot be negative $(K_i^{''}[E(0)_i^{\mathrm{BAU}}] = 0)$. We have used the logarithm in the marginal cost function to guarantee that marginal cost tend towards infinity as the emissions in a country come down to zero. Given the empirical result of $\lambda_i > 0$ for all i, this non-linear cost function guarantees small increases in marginal cost for low emission reductions, whereas marginal cost increases progressively for high emission reductions. In that sense, this marginal cost function represents a compromise between empirical models which show relatively high marginal costs for emission reductions compared to 'no regret policies', which report small marginal cost over a substantial range of emission reductions (see IPCC, 1996a, chapter 9). The 135 marginal cost and marginal benefit functions allow the calculation of emission reductions for each of the 135 countries.

It must be noticed that the 'emission game' presented above is modeled as a static one. In that sense, the countries take one ultimate decision about their emission reductions. This appears controversial, as this theoretical formulation of the problem does not allow repeated optimizing behavior, which would seem realistic in the case of global warming. However, due to the computational efforts that the dynamic formulation of the model for 135 countries would have required, the simpler static interpretation has been chosen. This is particularly true for the analysis of potential coalitions of countries (see Section 4), the dynamic analysis of which does not seem tractable. Nevertheless, more research needs to be invested in the dynamic formulation of regional, disaggregated global warming models.

Furthermore, it should be noted that the estimations of cost and damages are taken as given. It cannot be ruled out, however, that the true figures deviate from these estimations. This could especially be true for the damage assessments which may underestimate the disutility of global warming, because they do not take into account that people are willing to give up some GDP just to avoid the risk of truly catastrophic damages. This point is made for instance, by Nordhaus and Boyer (2000), (Table 4.9), who show that the willingness to pay to avoid the risk of catastrophic damages is more than half the 'tangible' damages in their model. In that case, one would underestimate the necessary amount of emission reductions.

Moreover, data on emission abatement and global warming are used in a deterministic way. Therefore, we do not explicitly take into consideration, a probability distribution with low probabilities for catastrophic damages (e.g. shutting off the Atlantic thermohaline conveyer, disintegration of the Antarctic ice sheets) and do not account for the possibility that the damages of global warming might be overestimated. Although, in the sensitivity analysis, the outcome of modified damage estimates (half damages and double damages) is shown and

Table 3
Pareto-optimal emission reductions

Region	Reductions in % of total reductions	Reductions in % of regional emissions
USA	14.6	20.5
Japan	2.2	14.2
European Union	3.8	8.8
Other OECD countries	1.1	8.2
Energy-exporting less developed countries	12.0	23.2
China	25.1	68.8
Former USSR	14.4	28.0
India	6.7	64.6
Former centrally planned East European countries	3.8	31.1
Dynamic Asian economies	2.1	22.0
Rest of the World	14.0	32.0
Total	100	27.8

reveals in that sense, at least partly the uncertain nature of global warming. Nevertheless, the issue of how optimal environmental policy would change with the parties' possibility to wait for their investment decisions in abatement technology until they learned more about the possible effects of GHG emissions remains

Table 4
Emission reductions in the Nash Behavior scenario

Country	Unilaterally optimal reductions (% of actual emissions)
China	66.7
India	65.9
Philippines	28.1
Former USSR	27.1
United States	22.1
Japan	15.8
Germany	11.8
Poland	9.9
Romania	8.8
France	7.5
UK	6.7
Norway	2.6
Finland	2.5

unaddressed.[7] Even though empirical results in dynamic optimization models differ from the empirical figures in our model, there is no indication that the general results and issues in this paper would be reversed in the case of the application of a more general dynamic optimization framework.

3. Efficient and less efficient levels of emission reductions

The following section compares different levels of emission reductions under various assumptions on the behavior of individual countries. Based on marginal cost and benefit (damage) functions for 135 countries, the following scenarios are presented:

- The *Pareto-optimal Scenario* given by the equality of the marginal cost functions with the sum of the partial derivatives of the damage functions with respect to the starting point emission level for each country, describes the efficient amount of emission reductions for each individual country.
- In contrast to this, the optimal amount of emission reductions for an individual country by taking the business as usual emissions of all other countries as given, is calculated under the *Nash Behavior Scenario*.
- As compared to the Nash Behavior Scenario, under which just one country behaves individually efficient, the *Nash Equilibrium Scenario* assumes rational behavior for all nations. Each country chooses its optimal amount of emission reductions given individual optimal emission reductions of all other countries.

