Sustainable Greenhouse Policies: The Rôle of Non-CO_2 Gases

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Abstract. This paper investigates the economic implications of a comprehensive approach to sustainable greenhouse policies that strives to stabilise the atmospheric concentration of the five major greenhouse gases at an ecologically determined threshold level. In a theoretical optimisation model conditions for an efficient allocation of abatement effort among pollutants and over time are derived. The model is empirically specified and adapted to a dynamic GAMS-algorithm. By various simulation runs for a time period of 200 years (1990 to 2190), the economics of greenhouse gas accumulation are explored. In particular, the long-run cost associated with the above stabilisation target are evaluated for two different policy scenarios: a comprehensive approach that covers all major greenhouse gases simultaneously and a 'piecemeal approach' that is limited to reducing CO_2 or a selected subset of greenhouse gases, respectively. By comparing the simulation results, the potential losses in efficiency associated with a piecemeal approach are evaluated, and some policy implications are discussed.

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1. Introduction

During the last decade, the emergence of global environmental problems (e.g., climate change and the depletion of the ozone layer) has revealed that the stability of the global ecological systems is a necessary precondition for the long-run sustainability of any economic development path. With respect to greenhouse policies, sustainability inevitably requires to stabilise the atmospheric concentration of greenhouse gases (see, e.g., Nordwijk Conference, 1989). This, however, does not necessarily imply an *immediate* stabilisation at the *current* levels. Instead, sustainable greenhouse policies could be guided by 'long-term risk management' as recommended by the UNEP Advisory Group on Greenhouse Gases (see Swart/Hootmans, 1991). This concept relies on deducing short-term emission targets from long-term stabilisation targets that are intended to safeguard the global environment for future generations by "*limiting the risk of rapid, unpredictable, and non-linear responses that could lead to extensive ecosystems damages*" (ibd.).

Compared to cost-benefit-analysis that requires a complete quantification of cost and (partly unknown) damages, the above approach seems to be a reasonable alternative to cope with global warming in the presence of uncertainty, irreversibility and possibly catastrophic consequences.[1] However, in order to stabilise the atmospheric concentration of greenhouse gases, global emissions would have to be reduced by more than 50% compared to the current levels (see IPCC, 1990). This, of course, implies a considerable cost burden. But there also exist considerable yet unexploited options for cost minimisation. In particular, the recent discussion on global warming focuses 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 cost because there exist several other trace gases (mainly methane, nitrous oxide and chloroflourocarbons) that also contribute to global warming. Hence, in order to pursue a given stabilisation target, it may be less costly to refrain in part from the required CO_2-reduction and to

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[1] It should be noted that there is no strict dichotomy between the above 'critical loads' approach and cost-benefit-analysis. Both concepts tend to coincide if one recognises in cost-benefit-analysis that damages as a function of atmospheric concentrations might exhibit threshold effects caused by non-linear dose-response relations (see, e.g., Dasgupta, 1982).

reduce the emissions of non-CO_2 greenhouse gases by an amount which is equivalent in terms of the prevented greenhouse effect. Such a comprehensive approach would have considerable impacts on agriculture because the emission of some of the most important non-CO_2 greenhouse gases is unavoidably linked with specific agricultural activities like, e.g., the use of nitrogen fertiliser and raising ruminant livestock (see Adams et al., 1992).

So far, only few authors have focused on a comprehensive approach that treats all major greenhouse gases simultaneously. Morgenstern (1991), Victor (1991), Swart (1992), Mohr et al. (1992) and Subak (1994) discuss some practical issues associated with a comprehensive approach like, e.g., the choice of policy instruments and monitoring requirements; Eckhaus (1992), Hoel/Isaksen (1993) and Schmalensee (1993) analyse how the damage caused by different greenhouse gases depends on economic variables like, e.g., the growth rate; and Reilly/Richards (1993) construct a damage index for different gases that includes climatic as well as non-climatic effects. Finally, Nordhaus (1993) uses a dynamic integrated climate-economy ('DICE') model in order to calculate an optimal transition path for controlling the emissions of CO_2, methane (CH_4), nitrous oxide (N_2O) and chlorofluorocarbons. However, the way how the DICE model incorporates the different greenhouse gases is ambiguous: Using their specific warming potentials, the gases are converted into CO_2-equivalents and treated as *a single homogenous pollutant* that behaves just like CO_2. This approach neglects that the gases under consideration differ not only by their specific warming potential but also by their *atmospheric lifetime*,[2] such that the long term impact of the emission of a given amount of CO_2-equivalents crucially depends on the chosen *mix* of gases (see, e.g., Hoel/Isaksen, 1993). A second problem associated with the treatment of non-CO_2 gases in the DICE model arises from the use of a single aggregated cost function in terms of CO_2-equivalents. This treatment implies the hardly justifiable a priori asumption that the cost of reducing one ton of CO_2-equivalent are identical for *all* gases under consideration.[3] Moreover, the cost function used in the DICE model has been derived from earlier estimates which cover only CO_2 and CFCs

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[2] For example, the atmospheric lifetime of CH_4 is only about 10 years, whereas the lifetime of CO_2 is about 50 to 200 years (see Section 3).

[3] In favour of the employment of a single cost function, one could be tempted to claim that this function already implies an efficient allocation of abatement effort *between* the different gases. However, as will be shown in Section 2, efficiency between the different gases requires more than just equating marginal cost per ton of CO_2-equivalent.

(see Nordhaus 1991) such that it actually cannot be applied to the whole range of gases under consideration. Essentially, the way how Nordhaus (1993) incorporates non-CO_2 gases is to inflate the original emissions of CO_2 by a certain factor and to replace the term 'carbon dioxide' by the term 'greenhouse gases'. This approach allows to identify an overall transition path for the control of all greenhouse gases *together*, but it offers no clue about the relative importance of the different gases and about the question how to allocate abatement effort *between* these gases.

Accounting for the overall perspective and the complex structure of the DICE model, the above mentioned simplifications concerning the treatment of non-CO_2 gases are clearly appropriate. But nevertheless, analysing the issue of CO_2 versus non-CO_2 gases in more detail might offer some additional insights that could be useful in formulating efficient policy strategies against global warming. In particular, only an explicit analysis of the substitution processes between the different gases allows to quantify the potential efficiency gains of a comprehensive approach that minimises abatement cost across the different gases. In the present paper, the theoretical and empirical implications of such a comprehensive approach will be explored. In particular, an empirical simulation model will be used to calculate efficient time paths of greenhouse gas control together with the corresponding cost figures. In Section 2, the theoretical model is introduced and conditions for an efficient solution are derived. In Section 3, the model is adapted to a simulation approach by quantifying cost functions and input data. In Sections 4 simulation results for different policy scenarios are reported, and in Section 5, the paper is completed by some policy conclusions.

