THE GLOBAL WARMING GAME –
SIMULATIONS OF A CO_2 REDUCTION AGREEMENT

by

Samuel Fankhauser and Snorre Kverndokk

CSERGE Working Paper GEC 92-10

THE GLOBAL WARMING GAME –
SIMULATIONS OF A CO_2 REDUCTION AGREEMENT

by

Samuel Fankhauser*
and
Snorre Kverndokk**

*Centre for Social and Economic Research
on the Global Environment (CSERGE), London

**Centre for Research in Economics and
Business Administration, SNF, Oslo

Acknowledgements

The Centre for Social and Economic Research on the Global Environment (CSERGE) is a designated research centre of the UK Economic and Social Research Council (ESRC).

We are indebted to R. Golombek, M. Hoel, A.J. James and D.W. Pearce for valuable comments and discussion, and to A.S. Manne and J. Oliveira-Martins (OECD) for providing us with data. Fankhauser also acknowledges the support of the Schweizerischer Nationalfonds für Forschung und Wissenschaft. The authors are solely responsible for remaining errors and any conclusions drawn. A more detailed version of the paper is available on request.

ISSN 0967-8875

Abstract

The paper analyses incentives for, and the benefits of a possible international cooperation to reduce CO_2 emissions. The negotiations are modelled as a (static) reciprocal-externality-game in CO_2 emissions between five world regions. CO_2 emissions affect the players in two ways: first, each country's income depends (via energy inputs) on the amount of CO_2 emitted; on the other hand, emissions may cause future damage due to climate change. Without cooperation, each player maximises its net benefits in setting marginal income equal to its marginal damage costs (Nash equilibrium). Under full cooperation marginal income equals the sum of the marginal damages (social optimum). The paper calculates illustrative estimates of these two equilibria. It shows that the currently observed differences in countries' attitudes towards a CO_2 reduction agreement can largely be explained by economic factors. It also shows, however, that from a pure cost-benefit point of view the internationally proposed reduction levels may be too high.

1. INTRODUCTION

Several papers have analysed the costs of reducing CO_2 emissions (see for instance Boero et al., 1991; Hoeller et al., 1991; and Nordhaus, 1991a for surveys of these studies). However, abating CO_2 emissions has two aspects, and an analysis of both costs and benefits of CO_2 emission abatement is essential for finding the optimal reduction level under an international CO_2 emissions agreement. At the moment there re relatively few studies analysing both sides of the CO_2 problem. Studies aiming in this direction are Nordhaus (1991b,c) and Peck and Teisberg (1991). However, they remain at an aggregate, worldwide level. This paper tries to introduce cost-benefit aspects on a more disaggregated level, i.e. to a world divided into different regions.

The process of a CO_2 reduction agreement is analysed as a numerical global game, where the different players, i.e. the different countries and regions, take into account both the costs and benefits from CO_2 abatement. The game is modelled as a static one period game in emissions of CO_2 for the year 2000, and is played by five regions: The United States (USA), all other OECD countries (OOECD), the countries of the former Soviet Union (USSR), China (CHINA) and the rest of the world (ROW). The only greenhouse gas emissions analysed are CO_2 emissions from the combustion of fossil fuels. CO_2 is the main greenhouse gas; it contributes about 50-80% of the total greenhouse effect, depending on the time horizon considered (IPCC 1990). It is not unlikely that an international agreement on reducing greenhouse gas emissions will concentrate on CO_2 emissions only.

Due to the great uncertainty in future scenarios for the greenhouse effect as well as the simplifications made in our model, the numerical results should only be taken as illustrative estimates. Nevertheless, we hope to make a contribution to the understanding of the economics of global warming, in particular in modelling incentives for emission reductions and willingness to cooperate in different geographical regions.

The structure of the paper is as follows: in Section 2 we give the basic theory of the global warming game, and derive the important equilibria. The climatological mechanisms leading to global warming, which will act as the side constraints of the game, are modelled in Section 3. The specifications of the income – and damage functions are outlined in Sections 4 and 5, while the results from the simulations under different scenarios are given in Section 6. Section 7 contains the sensitivity analysis, and conclusions are summarised in Section 8.