Under the Nash Behavior and the Nash Equilibrium Scenario, countries do not consider any damages from their own emissions on other countries. Therefore, it does not come as a surprise that these two scenarios provide lower emission reductions as compared to the Pareto-optimal Scenario. By comparing the business as usual reduction levels with the Nash and the Pareto-optimal Scenario, respectively, we can show whether global climate change is more a national or a global problem. Due to the uncertainties, it would be unrealistic to expect this cost benefit analysis to provide exact and undisputed figures for emission reductions. Nevertheless, it will be shown that models like this represent a practical tool for guaranteeing useful insights into important aspects of the global warming debate. After the discussion as to why countries do not reduce their emissions under the status quo, a sensitivity analysis is presented to discern the influence of chosen data and model parameters on empirical results.

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[7] A consideration of this ‘real option approach’ in investment decisions, which was suggested by Dixit and Pindyck (1994) would again require a dynamic optimization model. Kolstad (1996), Narain and Fisher (2000), or Fisher and Narain (2000) provide theoretical applications of this approach to the global warming problem and the question of optimal abatement strategies for GHG emissions in a one country setting.

3.1. The Pareto-optimal scenario

The, Pareto-optimal amount of emission reductions can be found by maximizing the global net benefit Π, which is the sum of the countries' individual welfare positions π_i:

$$\max_{E(0)_1,\dots,E(0)_n} \Pi = \sum_{i=1}^{n} \pi_i \quad \text{where} \quad \pi_i = K_i(E(0)_i) - D_i(E(0)_i, E(0)_{-i}).$$

The net benefit of a country π_i is given by the difference of costs K_i $(E(0)_i)$ and damages D_i $(E(0)_i,\ E(0)_{-i})$ of CO_2 emissions, and n denotes the number of countries.

Since the countries are emitting with different emission growth rates, a change in the emission level at the starting point $E(0)_i$ will have different effects on the global GHG concentration depending on the country, which is changing its starting point emissions. Consequently, CO_2 emissions do not represent a pure public good in this model. Instead of a perfect public good problem in which the optimal amount of emissions would be characterized by the Samuelson condition, one has to allow for an imperfect public good. Therefore, the Pareto-optimal amount of emission reductions is characterized by the condition that for each country i, the marginal costs of emission abatement has to be equal to the sum of the partial derivatives of the damage functions with respect to $E(0)_i$:

$$K_i'(E(0)_i) = \sum_{j=1}^{n} \frac{\partial D_j(E(0)_1,\dots,E(0)_n)}{\partial E(0)_i} \quad \forall i. \tag{1}$$

Consequently, marginal cost will not be the same for all countries in the optimum as it is required for a perfect public good. In contrast to the Samuelson condition, which implies that emissions are reduced most in the country where one additional unit of emissions has the smallest impact on the gross domestic product, different emission growth rates influence the efficient amount of CO_2 emissions as well.

The calculation of optimal emission reductions requires solving a non-linear system of 135 variables defined by the 135 optimality conditions [see Eq. (1)]. Depending on the given model, the data on cost and damages and the chosen parameter values (e.g. discount rate), the solution of the non-linear system of equations may result either in a stable or in an unstable equilibrium. Since it was not possible to calculate the solution of the non-linear system of equations directly,[8] it was impossible to compute unstable equilibria. However, for parameter values that guarantee stable outcomes, it was possible to simulate the equilibrium

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[8] By means of various numerical methods supplied by conventional analytical and numerical software packages, it was still not possible to calculate the equilibrium for systems of equations with more than approximately 70 countries.

by employing the contraction mapping theorem (Stokey and Lucas, 1989). Given a 'guess' for the optimal amount of starting point emissions and applying the reaction functions as a contraction mapping the *unique* fixed point in the form of the Pareto-optimum, can be calculated numerically. To express the procedure in a less formal way, the equilibria was simulated numerically by moving along the reaction functions to their stable intersection, just by simply plugging in the result of one reaction function as an input into another reaction function until convergence is reached. In that sense, the contraction-mapping theorem can be used as an indicator to discriminate stable from unstable equilibria: if the contraction mapping converges to a fixed point, one has a stable equilibrium. Otherwise, an unstable equilibrium is given (concerning the issue of stable and unstable equilibria in our models see also footnote 11).

Based on our model, the Pareto optimum would require greenhouse gas emissions to be reduced by 27.8% if the countries cling to the actual emission growth rates. The regional distribution of aggregated emission reductions of the individual countries[9] can be seen in Table 3. It turns out that from an efficiency point of view with the exception of the US, the less developed world (e.g. India, China, Rest of the World, Former Centrally Planned East European Countries, etc.) has to carry the main burden of solving the global warming problem, which of course, raises questions of equity.[10] Looking at Table 3, this result is not only supported by the percentage reductions of regional emissions, but also by the less developed world's share of total reductions. This imbalance apparently follows from the low level of energy efficiency in the less developed world.