2. The Model

The starting point of the present analysis is a generalised version of a model originally developed in Michaelis (1992): Assume there exist n greenhouse gases G_i (i=1,2,...,n), the specific greenhouse warming potentials of which are indicated by α_i.[4] Let $\hat{e}_i(t)$ denote

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[4] Note that α_i indicates the amount of CO_2 that is equivalent to one unit of G_i in terms of the *instantaneous* greenhouse impact. In contrast, 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 basic emission levels that 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: $\hat{e}_i(t)= (1+g_i)^t\hat{e}_i(0)$. 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 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 processes that are characterised by constant disintegration rates q_i $(0<q_i\leq 1)$. Hence, the change in stock between two periods t and t+1 can be described by the difference equation:

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

Assuming initial stocks $s_i(0)\geq 0$ and converting all gases into CO_2-equivalents by weighting them with their greenhouse coefficients α_i , the following relationship between initial stocks, basic emission levels, abatement activities and the current total stock of greenhouse gases, measured in terms of CO_2-equivalents, can be derived from (1) and (2):

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

Equation (3) serves to define the ecological constraints of the model. Scientific evidence suggests that the rise in global mean temperature is directly related to the growth in stock s(t).[5] Since the ecosystems' capability to adapt to global warming is restricted to a certain maximum rise in mean temperature compared to pre-industrial levels (e.g., Swart/ Hootmans, 1991) it is assumed that s(t) is not allowed to exceed an exogenously given limit of s° units in terms of CO_2-equivalents. However, as pointed out by the UNEP's Advisory Group on Greenhouse Gases, the ecosystems' adaptive capability depends not only on the *absolute increase* in temperature, but also on the *rate of change* in temperature (ibd.).[6] In

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the present analysis it is more appropriate to separate these two effects by using instantaneous warming potentials in combination with an explicit consideration of the disintegration process.

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

[6] For example, the Advisory Group expects that "*a maximum rate of sea level rise less than 2 centimetres per decade would permit the vast majority of vulnerable ecosystems, such as coastal*

order to capture this effect, it is additionally assumed that s(t) has to satisfy a second constraint $s(t) \leq (1+\gamma)s(t-1)$, where γ indicates the maximum permissible rate of growth in stock s(t). In Section 3, both constraints on s(t) will be quantified using the well-known relationship between radiative forcing, climate feedback and global warming.

Finally, the economics of greenhouse gas control are characterised by n abatement cost functions $c_i[v_i(t)]$ which are assumed to exhibit the usual properties:

$$\frac{\partial c_i(t)}{\partial v_i(t)} > 0 \text{ for } v_i(t) > 0, \quad \lim_{v_i(t) \to \bar{e}_i(t)} \frac{\partial c_i(t)}{\partial v_i(t)} = \infty, \quad \lim_{v_i(t) \to 0} \frac{\partial c_i(t)}{\partial v_i(t)} = 0, \text{ and } \partial^2 c_i / \partial v_i(t)^2 > 0. \tag{4}$$

Now consider a central planning agency setting up plans for a finite time horizon of T periods t=1,2,...T. In order to obtain the efficient combination of abatement activities among greenhouse gases and over time, the agency has to minimise the present value of aggregated abatement cost subject to $s(t) \leq s^\circ$ and $s(t) \leq (1+\gamma)s(t-1)$. Denoting the discount rate by r and differentiating the corresponding Lagrangean,

$$L = \sum_{t=1}^{T} \sum_{i=1}^{n} (1+r)^{1-t} c_i\left[v_i(t)\right] + \sum_{t=1}^{T} \left[\sigma(t)\left[s^\circ - s(t)\right] + \mu(t)\left[(1+\gamma)s(t-1) - s(t)\right]\right],$$

yields the following first order conditions where an interior solution is guaranteed by (4):

$$(1+r)^{1-t} \frac{\partial c_i(t)}{\partial v_i(t)} = -\sum_{\tau=t}^{T} \left[\sigma(\tau) - \mu(\tau) + (1+\gamma)\mu(\tau+1)\right] \frac{\partial s(\tau)}{\partial v_i(t)}. \tag{5}$$

Hence, the present value of marginal abatement cost, shown on the LHS of [5], should be equated with the cumulated marginal impact of abatement activities on the future stock s(t) weighted by the Langrangean multipliers $\sigma(t)$ and $\mu(t)$. The latter, in turn, have to satisfy the Kuhn-Tucker Theorem, i.e.:

$$\sigma(t) \cdot \left[s^\circ - s(t)\right] = 0 \quad \text{and} \quad \mu(t) \cdot \left[(1+\gamma)s(t-1) - s(t)\right] = 0. \tag{6}$$

The interaction of these two multipliers governs the development of s(t) along the optimal time path. In particular, the resulting time path can be divided into three subsequent phases that are distinguished by the sign of $\sigma(t)$ and $\mu(t)$. During the first phase, the final

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wetlands and coral reefs, to adapt; more than 5 centimetres per decade would rapidly increase damages to ecosystems" (Swart/Hootsmans, 1991, p.130).

stock s° is not yet reached but the constraint $s(t) \le (1+\gamma)s(t-1)$ is binding and the accumulation of greenhouse gases is slowed down compared to the unrestricted path (i.e. $\sigma(t)=0$ and $\mu(t)>0$). During the second phase, none of the two constraints is binding and the accumulation of greenhouse gases is purely governed by dynamic efficiency (i.e. $\sigma(t)= \mu(t)=0$). And during the third phase, the final level s° is reached and the remaining greenhouse gas emissions have to be reduced to the amount of natural degradation (i.e. $\sigma(t)>0$ and $\mu(t)=0$).