2. THE BASIC THEORY

From an economist's point of view global warming is a typical open access resource problem. The atmosphere is used jointly by all countries of the world to dispose of, among other substances, CO_2, which is emitted as a by-product of GNP-producing activities. However, the accumulation of CO_2 in the atmosphere may have negative effects in the future (in the form of climate change) not only for the emitting country but for the world as a whole, i.e. each emitter imposes a negative externality on the rest of the world. These features can be formalised as a reciprocal externality game in which players (countries) trade off income and damage from emissions to maximise net benefits (see, e.g. Mäler, 1990).

Greenhouse gases are also typical examples of stock pollutants, since it is only the atmospheric concentration (the stock) which affects the climate, while the flow of emissions as such would be harmless (at least with respect to climate change). Problems of stock pollutants are usually analysed in a dynamic framework. In the case of CO_2 this would imply a model in which each player i is maximising a net benefit function of the form

$$\max NB_i = \sum_{t=o}^{\tau}[Y_{it}(e_{it}) - D_{it}(T_t)]\delta^t \qquad (1)$$

subject to

$$T_t = f_t(\sum_{j=1}^{n} e_{j0}, \ldots, \sum_{j=1}^{n} e_{jt}) \qquad (2)$$

where $Y_i(.)$ is a concave income function for player i, with CO_2 emissions e_{it} being the only input factor. $D_{it}(.)$ is a convex function denoting the damage from climate change in period t. To simplify matters, the various aspects of a changing climate (sea level rise, changes in precipitation, etc.) are represented by a single variable, viz. the incremental temperature since preindustrial time (1750-1800), T_t. The link between emissions and temperature rise is described in the side constraint. δ, finally, is the discount factor.

Unfortunately, the long term character of global warming – impacts are only felt some 30 to 50 years after an emissions, but then may persist for as much as two centuries – makes dynamic analysis rather difficult. Any reasonable time horizon would go far beyond the available forecasts. The following assumption is therefore introduced: we suppose that countries have already agreed on a CO_2 reduction treaty which will come into force in period 1. The maximising agent in period 0 is thus left with only one decision variable, viz. the optimal emissions level in period 0. All other emissions are determined by the treaty. The analysis has consequently become static, i.e. instead of defining an optimal emissions path over time we now calculate the optimal emissions for only one point in time. Implicitly this corresponds to the notion of myopic agents whose economic planning is only short term. Alternatively, the analysis can be seen as one of optimal timing: what is the effect of implementing agreement today instead of waiting until the next period?

We further assume that the relative reduction levels fixed in this assumed treaty are the same as those found socially optimal for period 0, i.e. we take the social optimum from the static game (see equation (7) below) as an approximation for the assumed future agreement of period 1. Like this the social optimum calculated in the game can also be interpreted as a static approximation of a dynamic optimum.

A static game of this sort can be described in the following way. Without cooperation each player i maximises own net benefits, NB_i with respect to own emissions in period 0, e_i. That is

$$\max NB_i = Y_i(e_i) + \sum_{t=0}^{\tau} D_{it}(T_t)\delta^t \tag{3}$$

where $\overline{e}_{it}$ are the exogenously determine CO_2 emissions for player i at time t, $t > 0$. Note that $\sum_t Y_{it}(\overline{e}_{it})\delta^t$ - the present value of future income – is therefore exogenous as well and will thus not affect the optimisation calculus. The climate constraint now takes the form

$$T_t = f_t(\sum_{j=1}^{n} e_j) \tag{4}$$

Incremental temperature is a function of the total emissions of all players at time 0, $\sum_j e_j$. Note that emissions in subsequent periods, while influencing T_t, are by assumption exogenous and therefore only enter as parameters.

The non-cooperative outcome is compared to the cooperative problem

$$\max \sum_{i=1}^{n} NB_i = \sum_{i=1}^{n} \left[Y_i(e_i) + \sum_{t=1}^{\tau} Y_{it}(\overline{e}_{it})\delta^t - \sum_{t=0}^{\tau} D_{it}(T_t)\delta^t \right] \tag{5}$$

The optimisation problems (3) and (5), subject to (4), yield two well-known results of public sector economics, often referred to as the Samuelson conditions (after Samuelson, 1954): Without cooperation each agent sets marginal income equal to own marginal damage, while a social optimum would require that the marginal income of each agent equals the sum of all marginal damages, i.e. that the externalities caused by each player are taken into account.