By and large, total emission reductions in our model are in line with the DICE Model (Nordhaus, 1991) or the RICE Model (Nordhaus and Yang, 1996), which present optimizing emission paths as well. Fig. 1 shows the business as usual path (RICE — Market Solution), and the Co-operative and the non-co-operative Equilibrium for the RICE Model. For comparative reasons, the business as usual path for the DICE Model (DICE — Business As Usual) is depicted as well. Even though both the DICE and RICE Model, and our analysis provide a comparable order of magnitude of the required emission reductions at the beginning of the simulation period, it must be noted that the models differ in their dynamics over time. Whereas our emission paths (HP00 Business as usual, HP00 Pareto-optimum, and HP00 Nash Equilibrium) start off from a lower level and grow more rapidly over time, Nordhaus presents considerably flatter absolute emission curves. One reason for this different characteristic is that Nordhaus has included an emissions damping factor over time that is not included in our model. As opposed to Nordhaus, we have not considered natural resource constraints that would make the introduction of backstop technologies rational. Therefore, we use higher

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[9] For the presentation of aggregated results, the classification of world regions in the OECD GREEN model is followed (compare Oliveira-Martins et al., 1992).

[10] Equity aspects are not addressed in this paper. For the implementation of a Pareto-optimal solution to the global warming problem that also accounts for equity, see Falkinger et al. (1996).

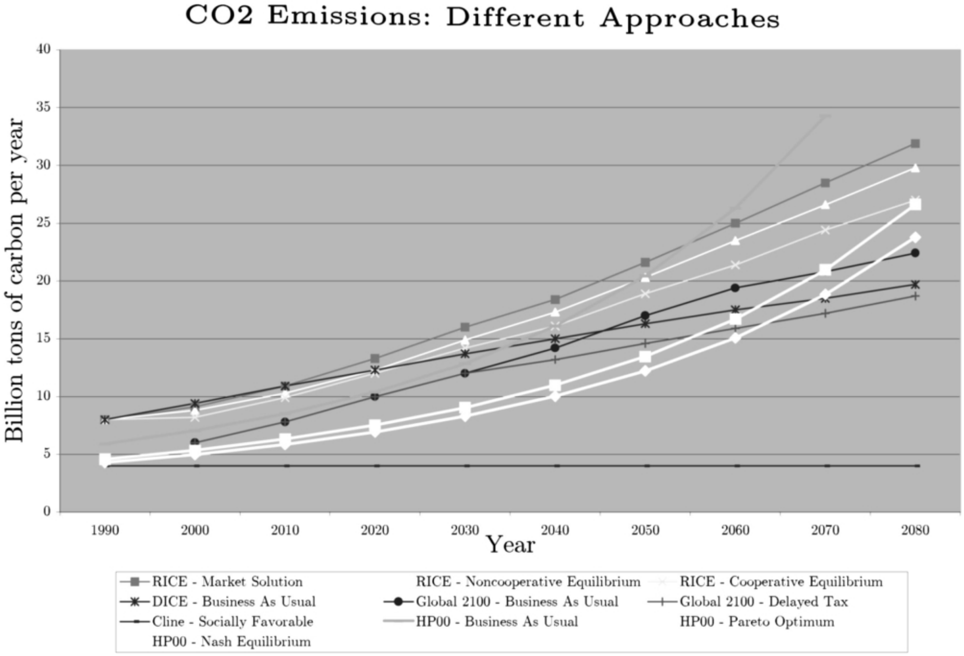

Fig. 1. CO_2 emissions — different approaches.

emission growth rates in our model compared to others. Besides the work of Nordhaus (1991) and Nordhaus and Yang (1996), there are other cost benefit studies on global warming from Manne et al. (1995) and Cline (1992). Manne et al. (1995) argue for the imposition of a delayed carbon tax of \$5/ton in 2030, and an increase of this tax by 5% annually (compare Global 2100 — Business As Usual and Delayed Tax in Fig. 1), which represents another moderate reduction proposal. Cline (1992, p. 377), finds that it would be socially favorable to stabilize GHG emissions to four billion tons of carbon annually, which is a significantly more aggressive proposal for reductions (Cline — Socially Favorable in Fig. 1).

