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THE ECONOMICS OF GREENHOUSE GAS ACCUMULATION
A Simulation Approach

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September 1992

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Abstract. This article investigates efficient policies against global warming in the case of multiple greenhouse gases. In a dynamic optimization model conditions for an efficient combination of greenhouse gases are derived. The model is empirically specified and adapted to a simulation approach. By various simulation runs, the economics of greenhouse gas accumulation are illuminated; and in particular, it is shown that a CO_2-policy alone would most likely lead to an allocation far from efficiency. These results indicate, that policy measures against global warming should allow for substituting between different greenhouse gases. Such a policy would mainly affect the agricultural sector because livestock and intensive farming techniques contribute significantly to the emission of greenhouse gases.

Introduction

The recent discussion on measures against global warming concentrates almost exclusively on the reduction of carbon dioxide (CO_2) emissions. However, there is no reason to believe that a CO_2-policy alone will ensure efficiency in terms of overall abatement costs because there exist several other greenhouse gases that also contribute to the increase in temperature (mainly methane CH_4, nitrous oxide N_2O, and the chlorofluorocarbons CFC_{11} and CFC_{12}). Hence, in order to sustain a desired level of mean temperature it may be less costly to refrain in part from the required CO_2-reduction and to reduce the emissions of, e.g., methane by an amount which is equivalent in terms of the prevented greenhouse effect. Substitution possibilities like these raise the problem how to allocate abatement activities among the different greenhouse gases and over time in order to ensure efficiency. The theoretical properties of this minimization problem are explored in Michaelis (1992).[1] In the present paper, I will shed some light on the empirical relevance of these findings. In particular, I will show that a 'piecemeal' approach that is limited to CO_2 will most likely lead to an allocation far from efficiency.

In Section 1, the theoretical model is introduced and conditions for an efficient solution are derived. In Section 2, the model is adapted to an simulation approach by specifying cost functions and input data. In Sections 3 through 5, various simulation results for differing time horizon and cost data are reported. In Section 6, some empirical illustrations are provided; and in Section 7, the paper is completed by some policy conclusions.

1. The Theoretical Model

The starting point of our analysis is a generalized version of a model originally developed in Michaelis (1992): Assume there exist n greenhouse gases G_i ($i=1,2,...,n$), let $\hat{e}_i(t)$ denote the basic emission levels which would occur in period t without abatement activities and let $v_i(t)$ denote the amount of pollutants prevented by abatement activities. The basic emission levels $\hat{e}_i(t)$ are assumed to grow with an exogenous rate g_i, i.e. $\hat{e}_i(t)=(1+g_i)^t\hat{e}_i(0)$. Hence, the amount of G_i actually emitted in period t, $e_i(t)$, is given by:

$$e_i(t) = (1+g_i)^t\hat{e}_i(0) - v_i(t). \tag{1}$$

The emitted greenhouse gases accumulate in the atmosphere, with $s_i(t)$ indicating the stock of G_i in the end of period t. Accumulated stocks, in turn, are partly degraded by natural proces-

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[1] In particular, it is shown how the efficient time path depends on the ecological characteristics of the gases (greenhouse potential, atmospheric lifetime) and on the planner's attitude towards intertemporal decison making (type and length of time horizon, discount rate).

ses. For simplification it is assumed that these processes can be described by constant disintegration rates q_i $(0 < q_i \leq 1)$ indicating that the degradation of the stock $s_i(t)$ during the course of one period is $q_i s_i(t)$. Hence, the change in stock between two periods t and t + 1 can be characterized by the difference equation:

$$s_i(t+1) - s_i(t) = e_i(t+1) - q_i s_i(t). \tag{2}$$

In order to facilitate aggregation, the stocks $s_i(t)$ are converted into CO_2-equivalents by weighting them with their specific greenhouse warming potentials, α_i.[2] Then, from (1) and (2), the following relationship between the initial stocks, the previous emissions and the current total stock of greenhouse gases, measured in terms of CO_2-equivalents, s(t), can be derived:

$$s(t) = \sum_{i=1}^{n} \alpha_i(1-q_i)^t s_i(0) + \sum_{\tau=1}^{t} \sum_{i=1}^{n} \alpha_i(1-q_i)^{t-\tau}[(1+g_i)^\tau \hat{e}_i(0) - v_i(\tau)]. \tag{3}$$

Eq. (3) serves to define the ecological constraint of the model. Metereological evidence suggests that the rise in global mean temperature is directly related to the growth in stock s(t).[3] Moreover, it has been estimated that the ecosystem's capability to cope with global warming is restricted to a maximum rise in mean temperature of approximatively 1° to 2° C above pre-industrial levels (c.f., e.g., Swart/Hootsmans, 1991). Hence, it might be reasonable to assume that s(t) is not allowed to exceed an exogenously given limit of s° units that corresponds to the maximum permissible increase in temperature. As shown in Michaelis (1992), this approach leads to a cost minimizing time path of abatement activities along which the stock of greenhouse gases grows according to a modified Hotelling-rule.

However, the ecosystem's adaptive capability depends not only on the *absolute increase* in temperature, but also on the *rate of change*. One alternative to include this additional constraint would be to define a second restriction $s(t+1) \leq (1+\mu)s(t)$, where $\mu > 0$ indicates the maximum permissible rate of growth in s(t). A second alternative, that will be adopted in the present paper, is to fix a (politically determined) target path $s(t) = s^*(t)$ that is assumed to satisfy

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[2] The greenhouse warming potentials employed above indicate the amount of CO_2 that is equivalent to one unit of G_i in terms of its *instantaneous* greenhouse impact. In contrast to this, some of the warming potentials used in the literature are calculated in such a way that they already *include* the disintegration rate. However, for the present analysis it is more appropriate to separate these two effects by using instantaneous greenhouse warming potentials in combination with an explicit consideration of the disintegration process.

[3] Note that for a given volume of the atmosphere there is a constant relationship between the stock of greenhouse gases and their atmospheric concentrations.

both constraints.[4] Inserting $s(t) = s^*(t)$ into (3) and rearranging terms yields the following condition that has to be satisfied by the abatement levels $v_i(t)$ in order to sustain the target path:

$$\sum_{\tau=1}^{t} \sum_{i=1}^{n} \alpha_i (1-q_i)^{t-\tau} v_i(\tau) = \sigma(t). \tag{4}$$

Here, $\sigma(t)$ contains all information on initial stocks, basic emissions and ecological constraints:

$$\sigma(t) := \sum_{i=1}^{n} \alpha_i (1-q_i)^{t} s_i(0) + \sum_{\tau=1}^{t} \sum_{i=1}^{n} \alpha_i (1-q_i)^{t-\tau} (1+g_i)^{\tau} \hat{e}_i(0) - s^*(t). \tag{5}$$

Before proceeding to complete the model it should be emphasized that the existence of differences in disintegration rates is of particular importance for the dynamics of the problem at hand. Suppose, for example, basic emissions in $t=1$ have to be reduced by an amount of $z>0$ units of CO_2-equivalents in order to sustain $s^*(1)$. This reduction can be accomplished by a multitude of different abatement levels $\{v_1(1), v_2(1), ..., v_n(1)\}$ that lead to different combinations of gases emitted to the atmosphere.[5] Under the unrealistic condition of equal disintegration rates, the mix of gases emitted in $t=1$ would not influence the decisions to be made in subsequent periods, and the planning problem could be solved by myopic cost minimization in each single period (see Michaelis, 1991). However, in reality disintegration rates are different and the mix of gases chosen in $t=1$ affects all subsequent periods: The more gases with comparatively low disintegration rates are emitted in $t=1$, the more abatement activities are c.p. necessary in $t=2,3,...,T$ in order to sustain the desired time path $s^*(t)$. Hence, solely the existence of differences in disintegration rates necessitates the employment of an intertemporal cost minimization procedure.