For the model outlines here, the Samuelson conditions take the following form. The non-cooperative case leads to a Nash equilibrium, and the first order conditions are

$$Y_i^{'} = \sum_{t=0}^{\tau} D_{it}^{'} \cdot f_t^{'} \cdot \delta^t \qquad (6)$$

for all i; a dash denotes first order derivatives, i.e. $f_t^{'} = \partial T_t / \partial \sum_j e_j$ etc. The product $D_{it}{'} f_t^{'}$ is hence the additional damage at time t, caused by an increase in today's emissions, and total marginal damage is the discounted sum of the additional future damage.

The first order conditions for problem (5), i.e. for the social optimum, are correspondingly[1]

$$Y_i^{'} = \sum_{j=1}^{n} \sum_{t=0}^{\tau} D_{jt}^{'} \cdot f_t^{'} \cdot \delta^t \qquad (7)$$

for all i.

We assume that, at the moment, countries are neither in equilibrium (6) nor (7). Instead, countries are still in a business as usual (BAU) situation, characterised by $Y_i^{'} = 0$. BAU is the optimal point in a situation in which environmental aspects are completely neglected. This could either be because of ignorance (i.e. under the assumption $f_t^{'} = 0$: the problem does not exist) or lack of concern (i.e. for a high discount rate: future impacts are disregarded)[2]. With respect to global warming, the world has probably been guilty in both respects.

---

[1] Note that equation (7) is also the optimal condition for a Nash bargaining problem, as long as we allow for sidepayments, i.e. the social optimum describes the only efficient cooperative outcome, independently of countries' bargaining powers.

[2] Note that under these assumptions $Y_i^{'} = 0$ satisfies both conditions (6) and (7). In the absence of an externality individual and social optimum coincide.

In the next three sections, the general functional forms used so far will be specified in order to simulate the two equilibria (6) and (7).

3. THE CLIMATE MODULE

The climatological mechanisms leading to global warming are modelled as a set of three equations: a temperature constraint, a stock constraint and an emissions equation[3].

The temperature constraint describes the reaction of temperature to a change in atmospheric CO_2 concentration. The relation between concentration and the equilibrium change in global mean temperature (i.e. the change which will occur after full adjustment) is usually approximated by the logarithmic function:

$$T_t^* = \omega \cdot \ln\left(\frac{Q_t}{Q^p}\right) \tag{8}$$

where T_t^* denotes the difference in global mean temperature between the new and the preindustrial equilibrium. Q_t is the atmospheric CO_2 concentration at time t and Q^p the preindustrial level. Because of the thermal inertia of oceans, however, the equilibrium will only be reached gradually. The temperature constraint is thus represented as a partial adjustment equation,

$$T_t = \alpha \cdot \omega \ln\left(\frac{Q_t}{Q^p}\right) + (1-\alpha)T_{t-1} \tag{9}$$

where α is the delay parameter which determines the speed of adjustment, $0 \le \alpha \le 1$.

The stock constraint is a basic representation of the carbon cycle and determines the level of atmospheric CO_2 concentration. CO_2 is assumed to dissipate at a constant rate, σ, thus

$$Q_t = \lambda E_{t-1} + (1-\sigma)Q_{t-1} \tag{10}$$

---

[3] The scientific aspects are based on IPCC (1990). For a similar representation see Nordhaus (1991b,c).

where E_{t-1} denotes total emissions in period $t-1$ (measured in CO_2 equivalents). The parameter λ translates emissions units (GtC) into the concentration units (ppm).

Total emissions E_t are determined in the emissions equation. E_t is basically the sum of all greenhouse gases emitted in period t,

$$E_t = \sum_k \beta_k s_{kt} \tag{11}$$

where the emission levels, s_{kt} are exogenously given in all periods and for all gases k (see Section 2), except for fossil fuel emissions in period 0, which are endogenous, i.e. $s_{F0} = \sum_j e_j$ (the subscript F stands for fossil fuels). β_k denotes the airborne fraction of gas k, i.e. the fraction of the emissions which is desposed in the atmosphere.