3.2. The Nash behavior scenario

The major argument in the climate change debate, which has led to inactivity of governments is the rejection of the usefulness for a single country to reduce its emissions, whereas all other nations would remain at their initial emission levels. Due to freeriding incentives, the claim is made for co-ordinated actions among the countries. We show that this argument does not necessarily hold, and that it may be rational for single countries to take the pioneering position and reduce individual GHG emissions, even in the absence of any ‘support’ from other countries. The framework to study this issue is the Nash Behavior Scenario. This scenario identifies optimal emission reductions for a single country holding emissions from all other nations constant at the BAU level. Formally this problem can be written as

$$\max_{E(0)_i} \pi_i = K_i(E(0)_i) - D_i(E(0)_i, E(0)_{-i}^{\mathrm{BAU}}).$$

Whether it is economically beneficial for a country to decrease its emissions as compared to the business as usual behavior, depends only on individual cost and benefit functions. If marginal cost of emission abatement are lower than the marginal benefits, economic incentives exist for individual emission reductions.

Countries with very high and low emission reductions under the Nash Behavior Scenario are depicted in Table 4. The figures indicate that especially the 'less developed world' ought to reduce their emissions unilaterally to arrive at the individually efficient allocation. Looking at the selected countries, China shows a very high percentage of efficient emission reductions (66.7%), followed by countries such as India (65.9%), Philippines (28.1%), or the former USSR (27.1%). With the exception of the US (22.1%), the business as usual behavior of industrialized countries is closer to their individually efficient scenario. Whereas the emission reduction potential for Japan is still 15.8%, the figures reduce to values between 2 and 12% for EU member states such as France, Norway, Germany, the UK or Finland.

Again, a low level of energy efficiency, higher marginal abatement cost of emission reductions in developed countries, higher marginal damages due to climate change in the less developed world and different emission growth rates can be held responsible for the results in Table 4.

3.3. The Nash equilibrium scenario

In comparison with the Nash Behavior Scenario, which analyzes the optimal response of a single country given the status quo behavior of all others, the Nash Equilibrium Scenario provides individually efficient emission reductions if all countries behave optimal simultaneously:

$$\max_{E(0)_i} \pi_i = K_i(E(0)_i) - D_i(E(0)_i, E(0)_{-i}) \quad \forall i.$$

Both the figures for aggregate reductions and reductions in percent of regional emissions in Table 5 are lower as compared to the Pareto-optimal Scenario. This is due to the public good effect, through which individual countries reduce a smaller amount of emissions in the Nash equilibrium since they do not take benefits to other countries into account when they decide on their own emission levels. In general, emission reductions of individual countries are similar to the reductions under the Nash Behavior Scenario.

As was pointed out in Section 3.1, the Pareto-optimal solution would require status quo emissions to be reduced by 27.8%. In contrast, the Nash equilibrium would call for 21.4% of emission reductions in total. This suggests that the global

Table 5
Emission reductions in the Nash Equilibrium scenario by regions

Region	Reductions in % of total reductions	Reductions in % of regional emissions
USA	18.7	20.3
Japan	2.9	14.1
European Union	4.0	7.2
Other OECD countries	1.0	5.6
Energy-exporting less developed countries	7.1	10.6
China	30.2	63.6
Former USSR	16.3	24.4
India	7.9	58.5
Former centrally planned East European countries	1.1	6.9
Dynamic Asian economies	1.9	15.4
Rest of the World	8.9	15.6
Total	100	21.4

warming problem can be split into two components. Whereas the 21.4% emission reductions indicate the countries' reluctance to balance individual marginal cost and benefits, the remaining 6.4% of unrealized, efficient reductions can be attributed to the global dimension covering the above-mentioned public good effect. Therefore, global warming reflects to a large extent, a national problem of individual countries.

The functional form of the cost and benefit curves can be made responsible for this result. Whereas the marginal benefit curves are linear functions, the marginal costs are low if only small emission reductions are made and the marginal cost curve becomes steep in the case of high emission reductions. Since the intersection of individual marginal cost and benefit curves lies in the steep part of the marginal cost curves where additional emission reductions are very expensive to realize, a 'vertical' addition of marginal benefit curves does not lead to further substantial emission reductions in comparison of the Pareto-optimum, compared with the Nash equilibrium.

For a list of selected countries, the numerical figures for both the national and transnational share of the global climate problem are depicted in Table 6. Whereas the first column covers Pareto-optimal emission reductions, the second column shows the share to be attributed to the global public good effect. The third column represents the gap between the status quo and the Nash equilibrium in percent of the Pareto-optimal amount of emission reductions. This share is denominated as local public good effect.