To complete the model it is finally assumed that the set of feasible abatement activities can be characterized by n abatement cost functions $c_i[v_i(t)]$.[6] In order to obtain the efficient combination of abatement activities among greenhouse gases and over time, the present value of the aggregated abatement costs has to be minimized subject to the constraint (4). Minimizing the corresponding Langrangean:

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[4] From a purely theoretical point of view the former approach might be superior because it implies more intertemporal flexibility. However, from an policy-oriented point of view the alternative adopted in this paper seems to be more realistic.

[5] Each combination of abatement levels that satisfies the condition $\alpha_1 v_1(t) + \alpha_2 v_2(t) + ... + \alpha_n v_n(t) = z$ yields a reduction in emissions of z units of CO_2-equivalents .

[6] The cost functions are assumed to possess the usual properties: $c_i'[v_i(t)] = 0$ for $v_i(t) = 0$, $c_i'[v_i(t)] > 0$ for $v_i(t) > 0$ and $c_i''[v_i(t)] > 0$ for $v_i(t) > 0$.

$$L := \sum_{t=1}^{T} \sum_{i=1}^{n} (1+r)^{1-t} c_i[v_i(t)] + \sum_{t=1}^{T} p(t) \Big[\sum_{\tau=1}^{t} \sum_{i=1}^{n} \alpha_i (1-q_i)^{t-\tau} v_i(\tau) - \sigma(t) \Big], \tag{6}$$

and eliminating the Lagrangean-multipliers p(t) yields the following condition that holds along the efficient path for any pair of gases $\{G_i, G_j\}$ and any pair of subsequent periods $\{t, t+1\}$:

$$\alpha_i^{-1}\Big[c'_i(t) - \frac{(1-q_i)}{(1+r)} c'_i(t+1)\Big] = \alpha_j^{-1}\Big[c'_j(t) - \frac{(1-q_j)}{(1+r)} c'_j(t+1)\Big]. \tag{7}$$

For $t=T$ eq. (7) reduces to $\alpha_i^{-1}c'_i(T)=\alpha_j^{-1}c'_j(T)$, i.e. marginal abatement cost per unit of CO_2-equivalent have to be equalized across gases because in the last period differences in disintegration rates do not matter anymore. Based on this observation the following relationship between marginal abatement cost can be derived from (7):

$$\alpha_i^{-1}c'_i(t) - \alpha_j^{-1}c'_j(t) = \left[\frac{q_j-q_i}{1+r}\right] \sum_{\tau=t+1}^{T} \alpha_i^{-1}c'_i(\tau) \left[\frac{1-q_j}{1+r}\right]^{\tau-(t+1)}. \tag{8}$$

Condition (8) represents the difference in marginal abatement cost per unit of CO_2-equivalent between G_i and G_j along the efficient time path. This equation clearly reveals the importance of differing disintegration rates as discussed above: Under the unrealistic assumption of equal rates $q_i=q_j$ the RHS of (8) reduces to zero, i.e. efficiency requires to equalize marginal abatement cost per unit of CO_2-equivalent across gases in each single period. Under more realistic assumptions, however, the existence of differences in disintegration rates drives a wedge between marginal abatement costs that is indicated by the RHS of (8). For $q_i<q_j$ this wedge implies $\alpha_i^{-1}c'_i(t)>\alpha_j^{-1}c'_j(t)$, i.e. lower disintegration rates demand for higher marginal abatement cost per unit of CO_2-equivalent. Moreover, as can be seen from the RHS of (8), this difference between marginal costs is c.p. the larger, the larger the difference in disintegration rates is, the smaller the discount rate is, and the longer the remaining time-horizon is.

2. A Simulation Approach

Conditions (5) and (7) provide a system of $m=n\text{x}T$ independent equations which determines the cost minimizing time path of abatement levels $v_i(t)$ that is consistent with the contraint $s(t)=s^*(t)$. In order to facilitate a numerical computation of this solution, quadratic cost functions $c_i[v_i(t)]=a_iv_i(t)^2$ with $a_i>0$ are defined. Differentiating $c_i[v_i(t)]$ with respect to $v_i(t)$ and inserting into (7) yields together with (5) a linear system of equations that can be written as $\mathbf{Ax}=\mathbf{b}$, where $\mathbf{x}$ and $\mathbf{b}$ are m-dimensional column vectors, and $\mathbf{A}$ indicates the coefficient matrix of order mxm (see *Appendix*). Using appropriate input data, this system can be solved through matrix inversion.

Table 1 shows the input data employed in the simulation runs. The first row indicates the instantaneous greenhouse warming potentials α_i of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and the chlorofluorocarbons CFC_{11} and CFC_{12} as published by the *Intergovernmental Panel on Climate Change* (cf. IPCC, 1990). At present, these five gases together contribute approximately 90% to the human-made greenhouse effect. Tropospheric ozone (O_3), which also contributes significantly to global warming, is not considered here because it takes a special position: O_3 is not directly emitted from anthropogenic sources but is created by highly complex and non-linear atmospheric processes that involve nitrogen oxides, methane, carbon monoxide and other trace gases. Hence, there exists no straigthforward way to include O_3 into the simulation model.

		α_i	q_i	$s_i(0)$	$\hat{e}_i(0)$	g_i	a_i
CO_2	(i=1)	1	0.0083	10^6	13300	0.011	1
CH_4	(i=2)	58	0.0952	4860	520	0.002	150
N_2O	(i=3)	206	0.0066	875	8	0.006	60000
CFC_{11}	(i=4)	3970	0.0165	0.8	0.05	-0.020	-
CFC_{12}	(i=5)	5750	0.0077	1.4	0.05	-0.020	-

Table 1: Input data to be used in the simulation runs (source: IPCC, 1990, own calculations).