The climate parameters are calibrated to match with the findings of IPCC (1990). To simplify matters we only distinguish between three different greenhouse gases: CO_2 from fossil fuel combustion, CO_2 from other sources (like deforestation and cement manufacturing) and other greenhouse gases (CH_4, N_2O and CFCs). We assume a constant growth rate for each type, which is derived from the predictions of IPCC (1990) and EPA (Lashof, 1991). A list with all parameter values is given in Table 1.

Table 1: The Climate Parameters

Parameter	**Value**	**Comments**
α	0.10	Delay parameter, for lag of 30 to 50 years
ω	3.61	Climate parameter, for climate sensitivity of 2.5°C
Q^p	208	Preindustrial CO_2 concentration in ppm
λ	0.47	Conversion factor GtC to ppm
δ	0.005	Dissipation rate, for atmospheric lifetime of 200 years
s_{OCO2t}	2.098	Other CO_2 emissions in base year 2000 (GtC)
	0.5%	Annual growth rate from base year emissions[a]
s_{OGHGt}	4.761	Other GHG emissions in base year 2000 (GtC equiv.)
	0.5%	Annual growth rate from base year emissions
s_{Ft}	as soc. opt.[b]	Emissions from fossil fuels in base year 2000 (GtC)
	1.5%	Annual growth rate of exog. fossil fuel emissions
β_{OGHG}	1.0	Airborne fraction of other greenhouse gases

β_{OCO2}	0.5	Airborne fraction of other CO_2, see IPCC (1990)
β_F	1.0	Airborne fraction of CO_2 from fossil fuels

Notes: a) $s_{OCO2t} = 2.098$ b) see Section 2

4. THE INCOME FUNCTION

4.1 The theory

The income function in this study expresses the maximum income a country can achieve under different emissions constraints of CO_2. If abating CO_2 emissions leads to lower income, this income reduction may be called the CO_2 abatement cost.

Note that the emissions constraint, while defined as a parameter in the context of the income function, is determined endogenously in the larger context of the game: its value is the result of agents' optimisation, i.e. the result of solving problem (3) or (5).

To further under stand the connection between income and CO_2 emissions, we can write the income function for a country in the following way:

$$F(e) = \max[\phi(v) - pv \mid av \leq e] \tag{12}$$

where the symbols are defined as follows:

v = column vector of energy inputs

p = row vector of energy prices

a = row vector of coefficients transforming energy consumption into CO_2 emissions

e = CO_2 emission constraint

Let $\phi(v) - pv$ express the gross domestic product (GDP) in a country, where $\phi(v)$ is the output value of goods and services at market prices. Energy is assumed to be the production inputs and hence the intermediate products. It can be shown (see Kverndokk, 1992) that if the GDP function is concave in energy inputs, the income function will be concave in emissions.

Define $\hat{e}$ as the emissions level which maximises GDP, i.e. $\delta\phi(v)/\delta v^m = p^m$ for all inputs m. Hence $\hat{e}$ can be interpreted as the emissions level without any CO_2 constraints in a scenario where the greenhouse effect is not taken into consideration. $\hat{e}$ will then be referred to as the BAU emissions level (see Section 2). We see that as long as $e \leq \hat{e}$, the income function will be an increasing function in actual emissions, av and v will therefore always be chosen such that $av = e$.

4.2 Specification of the Function

The concave income function used in this study is taken from Kverndokk (1992) and is expressed in equation (13) (the region subscript, i is left out for simplicity).

$$Y(e) = \hat{Y} - \frac{q\hat{e}}{b}\left[\frac{\hat{e} - e}{\hat{e}}\right]^{b} \qquad (13)$$

where: $$\hat{Y} = Y(\hat{e}) \qquad (14)$$

That is, $\hat{Y}$ denotes GDP in the BAU scenario, i.e. GDP without any CO_2 constraints, in the case where no attention is paid to the greenhouse effect.