Apart from a series of countries that can be characterized by a high global public good effect (e.g. Chad, Nepal and Singapore), other countries appear to be

Table 6
Decomposition of efficient emission reductions by country

Country	Pareto-optimal reductions of individual emissions (%)	Global public good effect (%)	Local public good effect (%)
Chad	20.6	88.1	11.9
Nepal	14.4	85.8	14.2
Singapore	11.4	48.1	51.9
Spain	5.2	27.3	72.7
Mexico	18.7	23.3	77.7
UK	7.3	16.6	83.4
USSR	28.0	12.8	87.2
Germany	12.1	10.8	89.2
India	64.6	9.5	90.5
China	68.8	7.5	92.5
USA	20.5	1.0	99.0

dominated by a high percentage of the local public good effect (e.g. India, China, and USA). It becomes obvious from Table 6 that the countries with high local public good percentages are those with high percentages of necessary emission reductions in the Pareto-optimal Scenario. Given the fact that these countries contribute considerably to global climatic change by their relatively high CO_2 emission levels, unilateral abatement strategies play an important role in the mitigation of global warming.

Bearing this in mind, the question arises whether policy co-ordinating global climate change conferences, may contribute to solving the greenhouse problem. Our empirical results indicate that even if countries overcome the freerider behavior, international co-operation only plays a relatively minor role in the solution to global climate change. In contrast to the attempt to find an internationally co-ordinated procedure to combat global warming, we argue that the economically rational behavior of the countries alone would provide a high potential for the improvement of the current situation. Environmental policy should therefore put more emphasis on attempts to implement optimal emission reductions at national levels.

3.4. Reasons for the deviation of the status quo from the nash equilibrium

Given the importance of national abatement measures, the question arises what the arguments for the policy failures to implement the Nash equilibrium are:

- Firstly, global warming does not only represent a public good at the international level. Obviously, the freerider behavior exists at the national level as well, which prevents efficient national greenhouse gas emissions.

- Secondly, myopic behavior of decision-makers may be made responsible for policy failure. According to the Public Choice theory, policymakers can be expected to base their decisions on short-term considerations rather than on long-term developments. The global warming problem exhibits the characteristic of short-run emission abatement costs, whereas future generations will primarily profit from emission reductions. If politicians do not adequately consider these benefits in future periods, actual emission reductions will fall too short. This fact can be illustrated by shortening the planning horizon m in our model with diminishing efficient emission reductions in the Pareto-optimal Scenario.
- And thirdly, policymakers may call the underlying database for economic global climate change analysis in question. In many countries, politicians react sceptically to the economic valuation of environmental damage. The criticism that is brought to the fore focuses on the validity and accuracy of 'non-market valuation techniques' such as the Contingent Valuation Method. Moreover, politicians do not often accept modern welfare economic concepts. For example, the consumer surplus is not generally accepted as a basic welfare measure. Policy makers stick rather, to expenditures as the appropriate and relevant measure if it comes to economic assessment of environmental change. Intangibles are usually ignored.

Going through the reasons for the deviation of the status quo from the Nash equilibrium, the question arises whether a solution for these problems can be found. As far as the national reluctance to emission reductions is concerned, we can only refer to the responsibility of the governments, as local authorities are endowed with the power and adequate instruments to guarantee an optimal emission policy in the long-run.

3.5. Sensitivity-analysis

Due to the uncertainties in the field of global climate change, sensitivity-analyses are necessary for the assessment of empirical models. To illustrate how sensitive our empirical results react to changes in key parameters, different scenarios are presented under which costs and benefits, GDP growth rates, discount rates and the length of the time period are varied. In contrast to the *Base Scenario* described above, *Scenarios 1–5* vary the discount rate r from 6 to 0.5%, together with a change of the GDP growth rate q_i[11] according to the values in Table 7. *Scenario 6* illustrates the influence of reducing the time horizon m from 200 to 150 years. In comparison with cost estimates provided by the GREEN model, other similar top down models present cost of greenhouse gas abatement. The Global 2100 Model from Manne/Richels (Manne, 1992), is one of those models which is used under

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[11] In our model the GDP growth rate has to be changed sufficiently in accordance with a change in the discount rate to maintain the necessary property of stable equilibria to facilitate solving the maximization problem according to the contraction-mapping theorem.

Table 7
Pareto-optimal reductions and reductions in the Nash equilibrium under different scenarios

Scenario	Change in	Pareto-optimal emission reductions (%)	Nash equilibrium emission reductions (%)
Base	$r = 4\%$, $m = 200$	27.8	21.4
1	$r = 6\%$ $q_i =$ unchanged	22.5	18.4
2	$r = 3\%$ $q_i = 1\%$	38.6	32.0
3	$r = 2\%$ $q_i = 0.5\%$	47.2	39.4
4	$r = 1\%$ $q_i = 0\%$	58.1	49.8
5	$r = 0.5\%$ $q_i = 0\%$	61.6	53.4
6	Time horizon $m = 150$ years	20.2	15.3
7	Abatement costs (Global 2100 model)	22.0	16.1
8	Double damages	34.2	27.1
9	Half damages	22.2	16.7

Scenario 7. The influence of decreasing and increasing environmental damage estimates is shown under *Scenarios 8* and *9*. *Scenario 8* assumes a cut in damages by half of the original estimates and *Scenario 9* shows the results for doubling the damages. Table 7 presents aggregate emission reductions for the Pareto-optimum and the Nash equilibrium under the different scenarios.