Direct estimates of the disintegration rates q_i are not available, but as shown elsewhere (cf. Michaelis, 1992) the magnitude of q_i can easily be derived from the gases' atmospheric lifetimes that are also published by the IPCC (1990). The resulting rates are given in the second row of Table 1. It should be noted, however, that the atmospheric lifetime used to calculate the disintegration rate of CO_2, 120 years, is not unambiguous because this timespan also includes periods in which the gas does not contribute to global warming because it is temporary converted into biomass. Consequently, it would also be reasonable to employ a higher disintegration rate in calculating the efficient time path. The likely effect of an adjustment to a higher disintegration rate will be in Section 5.

Concerning the initial stocks $s_i(0)$ and the basic emissions levels $\hat{e}_i(0)$ it is important to realize that the cost minimizing solution only depends on the *relative* magnitudes of these figures. Therefore, the initial stock of carbon dioxide, $s_1(0)$, has been normalized to an (arbitrarily chosen) amount of 10^6 units. Based on this benchmark the initial stocks of the remaining gases have been adjusted in such a way that the resulting composition of the total initial stock s(0) reflects the actual atmospheric concentrations in the late eigthies (see IPCC, 1990).

Similarily, the initial basic emission levels, $\hat{e}_i(0)$, have been adjusted in such a way that for each gas the growth in stock, that would result under a status quo regime (i.e. without abatement activities), corresponds to the respective growth in atmospheric concentration that actually has been estimated by the IPCC (1990). The growth in basic emission levels, indicated by g_i, has been calculated according to the long-term 'business as usual'-scenario of the IPCC (1990).[7] In the case of CFC_{11} and CFC_{12}, however, another approach has been chosen in order to incorporate the likely impact of the Montreal Protocol. Here it is assumed that compulsory plans concerning the reduction of CFCs have already come into force, and the resulting decrease in emissions is modelled by negative growth rates g_4 and g_5. This approach implies that the emissions of CFC_{11} and CFC_{12} affect the ecological constraint, but they are not subject to the cost minimization procedure.

The likely magnitude of the growth rates g_4 and g_5 is highly uncertain because the number of countries that ultimately will ratify the protocol and the extent to which the parties actually will comply with the protocol is unknown yet. Different scenarios published by the *Office of Technology Assessment* (OTA, 1989) indicate that the average annual growth in global consumption of CFC_{11} and CFC_{12} may range from -2.6% in the most optimistic case to +3.9% under worst-case assumptions. In the present paper a rather optimistic view of the prospects of Montreal is adopted, and it is assumed that the emissions of CFC_{11} and CFC_{12} are reduced by 2% per year.[8]

Empirical estimates of abatement costs are only available for CO_2 and CFCs (see, e.g., Nordhaus, 1991) but not for CH_4 and N_2O. For the FRG and comparable countries of the northern hemisphere, there is ample evidence to believe that the abatement of one ton of N_2O is much more costly than the abatement of one ton of CH_4 which, in turn, is much more costly than the abatement of one ton of CO_2 (see Section 6). However, a precise quantification of

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[7] This scenario predicts for the period of 1990 to 2100 a total increase in emissions of about 260%, 90% and 28% for CO_2, CH_4 and N_2O, respectively.

[8] This assumption, however, neglects substantial time lags that may exist between reductions in consumption and reductions in emissions (see Hammit, 1987).

these costs is far beyond the scope of the present paper. Therefore, more heuristic approach is adopted: In the first step, for pure illustrative purposes more or less arbitrarily chosen cost parameters a_i are employed in order to demonstrate the dynamics of the simulation model (see Table 1).[9] In the second step, numerous simulation runs with varying cost parameters are calculated in order to assess for which range of parameters a piecemeal approach leads to an acceptable approximation of the efficient solution. And finally, it is discussed whether or not real abatement costs are likely to be in the range identified above.

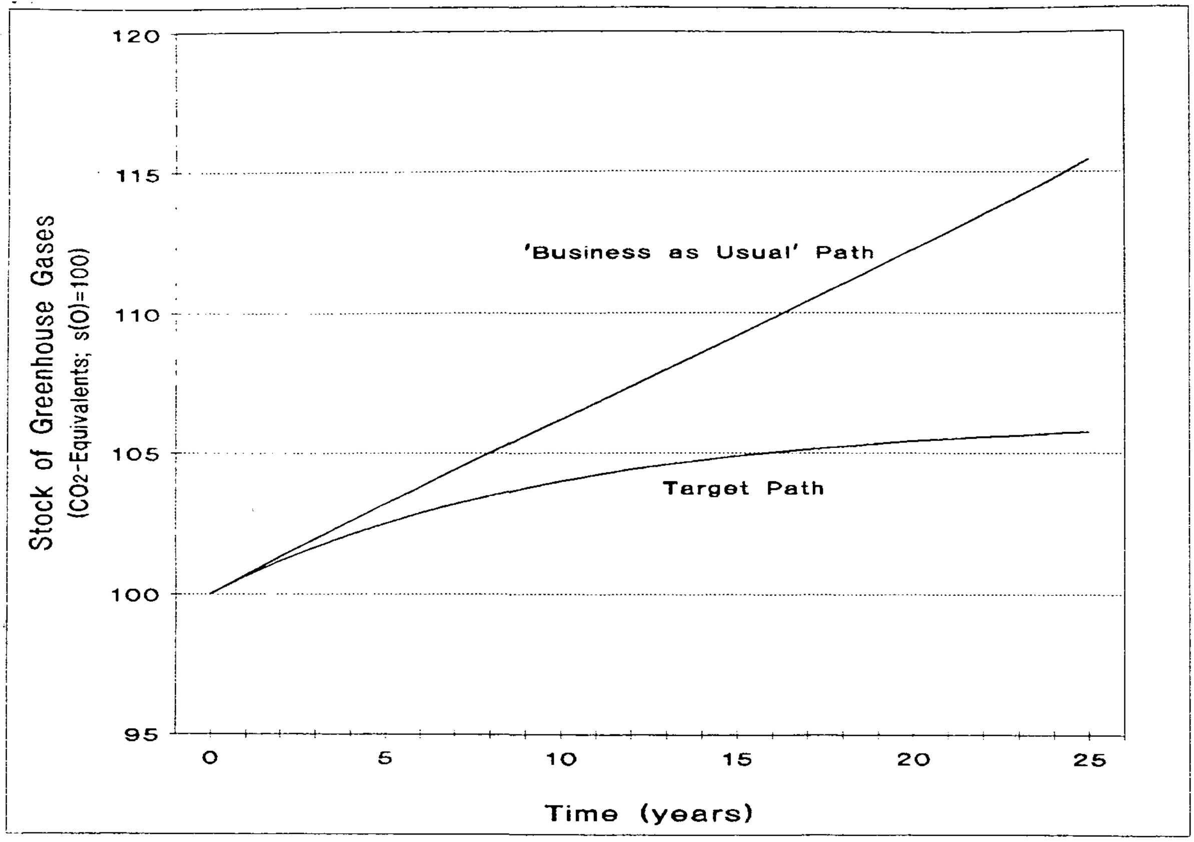

Figure 1: Stock of greenhouse gases: 'Business as usual'-path versus target path.