The actual partitioning of the time horizon depends on the specification of the model parameters, where the discount rate r is of particular importance. Ceteris paribus, an increase in r accelerates the accumulation of greenhouse gases thereby extends the first and the third phase and diminishes the second one. Two polar extremes can be distinguished. On the one hand, for a sufficiently high r, the second phase may completely vanish such that s(t) follows a '*most rapid approach*'-path with $s(t)=(1+\gamma)s(t-1)$ until the final stock s° is reached. On the other hand, for a sufficiently low r, the constraint $s(t) \le (1+\gamma)s(t-1)$ may never bind and s° may be reached not before the last period such that the second phase dominates the complete time path. This latter case may be termed as the *pure Hotelling-case* since marginal abatement cost evolve according to a modified Hotelling rule. Accounting for $\partial s(\tau)/\partial v_i(t) = -\alpha_i(1-q_i)^{\tau-t}$ and inserting $\mu(t)=\sigma(t)=0$ into (5) leads to $(1+r)^{1-t}\partial c_i(t)/\partial v_i(t) = \sigma(T)\alpha_i(1-q_i)^{T-t}$. This implies the following conditions which hold along the optimal time path for any pair of pollutants $\{G_i, G_j\}$ and any pair of subsequent periods {t, t+1}:

$$\frac{\partial c_i(t)/\partial v_i(t)}{\partial c_j(t)/\partial v_j(t)} = \frac{\alpha_i}{\alpha_j}\left[\frac{1-q_i}{1-q_j}\right]^{T-t}, \tag{7a}$$

$$\frac{\partial c_i(t+1)/\partial v_i(t+1)}{\partial c_i(t)/\partial v_i(t)} = \frac{(1+r)}{(1-q_i)}. \tag{7b}$$

The interpretation of this special case is straightforward: Condition (7a) indicates the efficient combination of abatement activities within each period, i.e. the static optimum, and (7b) describes the movement of the system over time, i.e. the dynamic optimum. According to (7a) abatement activities have to be combined between the different gases in such a way that the ratio of marginal abatement cost equals the ratio of the greenhouse coefficients multiplied by the weighted ratio of the respective disintegration rates.[7] Consequently, the share of abatement activities regarding pollutant G_i is c.p. the greater the higher is the greenhouse coefficient α_i and the smaller is the disintegration rate q_i. Moreover, the influence of the disintegration rates is the stronger the longer is the remaining time horizon. In the course of time, the latter effect leads to a shift in abatement effort towards greenhouse gases with comparatively high disintegration rates. This reallocation can also be verified by the dynamic efficiency condition (7b) which indicates that marginal abatement cost increase over time with the rate $(1+r)/(1-q_i)$.

These results, however, are only valid for the pure Hotelling-case with $\mu(t)=\sigma(t)=0$. In the general case, the properties of the efficient time path are less obvious, where even a temporary decline of marginal abatement cost cannot be ruled out. For a more detailed discussion see Michaelis (1997, pp.85-88).

3. A Simulation Approach

Three sets of data and assumptions are necessary for an empirical application of the above model: First, the basic data on stocks and flows of greenhouse gases including a quantification of the model's ecological constraints. Second, abatement cost functions for the different greenhouse gases. And third, an appropriate specification of the discount rate and the time horizon.

Stocks and Flows of Greenhouse Gases

To keep the demands on data availability and computational capacity within a manageable range, the model is restricted to the five major greenhouse gases which together contribute almost 90 % to the man-made greenhouse effect: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and the chlorofluorocarbons CFC11 and CFC12.[8] The

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[7] In the special case of equal disintegration rates (7a) simply requires that marginal cost per unit of CO_2-equivalent should be equalised across gases. This is of particular importance with respect to CO_2 and N_2O the disintegration rates of which are almost identical (see Section 4).

[8] In order to account for the remaining greenhouse gases (specially tropospheric ozone), the initial stock of the five gases mentioned above is inflated by an amount of 15 % and it is assumed that the resulting stock of ‘other gases’ does not change over time (i.e., emissions per period equal disintegration).

first line of Table 1 indicates the greenhouse gases' instantaneous greenhouse warming potentials α_i as published by the *Intergovernmental Panel on Climate Change* (see IPCC 1990). The second line indicates the greenhouse gases' atmospheric lifetimes c_i that have been used to calculate the disintegration rates q_i shown in the third line of Table 1.[9] The fourth line shows the initial stocks at the beginning of the nineties, and the fifth line indicates the basic emission levels that have been adjusted to the initial stocks in such a way that for each gas the unrestricted growth in stock corresponds to the respective growth in atmospheric concentration that actually has been measured for the period of 1990 to 1991 (see, e.g., Enquete 1992).[10] Finally, the growth rates γ_i shown in the sixth line of Table 1 have been calculated according to the IPCC's long-term 'business as usual'-scenario for CO_2, CH_4 and N_2O, whereas CFC11 and CFC12 are assumed to increase by 1% per year under status quo-conditions, i.e. without the provisions of the *Montreal Protocol on Substances that Deplete the Ozone Layer* and the accompanying treaties (see, e.g., Heister 1993).

	CO_2	CH_4	N_2O	CFC11	CFC12
Greenhouse warming potential α_i	1	58	206	3,970	5,750
Atmospheric lifetime c_i [years]	200	10	140	65	130
Disintegration rate q_i	0.0050	0.0952	0.0071	0.0153	0.0077
Initial stock $s_i(0)$ [10^6 tons]	2,710,000	4,800	1,400	6.7	10.2
Basic emissions $\hat{e}_i(0)$ [10^6 tons]	26,000	350 (+197)	4.7 (+8.5)	0.3	0.4
Growth in basic emissions γ_i	0.012	0.009	0.003	0.01	0.01

Table 1. Basic data on greenhoue gases (sources: IPCC 1990, Enquete 1990, 1992).

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[9] As shown in Michaelis (1992), q_i can be calculated from c_i using $q_i = 1 - \exp(-1/c_i)$. It should be noted, however, that the atmospheric lifetime of CO_2 is subject to considerable uncertainty. The estimates range from 50 to 200 years (see Enquete, 1992, p. 37). The above used figure of 200 years has been chosen because it leads to a calculated magnitude of basic emissions that is in line with the actual emissions of CO_2 estimated for 1990.

[10] Numbers in brackets indicate additional emissions of CH_4 and N_2O from non-anthropogenous sources (e.g., termites) which are not subject to abatement measures.

In defining the ecological constraints it is assumed that the absolute rise in global mean temperature should not exceed 2.5°C which corresponds to a *doubling* of the atmospheric greenhouse gas concentration compared to the pre-industrial level (e.g., Crosson 1990). It should carefully be noted, however, that a large part of this ‘greenhouse budget’ has already been used up. For 1990 it can be calculated that the concentration of greenhouse gases was already about 50 % above pre-industrial levels (e.g., Holmén 1992, Enquete 1992). Hence, with 1990 as base year the further increase in concentration has to be limited to about 35 % which implies for the above model that the stock s(t) should not exceed the upper bound of $1.35 \cdot s(0)$. Moreover, according to Crosson (1990) it is assumed that the rate of change in global mean temperature should not exceed 0.1-0.2°C per decade which corresponds to a maximum permissible growth in stock s(t) of about 4 % per decade (see Michaelis 1997, pp.106-108).