The following features can be observed from the sensitivity analysis. Firstly, it is obvious from Table 7 that the model is sensitive to the chosen discount, rate and the GDP growth rate. A cut of the discount rate to 0.5%, more than doubles the necessary emission reductions in the Pareto-optimum. Secondly, a variation of the abatement costs as well as a decrease of the time horizon, leads to moderate changes of the Pareto-optimal emission reductions. The switch in abatement cost from the GREEN to the Global 2100 model with higher abatement cost, leads to a decrease in emission reductions by approximately four percentage points as compared to the Base Scenario. The reduction of the time horizon m by 25% leads to a decrease of the efficient amount of emission reductions by approximately 20%. Thirdly, the model is very robust even to substantial changes in damage estimates. Scenario 8 with doubling the original damages, increases the Pareto-optimum only by 6.4% points. According to Scenario 9, the reduction in damages by one half reduced the Pareto-optimal amount of emission reductions by 5.6% points. Apart from the influence of the chosen discount rate, the sensitivity analysis shows moderate changes in emission reductions for the variation of fundamental model parameters. In general, it should be noted that the results of the scenarios both for the Pareto-optimum and the Nash equilibrium, change towards the expected direction. Moreover, the importance of local abatement strategies and the dominance of the local public good effect remains irrespective of the change in key parameters.

4. Coalitions

This section focuses on the potential for the development of voluntary international environmental agreements (IEA) to solve the aforementioned global public good effect.

The question is addressed as to whether coalitions for emission reductions form themselves under the presence of public goods. In practice, no international authority exists to enforce efficient solutions to global public good problems. Therefore, any kind of viable international co-operation on global climate change needs to be *self* enforcing. If it can be shown that the potential for the formation of self-enforcing coalitions is low, there is further evidence that international conferences may fail and national abatement strategies are important.

Voluntary IEAs have been investigated by Barrett (1994), Carraro and Siniscalco (1993) or Carraro (1997). The general conclusion that can be drawn from these analyses is that whenever global net benefits from full co-operation are substantial, only small groups of countries will form coalitions. A few papers investigate the development of IEAs for different groups of identical countries (Hoel, 1992) or (Barrett, 1997). Their results of only a small number of coalition members suffer from their application of specific theoretical cost and benefit functions.

Therefore, it seems worthwhile to investigate the potential of IEAs based on actual empirical marginal cost and benefit functions. In real life, it is obvious that all countries are different in size and also in economic cost and damage estimates, which means that different cost and damage functions have to be applied for each country. A small number of (large) countries might reduce their individual emissions considerably, which would lead to substantial global emission reductions.

We simulate empirically both co-operative and non-co-operative coalitions. Whereas non-co-operative coalition models investigate possible outcomes of negotiations between the players in the absence of monetary side payments, co-operative coalitions explicitly allow for side payments among coalition members.

Under the *non-cooperative* model, the coalition's maximization problem can be written as follows:

$$\max_{\{E(0)_i\}_{i \in I_S}} \Pi_S \quad \text{given } E(0)_j \text{ for all } j \in I_{NS} \text{ and } k \in (I_S - \{i\})$$

$$\text{with } \Pi_S = \sum_{i \in I_S} \pi_i = \sum_{i \in I_S} (K_i(E(0)_i) - D_i(E(0)_i, E(0)_k, E(0)_j)),$$

with I_S the group of signatories or coalition members, and I_{NS} the group of non-signatories. For each non-coalition member $j \in I_{NS}$ and $l \in (I_{NS} - \{j\})$ we have

$$\max_{E(0)_j} \pi_j = K_j(E(0)_j) - D_j(E(0)_j, E(0)_l, E(0)_i)$$

$$\text{given } E(0)_i \text{ for all } i \in I_S.$$

The solution to this maximization problem results in emission reduction levels and net benefit positions for the countries under a possible coalition I_S.

As compared to the non-cooperative coalition model, the *co-operative* setting provides identical abatement levels, whereas the payoffs between the players differ. Therefore, it is important how the coalition's profit is distributed among the members of a coalition. Co-operative game theory offers different concepts on the distribution of coalition profits among which the Shapley value has been chosen for our analysis. This value is unique, and it can be interpreted as fair since it distributes the coalition profit according to the average of each player's marginal contribution. The formal calculation of the Shapley value Φ_i for country $i \in I_S$ reads as follows:

$$\Phi_i = \sum_{S \subset I_S} \frac{(s-1)!(|I_S| - s)!}{|I_S|!} (v(S) - v(S - \{i\})).$$

In this formula S denotes a subcoalition of I_S, and $v(S)$ represents the additional coalition payoff of S as compared to the Nash equilibrium for all members of S. The variables s and $|I_S|$ refer to the number of countries in the subcoalition S, and the number of coalition partners in the whole group of signatories I_S, respectively. For a given group of signatories I_S, the net benefit of a coalition member i is then given by the sum of the net benefit in the Nash equilibrium and the Shapley value Φ_i.