Further: $$q = \frac{\partial Y(0)}{\partial e} \qquad (15)$$

i.e. q is the shadow price of CO_2 under the constraint $e = 0$. q can be interpreted as the tax on CO2 emissions which leads to a substitution away from fossil fuels to non-fossil backstop technologies (the switch price of CO_2). At this specified rate, no carbonous energy inputs will be consumed, and consequently no emissions due to fossil fuel will occur. b is a technology parameter, which together with q, $\hat{e}$ and $\hat{Y}$ describes the technology of the country. We assume b<1 and q>0, to assure concavity for $e \leq \hat{e}$. Further we require $b \geq q\hat{e}/\hat{Y}$, which implies $Y(0) \geq 0$, i.e. GDP will always be non-negative. The functions were calibrated using the data from Manne and Richels (1992) and the resulting parameter values are shown in Table 2. For further characteristics of the income function see Kverndokk (1992).

Table 2: The Parameters of the Income Functions (for the base year 2000)

	USA	OOECD	USSR	CHINA	ROW	
b	2.041303	2.069804	2.042257	2.070650	1.723131	technol. parameter
q	1016.06	1016.06	1016.06	1016.06	1143.80	switch price of CO_2 (1990 $/tC)
$\hat{e}$	1.676	1.612	1.236	0.821	1.885	BAU CO_2 emiss. (GtC)
$\hat{Y}$	7117	13322	3384	1706	4757	BAU GDP (1990 bn$)

5. THE DAMAGE FUNCTION

Compared to the abatement or income side, relatively little work has been done on the damage function. While there are quite a few papers which describe damage qualitatively or concentrate on special aspects or regions, the only attempts towards a monetary valuation of total damage seem to be Cline (1992) and Nordhaus (1991b,c) although they mainly provide a point estimate and not a whole function.

Explicit specifications of damage functions are found in Peck and Teisberg (1991) and Barrett (1991)[4]. Following these studies we assume a convex function of the form

$$D_{it}(T_t) = k_i(1+h_i)^{t} \cdot \left(\frac{T_t}{\Lambda}\right)^{\gamma} \tag{16}$$

Annual damage is assumed to grow proportionally with income, where the rate of economic growth in country i is denoted by h_i. k_i is a point estimate of the damage for country i caused by a hypothetical temperature increase of Λ°C in period 0. More technically, for a temperature rise between preindustrial time and period 0 of $T_0 = \Lambda$, damage becomes $D_{i0}(T_0) = k_i$. γ finally determines the degree of convexity.

---

[4] Some ideas about a damage function (based on point estimates) are also found in Cline (1992), while Nordhaus (1991b,c) assumes constant marginal damage.

The parameters of the damage function, more than any of the other figures, are subject to very high uncertainty and the probability range is correspondingly wide. To take this into account we work with three different scenarios, denoted as lower case (I), medium case (II) and upper case (III).

All available data refer to the damage caused by a doubling of CO_2 concentration ($2xCO_2$) which corresponds to a temperature increase of roughly 2.5˚C, thus in all scenarios Λ=2.5. For the United States, Cline (1992) calculates that $2xCO_2$ could cause a damage of around 1.1% of GDP, while the widely quoted studies by Nordhaus (1991b,c) assume a range of 0.25% to 2% of GDP (based on a point estimate of 0.25% of GDP). Although calculated for the United States, Nordhaus assumes that these figures can be generalised to hold for the world as a whole. A forthcoming study by Fankhauser (1992) on the other hand, suggests that the US damage may be below the world average. We therefore assume a damage of 1.5% of the gross world product (GWP) in the lower scenario (I) and 2% in the medium case (II). In the upper case (III) damage amounts to 3% of GWP. The damage distribution pattern of Fankhauser (1992) implies the k-values shown in Table 3.