In addition to the data presented in Table 1 a suitable target path $s^*(t)$ has to be defined. As emphasized by Swart(1992), a policy that is intended to be sustainable in the long run has to aim at stabilizing the atmospheric concentration of greenhouse gases (see Swart 1992, p.39). Therefore, $s^*(t)$ is defined in terms of a growth rate $\mu(t)$ that diminishes over time: $s^*(t) = [1+\mu(t)]s^*(t-1)$ with $s^*(0) = s(0)$ and $\mu(t) = 0.9^{t-1}\mu^{\circ}$. In order to facilitate a smooth adaption to

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[9] Note that a_1 can be normalized to $a_1 = 1$ because the optimal solution of the model depends only on the *ratio* between the cost parameters, but not on their absolute magnitude.

the target path the initial growth rate μ^o equals the initial 'business as usual' growth in s(t) that amounts to about 0.6%. Figure 1 shows the resulting target path for a time-span of 25 years together with the 'business as usual'-path that would occur without any reduction measures concerning CO_2, CH_4 and N_2O. As can be seen, under 'business as usual'-conditions the stock of greenhouse gases grows with an almost constant rate, whereas the target path implies a stabilization at a level of about 6% above the initial stock.

3. Simulation Results in the Case of a Finite Time Horizon

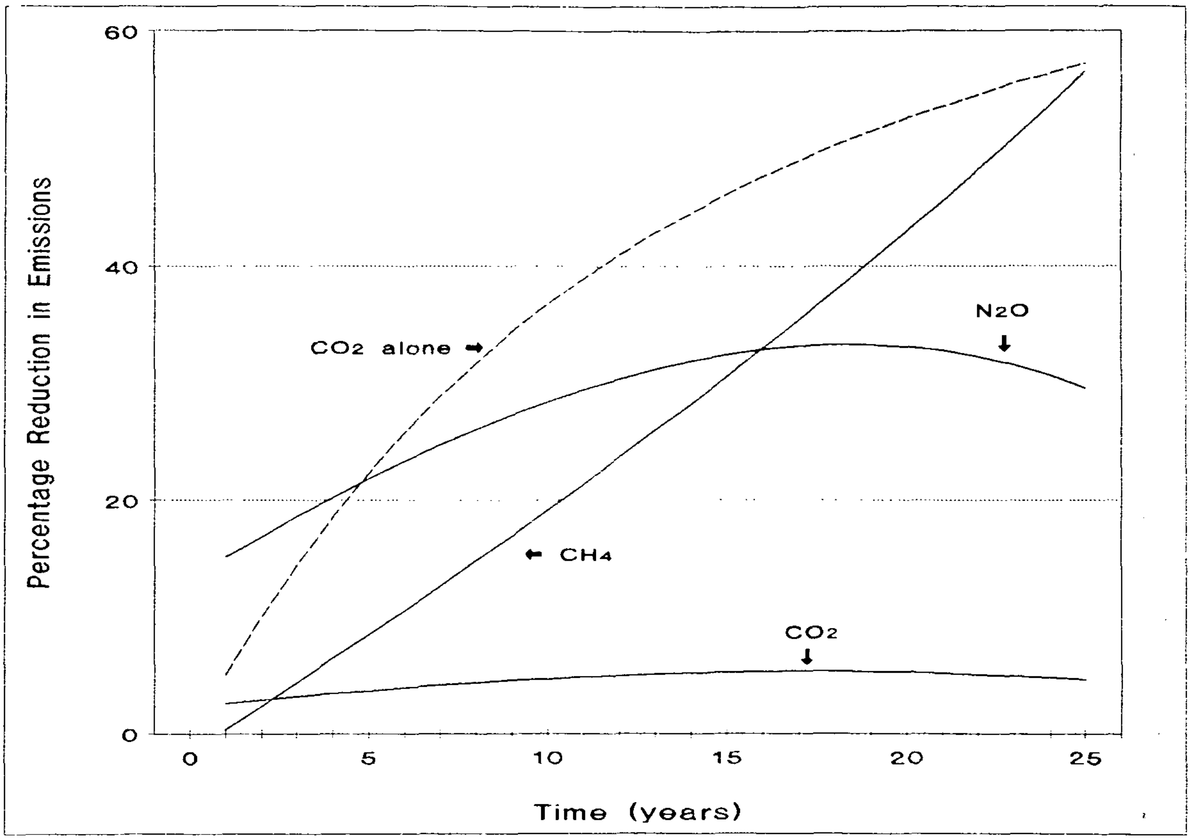

Figure 2: Percentage reduction of greenhouse gases: Piecemeal approach versus comprehensive approach in the case of a finite time horizon.

Figure 2 shows the percentage reduction in emissions of CO_2, CH_4 and N_2O - i.e. the ratio between $v_i(t)$ and $\hat{e}_i(t)$ - that is necessary to sustain $s^*(t)$ at minimum cost provided a discount rate of 5% and a finite time horizon of 25 years. Additionally, the dashed line 'CO_2 alone' indicates the percentage reduction of CO_2 that would be required under a piecemeal approach.[10] This percentage considerably increases over time because in the latter case reductions in CO_2 emissions have to compensate for increasing basic emission levels of all greenhouse gases (except CFCs).

Given the cost parameters specified in Table 1, efficiency requires significant reductions in the emissions of CH_4 and N_2O, whereas only minor reductions in CO_2 emissions are necessary (see Figure 2). As a consequence, there is a remarkable gap between the percentage abatement in CO_2 emissions under a comprehensive approach at the one hand and a piecemeal approach at the other hand. This gap indicates that in the case at hand a piecemeal approach would result in an allocation far from efficiency.[11]

Of course, the particular shape of the time path depicted in Figure 2 crucially depends on the assumption of a finite time horizon. In particular, the influence of differing disintegration rates diminishes over time and becomes the smaller the closer one comes to the end of the horizon (see Section 1). However, the notion of a finite time horizon which is held fixed even when the final period is approached might be unrealistic from a political point of view. But the alternative idea of a decision maker who plans over an infinite number of time periods also seems to be naïve due to several reasons like, e.g., planning costs and uncertainty about the distant future. A possible way out of this dilemma may be to assume a time horizon that is finite but 'sufficiently long' concerning the issue of global warming. According to Cline (1991) this would require a time horizon of at least 250 to 300 years. However, from the political economy of public decision making there is ample evidence to believe that the political process is not able to cope with the demand for such a long time horizon (e.g. Downs, 1957). A sensible way to overcome this dilemma is offered by the idea of *sequential overlapping planning* (see Faber/ Proops, 1990; Schmutzler, 1991) that will be introduced in the next Section.