Abatement Cost

An appropriate functional form of $c_i[v_i(t)]$ that satisfies all requirements formulated in (4) is given by $c_i[v_i(t)] = a_i v_i(t)^{\theta_{i1}} / [\hat{e}_i(t) - v_i(t)]^{\theta_{i2}}$ where the parameters $\theta_{i1} \geq 1$ and $\theta_{i2} \geq 0$ determine the slope of the abatement cost curves and a_i fixes their absolute level.[11] In order to calibrate this cost function for the different greenhouse gases, a uniform percentage reduction of 20% compared to the initial basic emissions is chosen as point of reference. Denoting marginal abatement cost calculated at this benchmark by MC_i and accounting for $v_i(t)=0.2\hat{e}_i(t)$, the cost coefficient a_i can be calculated for any given pair of θ_{i1} and θ_{i2} using the first derivative of $c_i[v_i(t)]$ (see Michaelis 1997, p.111).

In quantifying MC_i as well as θ_{i1} and θ_{i2}, it should be recognised that the present model deals with g*lobal* emissions such that the above function has to be interpreted as a *global* cost function.[12] Concerning CO_2 abatement by energy-related policies (like, e.g., fuel-switching) a widely accepted estimate of MC_i is \$ 45 per ton of carbon or \$ 12 per ton of CO_2, respectively (see Nordhaus, 1991). However, only about 80-85% of global CO_2

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[11] In contrast to the approach chosen above, Nordhaus (1993) uses a simple exponential function of the type $c(v)=av^{\theta}$ with $\theta>1$. This cost function, however, exhibits the unrealistic property that the switch to a *completely* carbon-free economy is possible at *finite* cost.

[12] It should carefully be noted that the use of *global* cost functions implies the assumption that it is possible to ensure an efficient international allocation of abatement activities by multilateral negotiations between the involved countries (see, e.g., Barrett, 1991; Stähler, 1993).

emissions can be traced back to the combustion of fossil fuels whereas the remaining 15-20% are caused by deforestation mainly in tropical regions. There is ample empirical evidence that limiting deforestation is much more efficient in terms of abatement cost per ton of carbon than energy-related measures. For example, Cline (1992) estimates that by limiting deforestation in just three countries (Brazil, Indonesia, Côte D'Ivoir) global CO_2 emissions could be reduced by about 6-8% at average cost of only \$ 1.6 per ton of CO_2. In order to capture such low-cost options, it is assumed that an overall least-cost strategy encompassing forestry as well as energy policies would incur marginal cost of only \$ 10 at a 20% reduction level. Using this figure and adjusting θ_{ij} at a level of $\theta_{i1}=2.1$ and $\theta_{i2}=0.1$ leads to a cost curve for CO_2-abatement which is well in line with the "consensus" estimate calculated by Nordhaus (1991) (see Michaelis 1997, pp.114-116).

Concerning CFC11 and CFC12, Nordhaus (1991) estimates that by substitution measures up to 80 % of emissions can be reduced at modest marginal cost of about \$ 5 per ton of CO_2 equivalent. After that point, however, any further reduction would be purely demand-side induced and marginal cost increase sharply. Assuming a mean value of demand elasticity of -0.2 leads to an estimate of MC_i in the order of magnitude \$ 1000 per ton of CFC11 and \$ 2500 per ton of CFC12 respectively, where θ_{ij} is fixed $\theta_{i1}=1.0$ and $\theta_{i2}=1.3$ for both types of CFC. With these parameters, the resulting cost curve exhibits relativley low marginal cost per ton of CO_2 equivalent up to a reduction level of about 80 % (see Michaelis 1997, p.127).

According to the IPCC (1992), the use of nitrogen fertiliser has to be regarded as the main source of global anthropogenic N_2O emissions. Empirical evidence suggests that about 1 to 4% of the utilised nitrogen is converted into N_2O and emitted to the atmosphere (Adger/Brown 1994:11). Accounting for the relative molecular mass of nitrogen and oxygen leads to an average emission coefficient of about 0.035 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 of about 28.5 tons. In the literature on agricultural economics, there are only few estimates of the overall cost associated with such a reduction in nitrogen input. For example, Adams et al. (1993) show for the USA, that a 50 % reduction of nitrogen input would induce annual cost of about \$ 640 millions which can be converted into average cost of \$ 4,900 per ton of N_2O. Similar figures for different reduction levels are derived by McCorriston/Sheldon (1989) for the UK and by

Andreasson (1990) for Sweden. As shown in Michaelis (1997, pp.130-131), these estimates can be fitted into a cost curve with parameters θ_{i1}=2.1 and θ_{i2}=0.1 and marginal cost at a 20 % reduction level of MC_i = \$ 4,500 per ton of N_2O.

Finally, in the case of CH_4, the variety of emission sources makes any cost estimate very difficult. Six different economic activities contribute significantly to global anthropogenic CH_4-emissions (Enquete 1990): cultivation of rice with a share of about 37 %, intensive livestock with 21.5 %, landfill tipping with 11.5 %, burning of biomass with 11.5 %, coal mining with 10 % and the production and distribution of natural gas with 8.5 %. Adams et al. (1993) estimate for the USA that limiting CH_4-emissions by reducing livestock would involve average cost of about \$ 1,200 to 4,200 per ton of CH_4. Similar cost figures for reducing livestock are derived by Adger/Moran (1993) with respect to the UK. For some of the other sources like, e.g., coal mining it seems that abatement cost are much lower but it is very difficult to find reliable data. In Michaelis (1997, pp.132-137) the available information on abatement cost for the different types of sources is collected and condensed into an overall cost curve with parameters θ_{i1}=2.1 and θ_{i2}=0.1 and marginal cost at a 20 % reduction level of MC_i = \$ 1,500 per ton of CH_4.

	CO_2	CH_4	N_2O	CFC11	CFC12
MC_i [\$/t of Greenhouse Gas][1]	10	1,500	4,500	1,000	2,500
Parameter θ_{i1}	2.3	2.3	2.3	1.0	1.0
Parameter θ_{i2}	0.1	0.1	0.1	1.3	1.3

[1] Marginal abatement cost at 20% reduction

Table 2. Cost parameters used in the simulation runs (for sources see Michaelis 1997, Chap. 9).

Table 2 summarises the cost parameters used in the simulation runs. It should carefully be noted, however, that these figures are subject to considerable uncertainty. In particular, any to attempt to estimate reliable cost figures for the reduction of N_2O and CH_4 suffers from a lack of suitable empirical data. Therefore, the simulation runs based on the cost figures shown in Table 2 have been supplemented by some sensitivity analysis the results of which are also presented in Section 4.