Given the net benefit positions of both non-cooperative and co-operative coalitions, the question needs to be analyzed as to whether a coalition is self-enforcing or not. D'Aspremont et al. (1983) introduced the notion of stable cartels which can be applied to the stability of IEAs as well. This notion distinguishes *strong* and *weak stability*. Whereas strong stability requires both the conditions of lower and upper stability to be fulfilled, weak stability requires just lower stability to be met. *Lower stability* implies that no coalition member can benefit from leaving the coalition, and the condition of *upper stability* requires that no non-signatory wants to join the coalition. The stronger condition of upper stability rules out myopic behavior of the countries in the following situation: If a non-signatory A joins a coalition due to an expected increase of its net benefit, it might happen that another coalition member B gets confronted with a reduced net benefit such that B will leave the coalition, and the coalition will break down. Finally, country A is worse off as compared to the situation before joining the coalition. To account for countries' awareness of these indirect impacts of their own behavior in the coalition forming process, the notion of weak stability was also employed here. Therefore, a smaller number of stable coalitions will result under the concept of strong stability, because the myopic behavior of potential coalition entrants will destroy possible coalitions, which would survive under weak stability.

The 135 countries in our analysis can form more than 4.3×10^{40} possible coalitions. Since this huge number is impossible to handle, seven different world regions were formed here for which we calculate the Pareto optimum and the Nash equilibrium were calculated as before (see Section 3). The regions[12] are: 'USA'; 'European Union'; 'Other OECD countries (including Japan)'; 'Former USSR and Eastern European Countries'; 'India and China'; 'Energy Exporting Less Developed Countries'; and 'Rest of the World'. After calculating the Nash equilibrium and the Pareto-optimum for the seven world regions, cost functions were linearized in such a way that the Pareto-optimum and the Nash equilibrium exactly coincide with the non-linear version.[13] The new aggregated figures for the different scenarios can be seen in Table 8.[14] It is obvious that the global public good effect decreases from 6.4% in column 1 to 3.5% in column 2, since a considerable share of emission reductions, which can be attributed to the global public good effect in the version with 135 countries, now represents a local public good effect in the seven regions version.

Altogether the seven world regions can form 121 different coalitions for which empirical results on both non-cooperative and co-operative agreements are being presented.

We found one coalition under the non-cooperative concept that has met the requirements of strong stability. The coalition between the 'European Union' and the 'Other OECD countries (including Japan)'. The drawback of this rather small strongly stable coalition is that it reduces the public good effect only from 3.46 to

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[12] The geographical neighborbood, as well as the correspondence of their economic development justifies the implicit assumption of already established coalitions within these world regions.

[13] If cost functions were not linearized, equilibria could only be simulated and not be calculated algebraically, which would have extended the computation efforts significantly.

[14] The imperfect public good character of the GHG emissions in our paper leads to slightly different equilibrium values for the Pareto Optimum for the 135 countries scenario, and the aggregated seven world regions model.

Table 8
Local and global public good effects for various models (% of actual emissions)

	135 countries non-linear functions	Seven regions non-linear functions	Seven regions linear functions
Local public good effect	21.4	24.2	24.2
Global public good effect	6.4	3.5	3.5
Sum	27.8	27.7	27.7

3.44% (= 0.72%), which is a negligible amount of emission reductions. Furthermore, three coalitions exist that only meet weak stability requirements. These coalitions — each of which consists of just two members — are: 'USA' with 'Rest of the World' (4.24%); 'European Union' with 'Rest of the World' (2.14%); and finally, 'USA' with 'European Union' (1.50%). Although the figures in brackets indicating the percentage of the global public good effect that would be reduced through the formation of the respective coalition, are higher as before the coalitions suffer from the fact that there is an incentive for another region to join these coalitions, which will result in a breakdown of the initial coalition.