4. Simulation Results in the Case of Sequential Planning

The notion of sequential overlapping planning describes an intertemporal decision process where plans are set up for a finite time horizon of T periods and after a certain number of periods, S ($S<T$), plans are reevaluated with the time horizon being T periods as before. Continuous repetition of this procedure leads to an (at least in principle) infinite number of

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[10] As can easily be calculated from (4) the percentage abatement of CO_2 emissions under a piecemeal approach is given by $v_1(t)=\sigma(t)-(1-q_1)\sigma(t-1)$.

[11] In fact, for the cost parameters employed above it can be calculated that the present value of aggregated abatement costs is about nine times as high in the piecemeal case compared to the cost minimizing comprehensive solution (see Section 5).

overlapping T-period plans, and the resulting sequence of the first S periods of each plan constitutes the time path that is actually realized. This approach represents a more realistic description of political decision making than the notion of a single (finite or infinite) time horizon because it reconciles short-term planning with long-term considerations.

In order to explore the impact of sequential planning, it is assumed that plans are reevaluated each year and the decision maker's time horizon covers always 12 years ahead (i.e. $S = 1$ and $T = 12$). Before analyzing the resulting time path, it is instructive to compare the abatement levels predicted by the first 12-year plan with the outcome of the 25-year plan described in the last Section. As indicated by Figure 3, reducing the time horizon from 25 to 12 years leads to higher percentage reductions in CH_4 emissions that are accompanied by smaller reductions in N_2O and CO_2 emissions. This shift in abatement activities occurs because a trunctation of the time horizon reduces the economic valuation of the natural disintegration processes, i.e. it becomes c.p. more attractive to reduce the emissions of the comparatively short-lived greenhouse gas CH_4.

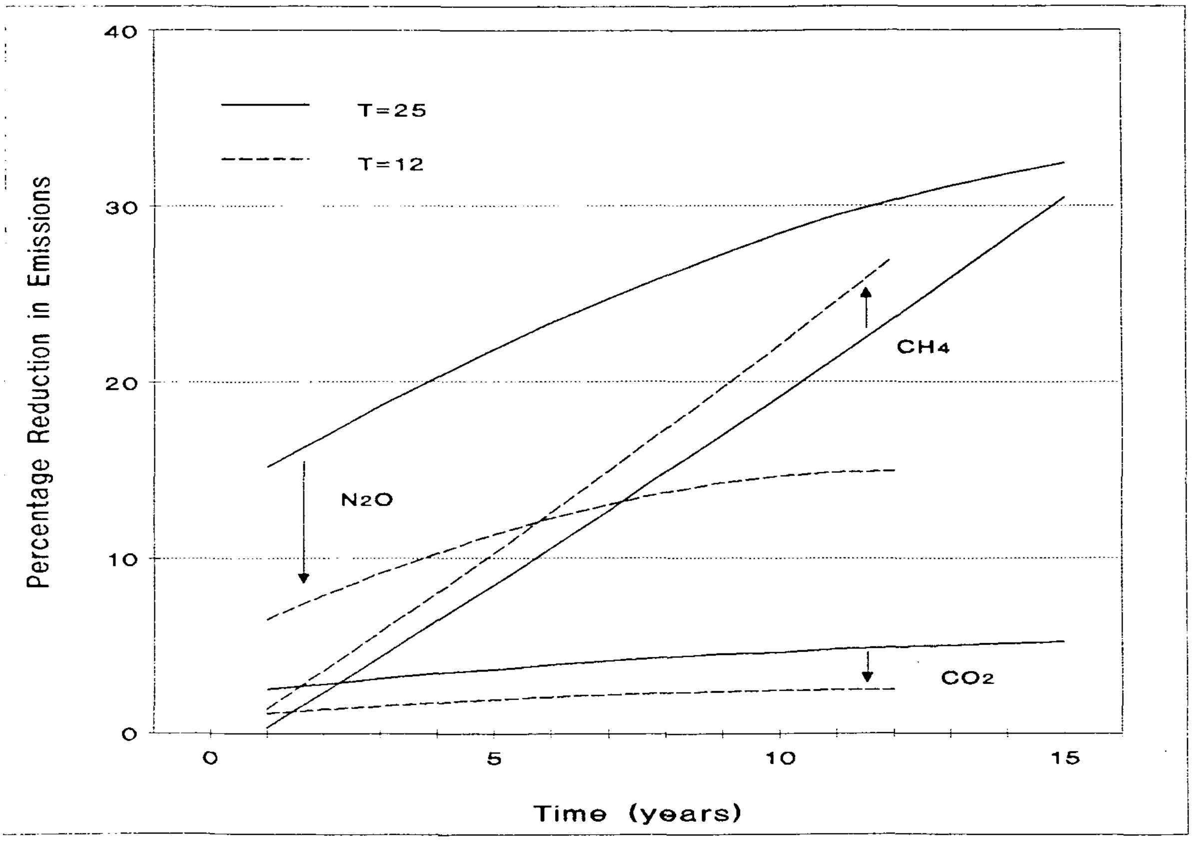

Figure 3: Percentage reduction of greenhouse gases: Effects of reducing the time horizon.

Figure 4 shows the time path resulting from the first 25 plan evaluations together with the finite horizon-path derived in the last Section. These curves reveal that the development of percentage reduction rates becomes more even and regular when the decision maker employs sequential planning instead of a finite time horizon. This alteration is caused by the dynamic properties of sequential planning: Because the actually employed time horizon always covers the same time-span ahead (12 years in the present example), the economic valuation of differences in disintegration rates does not change over time and therefore the efficient time path evens out.