Table 3: Point Estimates for the 2.5˚C Damage (for the base year 2000)

k-value (bn$1990)	Low Case	Medium Case	Upper Case	%
USA	74.96	99.94	149.92	16.5
OOECD	195.34	260.46	390.69	43.0
USSR	11.36	15.14	22.71	2.5
CHINA	6.81	9.09	13.63	1.5
ROW	165.82	221.09	331.63	36.5
WORLD (%GWP)	454.29 (1.5%)	605.72 (2%)	908.58 (3%)	100

For γ we work with the three assumptions γ=1 (case I), γ=2 (case II) and γ=3 (case III). Because of data restrictions, the same γ-values are used for all countries. Over a time horizon of 200 years it is hard to predict the rate of economic growth, h_i. However, more important than the absolute value is the ratio of h_i to the discount factor δ. The choice of the correct discount rate for environmental projects has traditionally been a subject of fierce discussions (see, e.g. Markandya and Pearce, 1991, for a recent survey). Without going into details, the arguments seem to suggest a rather low discount rate close to the rate of economic growth and we therefore assume a difference of 0.5 percentage points. For an average future growth rate of 3% in all regions this would imply a discount rate of 3.5% (i.e. δ =1/1.035 = 0.966).

6. SIMULATION RESULTS[5]

6.1 The non-cooperative Nash equilibrium

The optimal emissions levels in a non-cooperative Nash equilibrium, compared to the emissions from the BAU scenario are shown in Table 4. The largest changes are faced by the OCED countries, especially by OOECD, where the optimal emissions may be more than 8% lower compared to BAU. For the non-OECD countries (USSR, CHINA and ROW) the changes in emissions are almost negligible in all scenarios. These results are due to the trade-off between abatement costs and damage costs. The OECD countries will face more than half the monetary damage due to the global warming. The portion of total damage is especially high for OOECD, while USSR and CHINA face a relatively small damage (see Table 3). In addition, the abatement costs are in general lower in the industrialised countries compared to most developing countries.

Table 4: **Non-cooperative Nash equilibrium,** % emissions reductions from BAU

	USA	OOECD	USSR	CHINA	ROW	TOTAL
Case I	0.4	1.2	0.1	0.1	0.1	0.4
Case II	1.1	3.1	0.2	0.1	0.4	1.1
Case III	3.1	8.3	0.5	0.4	1.7	3.1

In interpreting the absolute reduction values we should, however, bear in mind that, by assuming cost efficiency in each region, we implicitly assume full cooperation within regions. That is, we assume that there exist optimal agreements between the countries of a region.

---

[5] The simulations were carried out on the GAMS/MINOS system. See Brooke et al. (1988).

High emissions reductions in the Nash equilibrium may be interpreted as high incentives for unilateral emission reductions. Our results would then suggest that such moves can only be expected from OOECD countries and maybe USA. As a matter of fact, the OECD countries are at the moment the only countries which have announced unilateral actions.

6.2 The social optimum

The optimal reduction rate in the social optimum varies quite a lot depending on the different damage cost scenarios, with the highest rate being around 15% (see Table 5). In Nordhaus (1991b,c) the optimal reduction of CO_2 emissions, including deforestation, varies from 22% to almost zero. Compared to these studies, our estimates are roughly within the same range. These results are, however, not directly comparable due to the different assumptions made. Out results also support Peck and Teisberg's (1991) conclusion, that the optimal reduction level is very sensitive to the form of the damage function (i.e. that value of γ). The optimal reduction rates in our study are on average lower than the recommendations of international conferences such as Toronto, 1988. Remember, however, that the present study is restricted to CO_2 emissions from fossil fuels combustion alone. Including other emission sources may lead to further greenhouse reductions, depending on the marginal abatement costs for these sources. Given the high uncertainty, further abatement can probably also be justified with risk aversion and irreversibility arguments.

Table 5: The social optimum, % emissions reductions from BAU

	USA	OOECD	USSR	CHINA	ROW	TOTAL
Case I	2.4	2.6	2.4	2.6	0.4	1.9
Case II	6.4	6.9	6.4	6.9	1.6	5.3
Case III	17.4	18.2	17.4	18.2	6.8	14.9

Table 5 also gives the cost efficient allocation of the abatement burden. It can be seen that USA and USSR on the one hand, and OOECD and CHINA on the other hand, follow each other in a parallel way – a result due to the mannerof specification of the income function. If we use the same functional form for all countries, the abatement costs or calculated carbon taxes will not differ as much as they probably would if the functional forms were different[6]. Given our specified income function, the cost efficient distribution of emissions among countries depends on the calibrated values of the q and b parameters. Due to the small differences in carbon tax rates and energy prices when applying the Manne and Richels figures to our income function, these parameters are almost equal for each region and we get the above result. Cost efficiency has, however, been extensively analysed in Kverndokk (1992) and is therefore not considered further in this study. The results, nevertheless, imply that a uniform reduction scheme may not be as far from first best as is usually assumed, at least for the industrialised countries.