Moreover, two coalitions were found under the co-operative framework which meet strong stability. These are 'India and China' together with 'Energy Exporting Less Developed Countries', and 'India and China' with 'Rest of the World'. Whereas the first co-operative coalition has the potential to reduce the global public good effect by 12.5%, the second coalition would reduce the global public good effect by 14.0%. Looking at the flows of the necessary monetary side payments according to the Shapley value, it turns out that the 'Energy Exporting Less Developed Countries' and the 'Rest of the World' would have to pay in each case to 'India and China', to keep the strongly stable co-operative coalition alive. It is obvious that given monetary side payments, all other coalitions consisting of two countries will fulfill the requirements of weak stability. Their contribution to the reduction of the global public good effect ranges from 0.7 to 11.2%. We found no weakly stable co-operative coalition with more than two coalition members.

The interpretation of our results makes clear that the parameters of cost and benefit functions are such that we can hardly expect the formation of *non-cooperative* international environmental agreements. Even if a coalition comes into being, it probably consists of only a few countries and the expected amount of emission reductions is negligible. Furthermore, there is no guarantee for the formation of the coalition that would provide the highest percentage of emission reductions ('USA' with 'Rest of the World') as compared to another stable coalition with lower emission reductions. As Ecchia and Mariotti (1997) have shown, this argument may change if the countries become farsighted in the sense that they consider the consequences of their behavior in the long-run; under certain conditions, full co-operation can be attained even in non-cooperative games if countries behave non-myopic, since the more farsighted the countries behave the more coalitions will survive. However, keeping the reasons for the deviation of the status quo from the Nash equilibrium in mind, this outcome seems unlikely to occur.

Under the co-operative framework, stable coalitions were found with more significant emission reductions due to the side payments. Given consensus on the Shapley value concept as the basis for the distribution of coalition payoffs, stable coalitions exist. Of course, the success of co-operative coalitions to improve the global warming problem depends on the countries' acceptance of the distribution of payoffs among the coalition members. Nevertheless, international environmental agreements of this type may serve as a helpful tool to gradually approach the socially optimal greenhouse gas emission level. However, apart from efficiency issues, distributional arguments need to be considered if the aim is to establish working coalitions in the real world. From a political point of view, it is relevant whether poor countries would have to pay to richer ones or vice versa. We found evidence that the only strongly stable co-operative coalition had required a net payer position for the 'Energy Exporting Less Developed Countries' and the 'Rest of the World' — regions with a majority of less developed countries. Therefore, from a political angle one may doubt whether stable environmental agreements would come into being through international negotiations that focus solely on CO_2 emission reductions. A higher potential for the formation of coalitions were probably achieved if the global warming problem would be discussed within a broader framework with other global issues being taken into consideration as well. Therefore, we plead for a package deal under which the inclusion of other global issues would expand the leeway to find politically acceptable coalitions that may achieve consensus on the global warming problem. In the negotiations on these package deals, distributional issues must be taken into particular consideration. In that sense, global issues like foreign aid for developing countries, the often discussed deduction of international debt from third world countries, or trade liberalization in favor of developing countries, are examples of such possible nexuses. In any of these cases, an extension of the, mandate of the United Nations Framework Convention on Climate Change UNFCCC, which forms the formal body for international conferences on global climate change, would be necessary.

5. Summary and concluding remarks

This paper presents empirical results on CO_2 emission reductions. It differs from previous work by (1) introducing explicit marginal cost and benefit functions for 135 countries, (2) distinguishing between a local and a global dimension of climate change, and (3) finally, by explicitly analyzing the potential for the formation of co-operative and non-cooperative international environmental agreements on global warming. The major conclusions to be drawn are as follows:

Firstly, the efficient Pareto scenario would require global CO_2 emissions to be reduced by 28%. Since it turns out that the less developed world would have to carry the main burden of physically reducing GHG emissions, distributional issues may prevent an efficient outcome.

Secondly, we found that the economic aspect of global warming could be split into two components. Only seven percentage points of the above-mentioned efficient emission reductions may be attributed to the global dimension whereas the remaining 21% points reflect the countries' reluctance to balance individual marginal cost and benefits. We conclude from this evidence that global warming does not only represent a transnational public good problem, but requires unilateral efforts as well. From this perspective, it would be beneficial for single countries to reduce individual emission levels, even in the absence of a co-ordinated international global policy.

Thirdly, it has been shown that the potential of international voluntary agreements to overcome the global warming problem is low. Under the non-cooperative framework, one cannot expect the formation of stable coalitions that would consist of a considerable number of countries and provide a significant reduction of greenhouse gas emissions. Whereas the introduction of side payments results in stable co-operative coalitions with substantial emission reductions, this could imply negative distributional effects in the sense that less developed countries would have to pay. Therefore, the formation of coalitions as a general tool to solve the global warming problem does not seem to be promising. Hence, we suggest broadening the mandate of the so-called COP conferences of the UNFCCC. The inclusion of other global issues like foreign aid or the deduction of international debt may expand the leeway to find acceptable political solutions for the global warming problem.

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