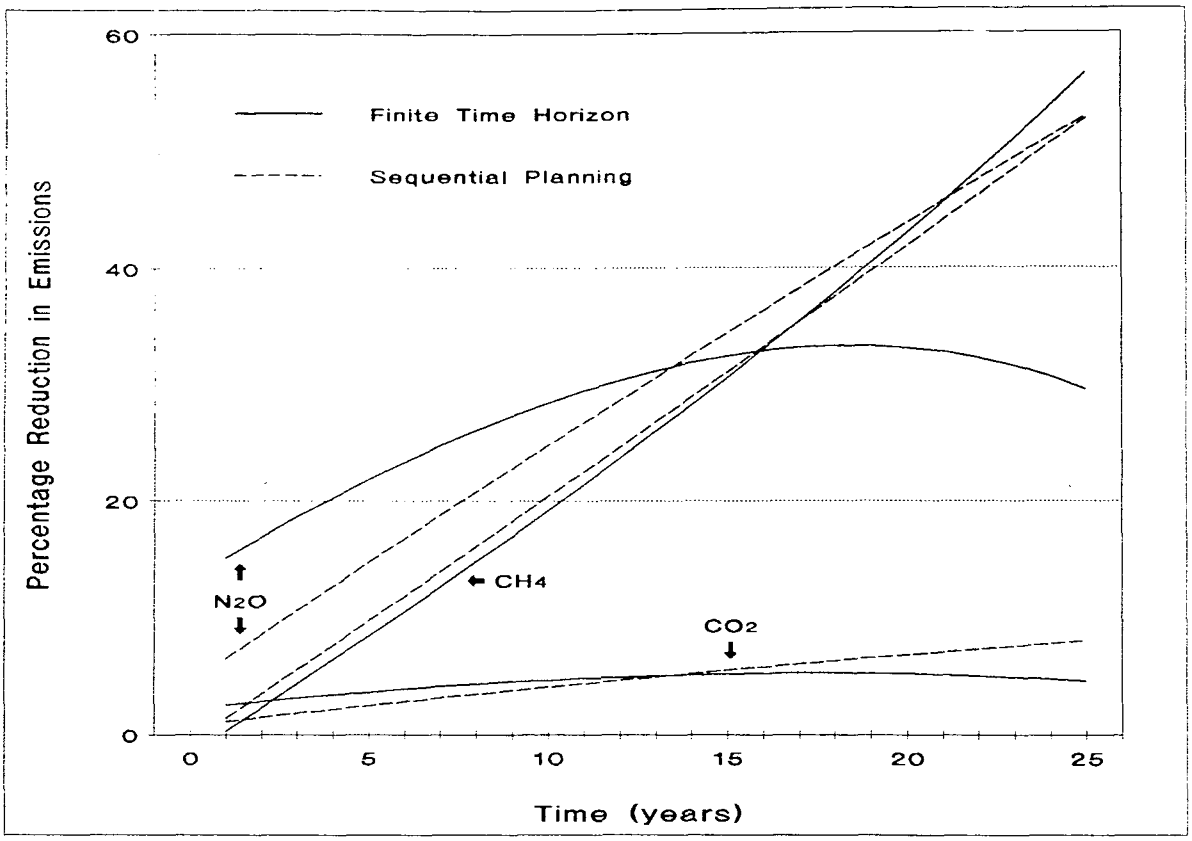

Figure 4: Percentage reduction of greenhouse gases: Sequential planning versus finite time horizon.

Moreover, an interesting change in the allocation of abatement effort among gases can be observed: During the first half of the time-scale considered in Figure 4, the number of years covered ahead by sequential planning - always 12 years - is larger than the number of years still covered ahead by the finite horizon-plan . Hence, under sequential planning it is more attractive to reduce the emissions of the comparatively short-lived greenhouse gas CH_4. And consequently, the mix of greenhouse gases emitted to the atmosphere contains less CH_4 and more of the other (long-lived) greenhouse gases. However, in the medium term this accumulation of larger amounts of long-lived greenhouse gases forces the economy to intensify abatement effort in order to compensate for slower natural disintegration processes. At the same time, the number of years covered ahead by sequential planning begins to exceed the number of years still covered ahead by the finite horizon-plan. As a consequence, for the last decade considered in Figur 4, the percentage reductions in emissions of N_2O and CO_2 obtained under sequential planning considerably exceed the respective figures predicted by the finite horizon-plan, whereas an opposite effect occurs with respect to CH_4.

However, apart from the differences discussed above, Figure 4 also shows that the main conclusion derived in Section 3 under the assumption of a single finite time horizon still remains valid in the more realistic case of sequential planning: After all, there still exists a considerable gap between the percentage abatement in CO_2 emissions under a piecemeal approach on the one hand and a comprehensive approach on the other hand. Hence, for the cost parameters assumed above, a policy that is limited to the reduction of CO_2 emissions is doomed to end up in an allocation far from efficiency. As will be shown in the next Section, this conclusion holds not only for the particular figures employed above, but for a wide range of cost parameters.

5. Sensitivity Analysis

In the last Sections it turned out that the cost data employed in the simulation runs are too small to permit efficiency under a piecemeal approach. Hence, in order to assess for which range of cost data a piecemeal approach leads to an acceptable approximation of the efficient solution, the parameters a_2 and a_3 have to be increased gradually.[12] The effects of such an increase are clear in principle: With increasing costs of reducing CH_4 and N_2O it becomes more attractive to reduce CO_2 emissions, and the differences between a piecemeal approach at the one hand and a comprehensive approach at the other hand diminish. Hence, with increasing costs of reducing CH_4 and N_2O the (relative) inefficiency of a piecemeal approach decreases. In order to obtain a quantitative indicator of this effect, the following ratio between aggregated abatement costs under both policy regimes is defined:

$$R := \left[\sum_{t=1}^{T} (1+r)^{1-t} a_1 v_1^{\circ}(t)^2 \right] / \left[\sum_{t=1}^{T} \sum_{i=1}^{3} (1+r)^{1-t} a_i v_i^{*}(t)^2 \right], \tag{9}$$

---

[12] Note that a_1 can be held fix at $a_1 = 1$ because the optimal solution depends only on the *ratio* between the cost parameters but not on their absolute magnitude.

where $v_1^{\circ}(t)$ and $v_i^{*}(t)$ denote the amount of greenhouse gas emissions to be prevented under a piecemeal regime and under a comprehensive regime, respectively. For example, $R = 2$ implies that the present value of aggregated abatement costs is twice as high in the piecemeal case compared to the cost minimizing comprehensive solution.

a_2 / a_3	150	300	600	1,200	2,500	5,000
60,000	9.87 8.83	6.31 5.25	4.55 3.46	3.69 2.40	3.24 2.14	2.98 1.93
100,000	9.21 8.79	5.62 4.96	3.83 3.19	2.94 2.31	2.46 1.85	2.23 1.64
200,000	8.73 8.34	5.13 4.76	3.32 2.97	2.42 2.09	1.94 1.63	1.71 1.43
400,000	8.49 8.24	4.89 4.65	3.09 2.87	2.18 1.97	1.69 1.52	1.47 1.31
1,000,000	8.35 8.18	4.75 4.59	2.95 2.76	2.04 1.92	1.55 1.46	1.33 1.25
2,000,000	8.30 8.16	4.70 4.57	2.90 2.73	1.99 1.89	1.51 1.44	1.28 1.23

Table 2: Effects of varying abatement costs on the relative efficiency of a piecemeal approach (source: own calculations).

Table 2 shows the magnitude of R for a variety of cost parameters a_2 and a_3, where the upper figures refer to the reference case of a finite time horizon of 25 years, and the lower figures refer to the case of sequential planning with a moving time horizon of 12 years. As can be seen from this table, even for cost parameters that appear - at least at first glance - to be considerably high, the model predicts enormous losses in efficiency due to a policy that is limited solely to the reduction of CO_2 emissions. Hence, even under favourable conditions, i.e. high abatement cost concerning non-CO_2 gases, the piecemeal approach might be no adequate policy response to global warming. This, of course, is only a very preliminary conclusion that has to be re-examined in the light of empirical information on abatement cost (see Section 6).