6.3 The Gains from Cooperation

The welfare gain from cooperation for a country is simply the difference between the net benefits in the cooperative and non-cooperative equilibria. Given our assumptions about future emission paths (see Section 2) the welfare gain actually shows the benefit of implementing the cooperative solution this year instead of waiting until next year, i.e. the gain from accelerated action. The simulated welfare gains are given in Table 6.

With less than 0.2% of GWP, the overall welfare gains from cooperating seem rather modest. However, note that this is only the gain from cooperating in one year. Further, remember that our assumption of cost efficiency within regions implies a high level of cooperation already in the non-cooperative solution (see Section 6.1).

Table 6: Welfare Gains from Cooperation, % of BAU GDP

	USA	OOECD	USSR	CHINA	ROW	TOTAL
Case I	-0.000	0.005	-0.007	-0.011	0.016	0.003
Case II	-0.000	0.038	-0.054	-0.077	0.116	0.025
Case III	0.005	0.312	-0.408	-0.574	0.840	0.192

More important than the absolute values are probably the directions of the welfare gains, which can be used to analyse the incentives for cooperation. The highest gains are in OOECD and ROW. These are the only regions for which the welfare gains are positive in all

---

[6] This is a general problem in most abatement cost studies.

scenarios. For USSR and CHINA the gains are negative in all scenarios, while they are mostly slightly negative for USA. This would imply that only OOECD and ROW have an incentive to cooperate, while USA, USSR and CHINA will be reluctant to do so without sidepayments. However, it is important to remember that ROW is a very heterogenous conglomerate of countries, which consists of, e.g. the Eastern European countries, OPEC, Asia and Africa. Hence it is not possible to outline an overall uniform strategy which is optimal for all these countries.

7. SENSITIVITY OF THE RESULTS

As a sensitivity test the income parameter b was also calibrated for the estimates of the GREEN model developed by the OECD (see Burniaux et al., 1991a,b)[7]. GREEN is in general more optimistic than Manne and Richels, and this leads to significantly higher reduction levels, especially for CHINA and USSR (see Table 7). The need for sidepayments to these two regions is thus even greater under the GREEN assumptions.

Table 7: Results for Income Parameter b based on GREEN (medium damage costs)

	USA	OOECD	USSR	CHINA	ROW[a]	TOTAL
Non-coop, % red.	2.6	3.0	4.4	5.1	9.7	5.1
Coop, % red.	10.6	6.6	25.5	30.0	17.5	16.2
Welfare gain, % GDP	0.047	0.132	-0.139	-0.206	0.239	0.080

Note: a) The results for ROW are not directly comparable, as the GEREEN study does not include all countries.

---

[7] Unfortunately the GREEN study does not provide enough information to calculate the q parameters as well.

Table 8: Sensitivity to Climate Parameters (medium damage case)

Worldwide optimal reduction level (% reduction from BAU)	Non-cooperative equilibrium	Cooperative equilibrium
Reference case (γ =2, 2% damage)	1.1	5.3
Climate Sensitivity		
2° ($\rightarrow \omega = 2.89$)	0.7	3.5
5° ($\rightarrow \omega = 7.21$)	4.4	20.7
Atmospheric lifetime		
100 yrs ($\rightarrow \sigma = 0.010$)	0.8	3.7
300 yrs ($\rightarrow \sigma = 0.003$)	1.2	6.0
Rate of discount		
3% ($\rightarrow \delta = 0.97$)	1.6	7.9
5% ($\rightarrow \delta = 0.95$)	0.5	2.2

With respect to the climate parameters, the results are most sensitive to changes in the temperature parameter ω, while the sensitivity with respect to the atmospheric lifetime of CO_2 is comparatively low. Again more important (and more controversial) are changes in the discount rate, see Table 8.