Discount Rate and Time Horizon

Finally, the discount rate and the time horizon have to be specified. Discounting future cost and benefits is known to be a crucial factor in analysing long-term environmental problems. Discount rates in the range of 5 to 10%, usually employed in public policy analysis, are widely believed to be inappropriate in the case of global warming because they imply an almost complete disregard of long-term effects (see, e.g., Cline 1992). Therefore, the following simulations employ a moderate discount rate of $r=3$ %. It should carefully be noted, however, that the impact of discounting is less dramatic in the present model than in usual cost-benefit-analysis. In the latter, increasing the discount rate typically leads to more damages in the long run. In contrast to this, the ecological constraints are fixed in the present model such that changing the discount rate induces only an intertemporal reallocation of abatement cost.

In determining an appropriate time horizon it should be recognised that global warming is predominantly caused by fossil fuel combustion. Hence, due to the finite resource base (coal, oil, gas) an infinite time horizon would clearly be inadequate. Instead, it seems reasonable to employ a finite time horizon that is long enough to allow for the occurrence of a low-cost noncarbon-technology for energy generation that will cut greenhouse gas emissions by an amount large enough to resolve the problem of global warming. For the present analysis, a time horizon of 200 years (1990 to 2190) has been chosen. However, experimentation with alternative time horizons has shown that prolonging T by some decades has no significant impact on the allocation of abatement activities during the first 80 to 100 years. In particular, the period when the final stock $s°$ is reached turned out to be insensitive with respect to increases in T.

4. Simulation Results[13]

Figure 1 shows the development of the total stock of greenhouse gases (billion tons of CO_2-equivalents) along the „business as usual"-path and along the efficient time path

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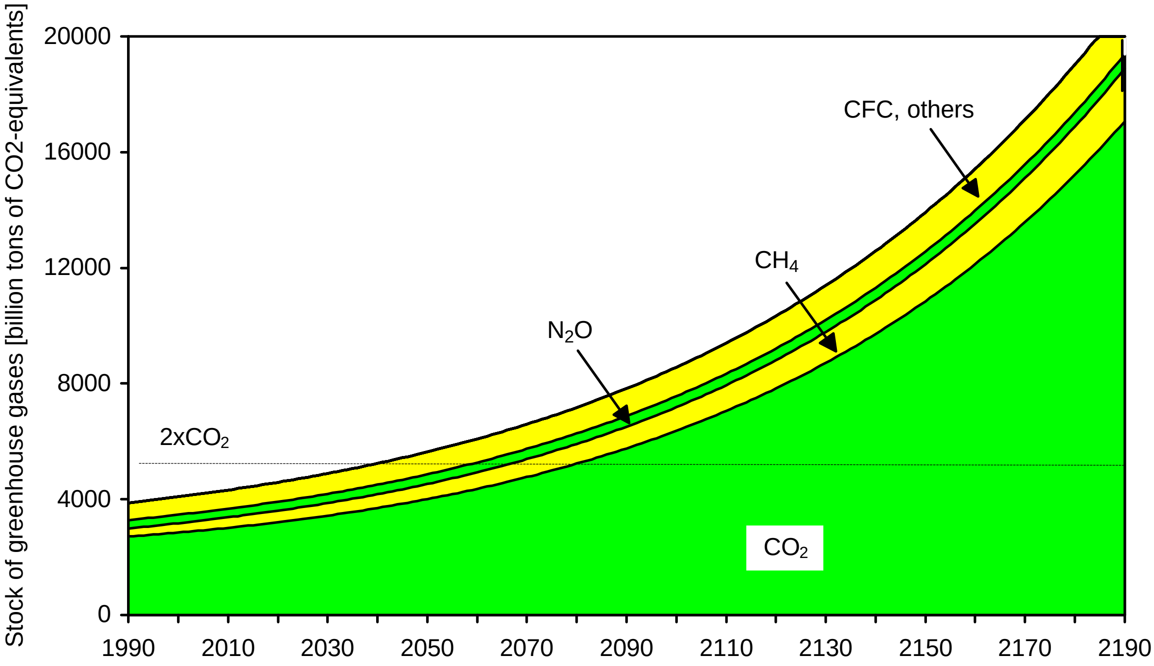
[13] All simulation runs have been calculated using the professional 2.05 version of GAMS-MINOS (see Brooke et al., 1988). To keep the demands on computational capacity within a manageable range, each time period covers five years. More detailed information on input files, model statistics and numerical results are available on request.

which results from minimising total abatement cost with respect to the constraints $s(t) \leq s°$ and $s(t) \leq (1+\gamma)s(t-1)$. The upper panel indicates that without any abatement measures the doubling of the atmospheric greenhouse gas concentration compared to the pre-industrial levels would already be reached after 50 years (see $2\times CO_2$ in Figure 1). Moreover, the growth in stock amounts to about 5 % per decade at the beginning of the time horizon and increases up to a final level of more than 11 % per decade. Hence, without abatement measures the constraint with respect to the maximum permissible increase in global mean temperature per decade would be violated from the beginning on.