However, before turning to a discussion of empirical abatement cost, two qualifications should be noted. Firstly, as mentioned in Section 2, due to ambiguities concerning the proper quantification of the atmospheric lifetime of CO_2, it would also be reasonable to employ a *higher* disintegration rate q_1. Such an increase in q_1, however, implies that it becomes c.p. less attractive to reduce the emissions of CO_2 and the gap between the two different policy increases. This, in turn, implies an increase in the ratio R, i.e. it becomes even more unlikely that the piecemeal approach leads to an acceptable approximation of the efficent solution.

Secondly, the degree of (relative) ineffeciency of the piecemeal approach crucially depends on the reference case determining the efficient solution. The outcome of the reference case, in turn, depends not only on the cost parameters but also on the discount rate and the time horizon employed by the decision maker. The effect of varying these figures is clear in principle: Lowering the discount rate or prolonging the time horizon increases the economic valuation of differences in disintegration rates, thereby discouraging measures aiming at reducing CH_4 and encouraging abatement activities related to CO_2 and N_2O. Hence, the gap between the percentage reductions in CO_2 under the different policy approachs, constituting the inefficieny of a piecemeal regime, is c.p. the smaller the smaller is the discount rate and the longer is the time horizon. However, assuming a longer time horizon than employed above seems to be unplausible due to the political economy discussed in Section 3. Moreover, in several simulations runs with non-negative discount rates below the magnitude of 5% that has been employed so far, it turned out that the impact of variations in r is almost insignificant. Hence, it can be supposed that for the relevant ranges of r and T the main conclusions derived above remain valid irrespective of the concrete magnitudes of r and T actually chosen by the decision maker.

6. Empirical Illustration

Although the simulation results summarized in Table 2 provide a first clue to the question in which case a piecemeal approach leads to an acceptable approximation of the efficient solution, the final answer depends on the definition of the term 'acceptable'. As an (arbitrarily chosen) illustrative example it may be assumed that the additional costs implied by the piecemeal approach should not exceed, say, 30% of the efficient costs (i.e. $R \leq 1.3$). In this case, the model predicts that the cost parameters should at least amount to $\hat{a}_2 = 5{,}000$ and $\hat{a}_3 = 400{,}000$ in order to justify a piecemeal approach (see Table 2). In the following it will be discussed whether or not real abatement cost are likely to meet this requirement.

The analysis, however, will be restricted to emission sources and abatement options that are typical for the developed countries of the northern hemisphere. As point of reference, a situation where all gases under consideration (i.e. CO_2, CH_4 and N_2O) are intended to be reduced by the same percentage amount of 20% compared to their basic emission levels is chosen. Empirical evidence provided by various studies on carbon taxation (for an overview see Barret, 1990) suggests that a tax rate of abaout \$ 150 per ton of carbon would be needed to achieve a 20% reduction in CO_2 emissions. For a conversion rate of about 3.7 tons of CO_2 per ton of carbon this implies marginal abatement cost of about \$ 40 per ton of CO_2. In the following, this figure will be used as benchmark. In doing so, it is assumed that the real cost structures actually can be described by quadratic cost functions of the type employed above.[13]

Given the assumption of quadratic cost functions, the ratio of marginal abatement cost between two gases G_i and G_j equals the ratio of cost parameters weighted by the ratio of abatement levels: $MC_i(v_i)/MC_j(v_j) = [a_i/a_j]\cdot[v_i/v_j]$. Rearranging terms and taking into account that a_1 has been normalized to $a_1 = 1$ yields: $a_i = [MC_i(v_i)\cdot v_1]/[MC_1(v_1)\cdot v_i]$. Hence, in order to satisfy $a_i \geq \hat{a}_i$, marginal cost per ton of CH_4 or N_2O, respectively, should at least amount to marginal cost per ton of CO_2 weigthed by $\hat{a}_i v_i/v_1$:

$$MC_i(v_i) \geq \frac{\hat{a}_i v_i}{v_1} \cdot MC_1(v_1) \qquad (i=2,3). \tag{10}$$

According to Table 1, an uniform percentage reduction in *all* gases under consideration implies a ratio of abatement levels of $v_2/v_1 = 1/25$ between CH_4 and CO_2 and $v_3/v_1 = 1/1700$ between N_2O and CO_2. Inserting these figures into (10) and accounting for $MC_1 = \$\ 40$, $\hat{a}_2 = 5{,}000$ and $\hat{a}_3 = 400{,}000$ results in to $MC_2 \geq \$\ 8{,}000$ and $MC_3 \geq \$\ 9{,}400$. In other words: Given the assumptions specified above, the model predicts that a piecemeal approach limited to CO_2 can only be justified in terms of efficiency if the marginal abatement cost for a 20% reduction amount to at least \$ 8,000 per ton of CH_4 and \$ 9,400 per ton of N_2O. As will be shown below, there is strong empirical evidence which suggest that these requirements are not met in reality.

Methane

In the industrialized countries of the northern hemisphere, the anthropogenic emissions of CH_4 can be traced back almost completely to three types of sources: livestock (ruminants), waste disposal at landfills; and leakages from fossil fuel cycles (coal mining, distribution of natural gas). For example, in the FRG, annual emissions of CH_4 amount to about 3 million tons, of which 31%, 27% and 38% are attributable to livestock, landfills and fossil fuel cycles, respectively (see Bundesregierung, 1992a).[14]

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[13] As suggested by Nordhaus (1992, p.50), this assumption may be not too far from reality at least in the case of carbon dioxide.

[14] These percentages can not be applied to other countries because they are heavily biased towards fuel cycles due to the bad condition of the energy systems in the former GDR.

Concerning efficient policies to reduce CH_4 emissions, it seems quite reasonable to suppose that any least-cost strategy would first of all aim at reducing agricultural emissions because all other options (i.e. overhauling leaky gas distribution systems; installing gas insulation equipment at landfills and coal mines) would involve extremely high capital costs. At present, the only practicable way to reduce agricultural emissions of CH_4 is a reduction in livestock itself because the CH_4-production per unit of livestock can hardly be influenced by measures like changes in feeding, and moreover, there exist no low-cost technologies to prevent the ruminants' digestive gases from escaping to the atmosphere (see Sauerbeck/Brunnert, 1990). Among all ruminants, milk cows possess by far the highest 'emissions coefficient' - about 0.1 tons of CH_4 per year and unit of cattle. Therefore, the following discussion concentrates on the option of reducing CH_4 emissions via reducing the number of milk cows. Hence, in order to guess whether the cost condition $a_2 \geq \hat{a}_2$ is met, it has to be asked whether the social value of the last ten milk cows, that have to be slaughtered in order to achieve the desired level of CH_4 reduction, is likely to amount to at least \$ 8,000.