8. CONCLUSIONS

In this paper we have analysed a static game in CO_2 emissions. The simulation results suggest optimal emissions reductions of 2 to 15% worldwide. This is consistent with other studies such as Nordhaus (1991b,c), but on average below the numbers usually advocated in the international debate. The simulations also imply that a socially optimal treaty, while clearly beneficial for the world in its entirety, may only be achieved if sidepayments are offered to at least China and the former Soviet Union, and probably the USA. The only countries with an incentive to unilateral reductions from a BAU scenario re the OECD members. The results are largely consistent to the real world, where so far the only countries considering unilateral moves are found within the OECD, and where China and the former Soviet Union have shown a rather restrained attitude during first attempts to establish an international CO_2 treaty. Due to the great uncertainty in the field and the simplifications made, the results from these simulations should only be taken as illustrative estimates, however.

References

Barrett, S. (1991) *An analysis of alternative instruments for negotiating a global warming treaty*, Draft, Environment Directorate, OECD, Paris.

Boero, G., Clarke, A. and Winters, L.A. (1991) *The macroeconomic consequences of controlling greenhouse gases – a survey*, Environmental Economic Research Series, UK Department of the Environment, London: HMSO.

Burniaux, J.M., Martin, J.P., Nicoletti, G. And Oliveira Martins, J. (1991a) *The costs of policies to reduce global emissions of CO_2: initial simulation results with GREEN*, Department of Economics and Statistics Working Paper No.103, OECD, Paris.

Burniaux, J.M., Martin, J.P., Nicoletti, G. And Oliveira Martins, J. (1991b) *GREEN – A multi-region dynamic general equilibrium model for quantifying the costs of curbing CO_2 emissions: a technical manual*, Department of Economics and Statistics Working Paper No.104, OECD, Paris.

Brooke, A., Kendrick, D. and Neeraus, A. (1988) *GAMS: A user's guide*, Redwood City: The Scientific Press.

Cline, W. (1992) Estimating the benefits of greenhouse warming abatement, in: OECD, *Negotiating a Global Warming Convention: Selected Topics*, OECD, Paris, forthcoming.

Fankhauser, S. (1992) *Some estimates of the damage caused by doubling the atmospheric CO_2 concentration*, CSERGE: London, forthcoming.

Hoeller, P., Dean, A. and Nicolaisen, J. (1991) *Macroeconomic implications of reducing greenhouse gas emissions: a survey of empirical studies*, OECD Economic Studies No.16, OECD: Paris.

Intergovernmental Panel on Climate Change (1990) *Climate Change, the IPCC Scientific Assessment*, (Report from Working Group I), Cambridge: Cambridge University Press.

Kverndokk, S. (1992) *Global CO_2 agreements: a cost efficient approach*, GEC Working Paper 92-01, CSERGE: London.

Lashof, D.A. (1991) EPA's Scenarios for future Greenhouse Gas Emissions and Global Warming, *Energy Journal*, 12(1):125-146.

Mäler, K.G. (1990) International Environmental Problems, *Oxford Review of Economic Policy* 6(1):80-108.

Manne, A.S. and Richels, A.G. (1992) *Buying greenhouse insurance – the economic costs of CO_2 emissions limits*, Cambridge, MA: MIT Press, forthcoming.

Markandya, A. and Pearce, D.W. (1991) Development, the Environment and the Social Rate of Discount, *The World Bank Research Observer* 6(2):137-152.

Nordhaus, W.D. (1991a) The cost of slowing climate change: a survey, *Energy Journal* 12(1):37-65.

Nordhaus, W.D. (1991b) A sketch of the economics of the greenhouse effect, *American Economic Review, Papers and Proceedings* 81(2):146-150.

Nordhaus, W.D. (1991c) To slow or not to slow: the economics of the greenhouse effect, *Economic Journal*, 101(407):920-937.

Peck, S.C. and Teisberg, T.J. (1991) CETA: a model for carbon emissions trajectory assessment, mimeo, Electric Power Research Institute, Palo Alto CA.

Samuelson, P.A. (1954) Pure theory of public expenditures, Review of Economics and Statistics 36:387-389.