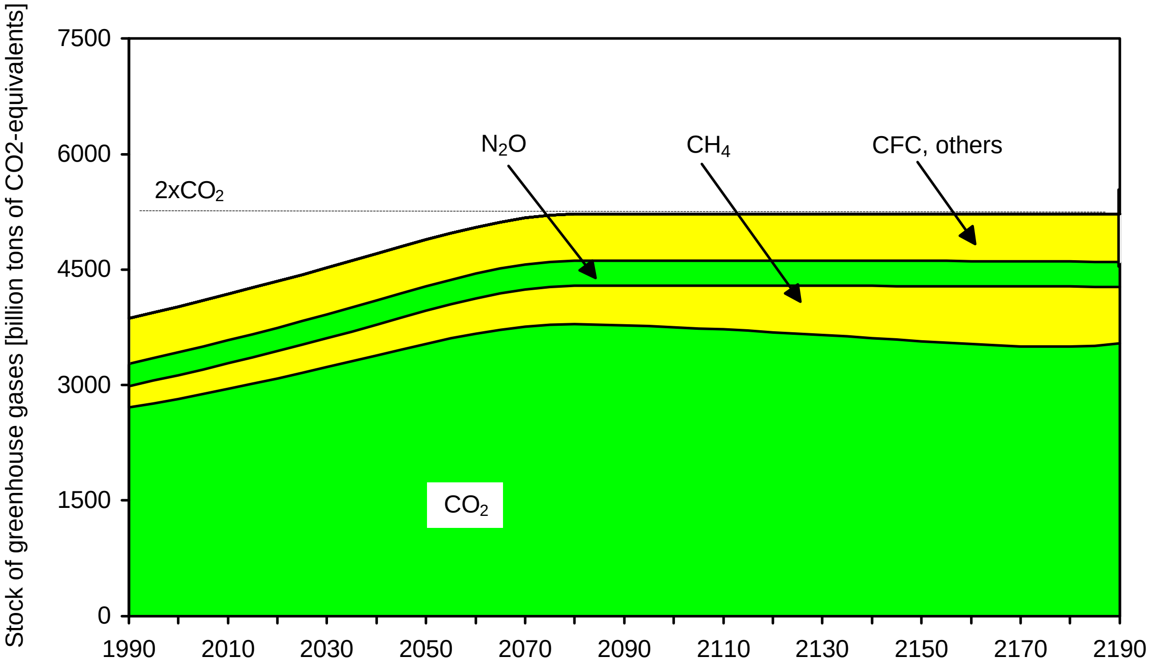


Figure 1. Stock of greenhouse gases along the „business as usual“-path (upper panel) and along the efficent time path (lower panel).

As already mentioned in Section 2, the efficient time path shown in the lower panel of Figure 1 can be divided into three subsequent phases. During the first 50 years, the constraint $s(t) \leq (1+\gamma)s(t-1)$ is binding and the stock s(t) grows with the maximum permissible rate of 4 % per decade. Hence, at the beginning of the time horizon economic efficiency and ecological stability cannot be brought into line: In order to avoid the risk of a breakdown of vulnerable ecosystems, the accumulation of greenhouse gases has to be slowed down compared to an unrestricted path purely driven by dynamic efficiency. During the next 40 years, none of the two constraints is binding and the system evolves as predicted by the modified Hotelling-rule [7a] and [7b]. Finally, with the beginning of 2080, the maximum permissible stock s° is reached. Consequently, even with moderate discounting of only 3 %, the existence of comparatively large natural disintegration capacities justifies a policy that exhausts the available „greenhouse budget“ within the first 90 years, such that after 2080 emissions have to be reduced to the level natural disintegration.

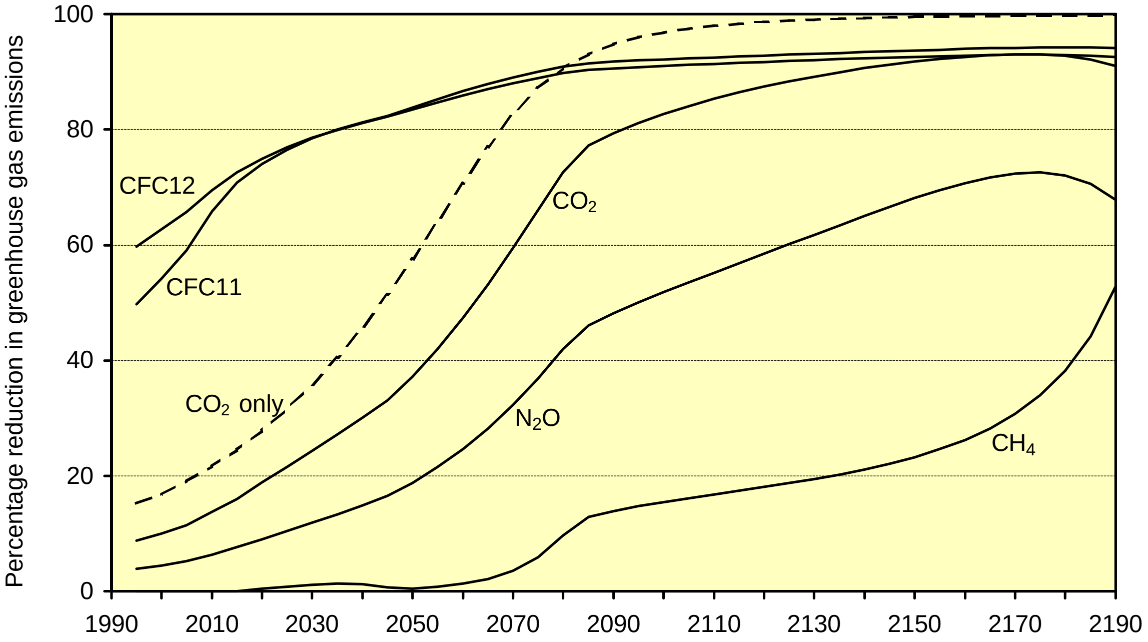


Figure 2. Percentage reduction in greenhouse gases compared to basic emission levels $\bar{e}_i(t)$.

Figure 2 shows the percentage reduction in greenhouse gases compared to the basic emission levels $\hat{e}_i(t)$ along the efficient time path. Additionally, the dashed line marked by „CO_2 only“ indicates the cost minimising reduction in carbon dioxide which would result under a piecemeal approach limited to the control of CO_2-emissions.[14] Concerning CFCs, the model predicts reduction rates that start that at 50-60 % and converge to a final level of about 92-94 %. These results suggest that an almost complete phasing out of CFCs - as laid down in the Montreal Protocol and its amendments - could already be justified by global warming without taking into account the additional damages caused to the earth's ozone layer. A second important implication of Figure 2 applies to the role of CH_4 and N_2O. Particularly during the second half of the time horizon, overall efficiency requires significant reductions in these two greenhouse gases. Hence, at the present stage of the analysis it cannot be ruled out that ignoring reduction possibilities related to CH_4 and N_2O could lead to an allocation far from efficiency.[15]

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[14] Note that the irregularities of the curves shown in Figure 2 are due to the transition between the different time phases as discussed in Section 2.

[15] The likely amount of excessive abatement cost caused by such an piecemeal approach is discussed below (see Figure 3).

The most striking implications of Figure 2, however, are related to CO_2. Even for the comprehensive approach, the percentage reduction in emissions starts at about 9 % and increases up to more than 90 % by the end of the time horizon. In the long term, these figures are much higher than the reduction targets of 20 or 25% presently discussed at the political level. Consequently, a reorientation towards the ecologically more ambitious aim of stabilising the atmospheric greenhouse gas concentration at a level which corresponds to an increase in global mean temperature of not more than 2.5°C would have a dramatic impact on today's greenhouse policies. In particular, reduction levels in the order of magnitude as indicated above are accompanied by correspondingly high marginal abatement cost which can also be interpreted as the tax rates that would be necessary to decentralise the efficient solution (e.g., Michaelis, 1992). The tax rate necessary to induce the required reductions in CO_2 emissions starts at about $ 3.5 per ton of CO_2 (or $ 13/t carbon, respectively) and gradually increases up to a maximum level of almost $ 150 per ton of CO_2 (or $ 560/ t carbon).