In a perfectly competitive environment the social costs of slaughtering a milk cow equal the individual farmer's loss in income corrected for the induced price effects on producers' and consumers' surplus. However, in the FRG, as well as in most other countries, the market for milk is not competitive but highly regulated by quotas and price floors inducing an enormous excess supply. Hence, it may be assumed that there exists considerable scope for reducing the number of milk cows without significantly increasing milk prices, so that total social costs can be approximated by the farmers' loss in income. In the FRG, for example, the farmers' average net income from milk production at present amounts to about \$ 600 per cow and year (see Bundesregierung, 1992b). This figure, however, includes a huge amount of indirect subsidies caused by the regulations mentioned above, so that the true social costs of reducing livestock may be well below the figure of \$ 600 per cow and year. Hence, as long as reducing livestock is possible without significantly increasing prices, it is quite reasonable to conclude that marginal social costs per ton of CH_4 (i.e. the equivalent of 10 cows) are not likely to add up to \$ 8,000.

Nitrous Oxide

As pointed out by the *German Enquete Commission on Protecting the Earth's Atmosphere* (cf. Enquete, 1990), the use of industrial and, to a smaller extent, organic nitrogen fertilizer has to be regarded as the main source of human-made N_2O in the countries of the northern hemisphere. Empirical evidence suggests that an average of about 2-3% of the utilized nitrogen is converted into N_2O and emitted to the atmosphere (cf. Sauerbeck/Brunnert 1990). Accounting for the relative molecular mass of nitrogen and oxygen this leads to an average emission coefficient of about 0.04 tons of N_2O per ton of nitrogen. Hence, reducing the emissions of

N_2O by one ton requires an average reduction in agricultural input of nitrogen in the order of magnitude of about 25 tons.

Assuming that prices remain unchanged, the social costs of reducing the agricultural input of nitrogen can be approximated by the farmers' loss in income corrected for direct and indirect subsidies. For example, in the FRG the annual input of nitrogen at present amounts to about 1,500,000 tons at a price of $ 650 per ton (see Statistisches Bundesamt, 1991). Under the assumptions that farmers behave rational (i.e. price of nitrogen = value of marginal product) and that nitrogen demand is given by a linear demand curve with an elasticity of -0.5 at current prices (cf. Andréasson, 1989) it can be calculated that marginal loss in income at a 20% reduction level amounts to $ 260 per ton of nitrogen.[15] Accounting for the emission coefficient derived above this implies a marginal loss in income of about $ 6,500 per ton of N_2O. Since this figure, furthermore, is not corrected for subsidies, and since it is based on the heroic assumption of rational behaviour, it seems obvious that marginal social costs per ton of N_2O are well below the benchmark of $ 9,400.

7. Policy Conclusions

Although the model presented above describes the respective economy-environment interactions within a considerably simplified framework, and although the empirical results derived from the model are highly speculative, the basic policy implication is obvious: A piecemeal approach that is limited to CO_2 alone is most likely to lead to an allocation far from efficiency. As the model illustrates, excessive abatement costs imposed on society by ignoring potential substitution possibilities between the different greenhouse gases may amount to 30% or more compared to the efficient solution. These results strongly suggest that policy measures against global warming should tackle not only carbon dioxide but also methane and nitrous oxides. A reasonable way to pursue an efficient allocation of abatement activities among greenhouse gases would be the implementation of a comprehensive charge system on greenhouse gases.[16] The most striking implication of such an approach may be that it would not only affect the use of fossile fuels but it would also impose a considerable burden on modern agriculture specialising in livestock and in intensive farming techniques because these activities contribute significantly the atmospheric accumulation of methane and nitrous oxide.

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[15] This can easily be calculated using the geometrical properties of linear demand functions. For an example, see Andréasson (1989).

[16] The theoretical and practical properties of such a charge system on greenhouse gases are discussed in Michaelis (1992).

Appendix

As shown in Section 2, from an empirical point of view the problem at hand boils down to the cost minimizing allocation of abatement activities among $n=3$ greenhouse gases, viz. CO_2, CH_4 and N_2O. In this case, the column vectors **x** and **b** are given by $\mathbf{x}' = [v_1(1)\ v_1(2)\ v_1(3) \ldots v_1(T)\ v_2(1) \ldots v_2(T)\ v_3(1) \ldots v_3(T)]$ and $\mathbf{b}' = [0\ 0 \ldots 0\ 0\ \sigma(1)\ \sigma(2)\ \sigma(3) \ldots \sigma(T)]$. Morever, the coefficient matrix **A** can be partitioned into 3x3 submatrices $\mathbf{A}_{ij}$ of order TxT,

$$\mathbf{A} = \begin{bmatrix} \mathbf{A}_{11} & \mathbf{A}_{12} & \mathbf{A}_{13} \\ \mathbf{A}_{21} & \mathbf{A}_{22} & \mathbf{A}_{23} \\ \mathbf{A}_{31} & \mathbf{A}_{32} & \mathbf{A}_{33} \end{bmatrix},$$

where $\mathbf{A}_{13}$ and $\mathbf{A}_{22}$ are null matrices, and $\mathbf{A}_{11}$, $\mathbf{A}_{12}$, $\mathbf{A}_{21}$ and $\mathbf{A}_{23}$ are given by $\mathbf{A}_{11} = \mathbf{A}_{21} = \mathbf{Z}_1$, $\mathbf{A}_{12} = \mathbf{Z}_2$ and $\mathbf{A}_{23} = \mathbf{Z}_3$, where $\mathbf{Z}_k$ ($k=1,2,3$) indicates:

$$\mathbf{Z}_k = \begin{bmatrix} (1+r)a_k/\alpha_k & (q_k-1)a_k/\alpha_k & 0 & \ldots & 0 \\ 0 & (1+r)a_k/\alpha_k & (q_k-1)a_k/\alpha_k & \ldots & 0 \\ 0 & 0 & (1+r)a_k/\alpha_k & \ldots & 0 \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ 0 & 0 & 0 & \ldots & (q_k-1)a_k/\alpha_k \\ 0 & 0 & 0 & \ldots & (1+r)a_k/\alpha_k \end{bmatrix}.$$

And finally, the remaining submatrices $\mathbf{A}_{3j}$ ($j=1,2,3$) are given by:

$$\mathbf{A}_{3j} = \begin{bmatrix} (1-q_j)^0\alpha_j & 0 & 0 & \ldots & 0 \\ (1-q_j)^1\alpha_j & (1-q_j)^0\alpha_j & 0 & \ldots & 0 \\ (1-q_j)^2\alpha_j & (1-q_j)^1\alpha_j & (1-q_j)^0\alpha_j & \ldots & 0 \\ (1-q_j)^3\alpha_j & (1-q_j)^2\alpha_j & (1-q_j)^1\alpha_j & \ldots & 0 \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ (1-q_j)^{T-1}\alpha_j & (1-q_j)^{T-2}\alpha_j & (1-q_j)^{T-3}\alpha_j & \ldots & (1-q_j)^{T-T}\alpha_j \end{bmatrix}.$$

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