Furthermore, Figure 2 shows that a piecemeal approach limited to the control of carbon dioxide emissions would require considerably higher reduction rates. The respective time path marked by „CO_2 only“ starts at about 15 % and converges up to a final level of more than 99 %. Hence, switching from the comprehensive approach to the piecemeal approach increases the necessary reduction in CO_2 emissions by about 6 percentages at the beginning of the time horizon. This difference grows up to a maximum of more than 20 percentages in period from 2050 to 2080 and after this it gradually declines to about 9 percentages at the end of the time horizon. In evaluating this shift in abatement activities, it should be recognised that each *percentage* of reductions in CO_2 emissions involves some hundred million tons of CO_2 in absolute terms. Moreover, due to increasing marginal cost, even a comparatively small expansion of abatement effort starting from an *already high* abatement level may have considerable economic consequences. This is illustrated by Figure 3 which compares the present value of annual abatement cost under piecemeal assumptions and for the efficient approach. Summed up over the whole time horizon, excessive abatement cost induced by neglecting reduction possibilities concerning non-CO_2 gases amount to about 75 % compared to the efficient solution.

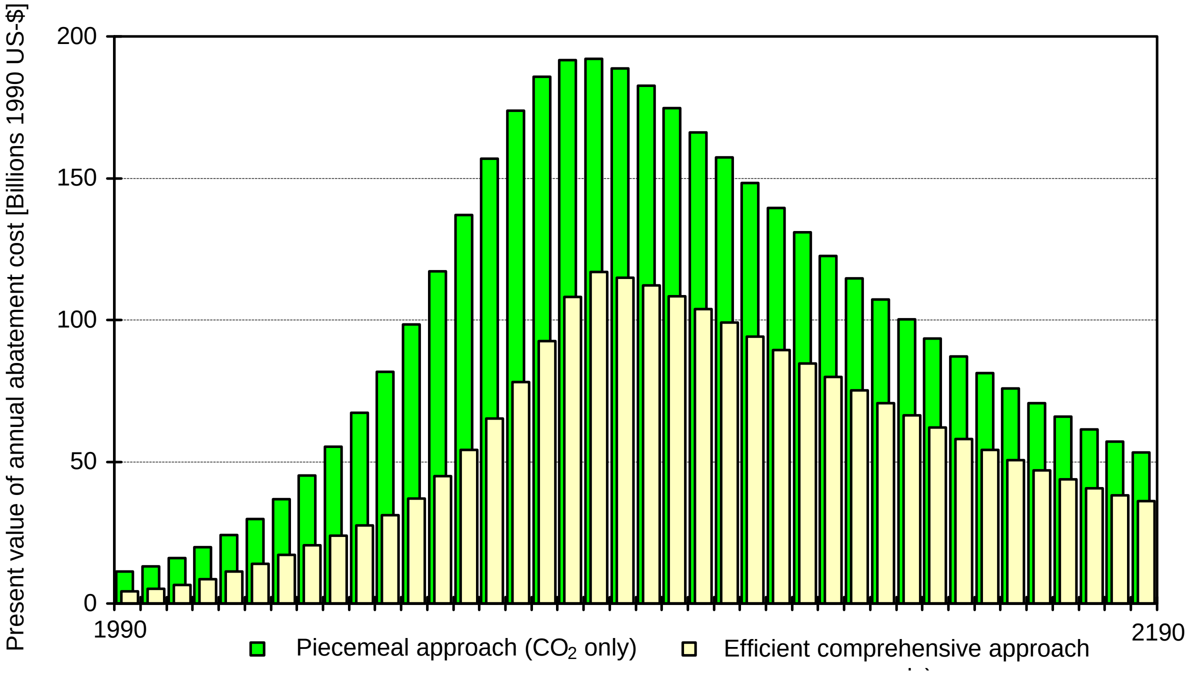

Figure 3. Present value of annual abatement cost (Billions of 1990 US-$).

Figure 3 confirms that a piecemeal approach limited to the reduction of CO_2 emissions would indeed lead to an allocation far from efficiency. However, it does not answer the question, *which* of the different non-CO_2 gases is responsible for these inefficiencies. To shed some light on this issue, some additional simulation runs have been calculated where only a part of the different gases are included into the control regime. The results of these calculations are summarised in Table 3 which shows the percentage increase in the present value of total abatement cost compared to the efficient solution that tackles *all* gases simultaneously. Table 3 reveals that the control of CFC-emissions is of crucial importance for efficient greenhouse policies whereas the impact of CH_4 and N_2O is only of minor importance: Excessive abatement cost caused by neglecting reduction possibilities concerning CH_4 and N_2O are only in the order of magnitude of 0.4 to 2.6 %, whereas the extra cost induced by a policy that does not controll CFC-emissions are at least ten to twenty times higher. The reasons for the minor importance of CH_4 and N_2O are different. Given the assumed cost paramters, the basic emissions of N_2O measured in terms of CO_2-equivalents are too low to have any significant impact on the above efficiency considerations. In contrast, the basic emissions of CH_4 measured in terms of CO_2-equivalents are more than twenty times higher but this effect is compensated by the comparatively low atmospheric lifetime of this gas.

	CFCs uncontrolled		CFCs controlled	
	CH_4 uncontrolled	CH_4 controlled	CH_4 uncontrolled	CH_4 controlled
N_2O uncontrolled	+ 75.6 %	+ 32.1 %	+ 2.6 %	+ 0.4 %
N_2O controlled	+ 62.2 %	+ 29.8 %	+ 1.2 %	+ 0.0 %

Table 3. Percentage increase in total abatement cost compared to the comprehensive solution.

The figures shown in Table 3 suggest that efficient greenhouse policies should concentrate on the control of CO_2 and CFCs because the additional efficiency gains which could be achieved by an inclusion of CH_4 and N_2O are most probably too small compared to the additional transaction cost caused by appropriate measures for the control of these gases.[16] This result, however, crucially depends on the cost parameters used for calculating the efficient solution. Assuming lower abatement cost for CH_4 and N_2O the model predicts higher reduction rates for these two gases that are accompanied by lower reduc-

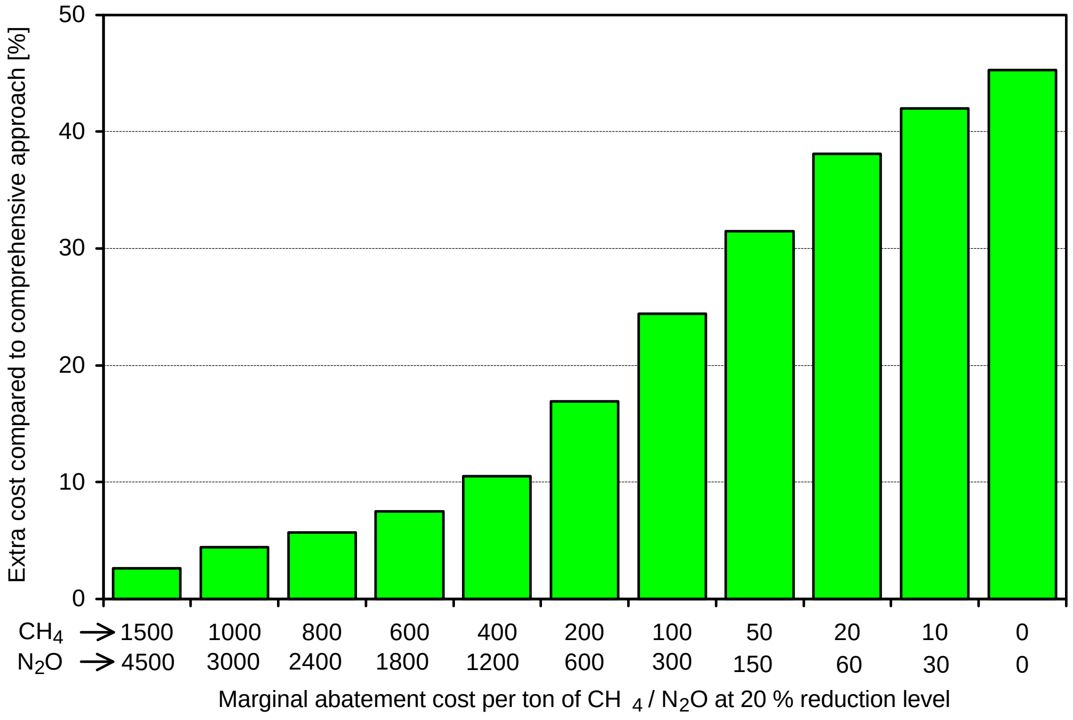

Figure 4. Excessive cost of a CO_2/CFC-policy compared to the comprehensive solution.

tion rates for the other gases. Consequently, the *lower* are the abatement cost for CH_4 and N_2O the *higher* are the losses in efficiency caused by a policy approach that does not include these two gases. Figure 4 shows how the (relative) amount of excessive abatement cost caused by a policy that relies only on the reduction of CO_2 and CFCs evolves if one gradually lowers marginal cost for the reduction for CH_4 and N_2O. These results indicate that the inefficiency of a CO_2/CFC-policy compared to the comprehensive approach does not exceed 10 to 12 % if marginal cost for CH_4 and N_2O are lowered by a factor of 3 or 4. However, if marginal cost for CH_4 and N_2O fall short of this limit, the inefficiency of a CO_2/CFC-policy increases considerably. For the extreme case of zero cost the model predicts an excessive burden in the order of magnitude of about 45 % compared to the efficient solution.[17] The policy implications of this sensitivity analysis are ambiguous. On the one hand, the above recommendation to concentrate on reducing the emissions of CO_2 and CFCs seems to be justified for a comparatively wide range of reasonable cost parameters. On the other hand, however, for sufficiently low abatement cost concerning CH_4 and N_2O it cannot be ruled out that neglecting these gases would lead to significant losses in efficiency. Hence, there is a strong need for further research that aims at generating reliable information on abatement cost for CH_4 and N_2O.

5. Summary and Conclusion

The present study has investigated the economic implications of sustainable greenhouse policies that strive to stabilise the atmospheric concentration of greenhouse gases at an ecologically determined threshold level that restricts the rise in global mean temperature to about 2.5°C compared to preindustrial times. In a theoretical optimisation model, conditions for an efficient allocation of abatement effort among pollutants and over time have been derived. In order to calculate efficient time paths of greenhouse gas control together

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[16] This is particularly true for CH_4 the control of which is complicated by the huge amount of different emission sources which have to be considered (see Section 3).

[17] Of course, assuming zero cost for reducing CH_4- and N_2O-emissions would be totally unrealistic. However, the above figure of excessive cost of about 45 % is nevertheless interesting because it indicates the upper bound of possible inefficiency.

with the corresponding cost figures, the model has been empirically specified and adapted to a dynamic GAMS-algorithm that covers the period of 1990 to 2190. Given the input data and cost parameters assumed in the base run simulations, the model predicts that the stabilisation target will be reached by the year 2080 such that for the remaining time horizon emissions have to be reduced to the level of natural degradation. The present value of total abatement cost associated with this stabilisation policy is estimated to range from about $ 5 billion p.a. at the beginning of the time horizon up to a maximum level of about $ 115 billion p.a. in the period of 2085 to 2090.

These cost figures, however, are derived from an efficient policy approach that tackles all major greenhouse gases simultaneously. In contrast to this, today's greenhouse policies are usually restricted to limiting CO_2-emissions. For such a piecemeal approach the model predicts additional abatement cost that sum up to about 75 % compared to the efficient solution. By various simulation runs it has been shown that the vast majority of this inefficiencies can be traced back to the uncontrolled growth in CFC-emissions. Therefore, including CFCs into a comprehensive control regime for greehouse gases considerably reduces overall abatement. In particular, the results of the simulation runs suggest that an almost complete phasing out of CFCs - as laid down in the Montreal Protocol and its amendments - could already be justified by global warming considerations without taking into account the additional damages caused to the earth's ozone layer. By the same token these results show that the future cost associated with greenhouse policies crucially depend on the success of related policy measures that aim at preventing the ozone layer by reducing CFC-emissions.

Concerning CH_4 and N_2O the policy implications of the above calculations are more ambiguous. For the estimates of marginal abatement cost used in the base run simulations the model predicts that excessive abatement cost caused by neglecting these gases are less than 3 % compared to the efficient solution. From this result it could be concluded that efficient greenhouse policies should concentrate CO_2 and CFCs since an additional inclusion of CH_4 and N_2O would yield only insignificant efficiency gains. The above percentage of excessive cost, however, turned out to be highly sensitive with respect to changes in the assumed figures for marginal abatement cost concerning CH_4 and N_2O. Since these figures are subject to considerable uncertainty the question whether CH_4 and N_2O should be included into a comprehensive policy approach can not be answered definitely. In particular, for sufficiently low abatement cost concerning CH_4 and N_2O it cannot be ruled out that neglecting these gases would lead to significant losses in efficiency. Hence, the only thing that can be concluded with certainty is that there exist a strong need for further research that aims at generating reliable information on abatement cost for CH_4 and N_2O.

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