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Stabilising the global greenhouse: A simulation model

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December 1993

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Abstract. This paper investigates the economic implications of a comprehensive approach to greenhouse policies that strives to stabilise the atmospheric concentration of 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 the period of 1990 to 2110, the economics of greenhouse gas accumulation are explored. In particular, the long-run cost associated with the above stabilisation target are evaluated for three different policy scenarios: i) a comprehensive approach that covers all major greenhouse gases simultaneously, ii) a piecemeal approach that is limited to reducing CO_2 emissions, and iii) a ten-year moratorium that postpones abatement effort until new scientific evidence on the greenhouse effect will become available. Comparing the simulation results suggests that a piecemeal approach would considerably increase total cost, whereas a ten-year moratorium might be reasonable even if the probability of 'good news' is comparatively small.

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 the concept of long-term risk management as recommended by the UNEP Advisory Group on Greenhouse Gases (see Swart/Hootmans, 1991). This approach aims at defining short-term emission targets on the basis of 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.[2] However, there is no reason to believe that a CO_2-policy alone will ensure efficiency in terms of overall abatement cost because several other trace gases also contribute to global warming (mainly methane, nitrous oxide, chlorofluorocarbons and tropospheric ozone). Hence, in order to pursue a given stabilisation target, it may be less costly to refrain in part from the required CO_2-

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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 recognizes 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).

2 So far, only few authors have focused on a comprehensive approach that treats all greenhouse gases simultaneously: Victor (1991), Swart (1992) and Mohr et al. (1992) discuss practical issues associated with a comprehensive approach like, e.g., the choice of policy instruments and monitoring requirements. Nordhaus (1991) estimates cost curves for slowing climate change that cover reduction measures aiming at both carbon dioxide and chlorofluorocarbons. Michaelis (1992a, 1992b) employs a dynamic optimisation model to derive conditions for an efficient allocation of abatement effort among greenhouse gases. Finally, Reilly/Richards (1993) construct a 'damage index' that incorporates climatic as well as non-climatic effects.

reduction and to reduce the emissions of, e.g., methane by an amount which is equivalent in terms of the prevented greenhouse effect.

In the present paper, the theoretical and empirical implications of such a comprehensive approach to stabilising the global greenhouse will be explored. In particular, a dynamic GAMS-algorithm will be used to calculate efficient time paths of greenhouse gas control together with the corresponding cost figures. In Sections 1 and 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 through 6, empirical simulation results for different policy scenarios are reported, and in Section 7, the paper is completed by some policy conclusions.

1. The Model

The starting point of the present analysis is a generalised version of a model originally developed in Michaelis (1992a): Assume there exist n greenhouse gases G_i ($i=1,2,...,n$), the specific greenhouse warming potentials of which are indicated by α_i.[3] Let $\hat{e}_i(t)$ denote 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, i.e. $\hat{e}_i(t)= (1+g_i)^t\hat{e}_i$. Hence, the amount of G_i actually emitted in period t, $e_i(t)$, is given by:

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

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. For simplification, it is assumed that these processes can be described by constant disintegration rates q_i ($0<q_i\leq 1$) such that the change in stock between two periods t and t+1 can be characterised 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

[3] The greenhouse warming potentials employed above indicate the amount of CO_2 that is equivalent to one unit of G_i in terms of the *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.

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):

$$s(t) = s[v_1(1),\ldots,v_n(t)] = \sum_{i=1}^{n}\alpha_i(1-q_i)^t s_i(0) + \sum_{\tau=1}^{t}\sum_{i=1}^{n}\alpha_i(1-q_i)^{t-\tau}\left[(1+g_i)^\tau \hat{e}_i - v_i(\tau)\right]. \quad (3)$$

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).[4] Moreover, the ecosystem's capability to adapt to global warming is restricted to a certain maximum rise in mean temperature compared to preindustrial levels (e.g., Swart/ Hootmans, 1991). Hence, it is assumed that s(t) is not allowed to exceed an exogenously given limit of s° units that corresponds to the maximum permissible increase in temperature. 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.).[5] Consequently, it is assumed that s(t) has to satisfy the additional constraint $s(t) \leq (1+\gamma)s(t-1)$, where γ indicates the maximum permissible rate of growth in stock s(t).[6] In Section 4, both constraints on s(t) will be quantified using the well-known relationship between radiative forcing, climate feedback and global warming (see, e.g., Cline, 1992).

Finally, the economics of greenhouse gas control are characterised by n abatement cost functions $(1+\delta_i)^{1-t}c_i[v_i(t)]$, where $\delta_i \geq 0$ indicates the rate of technical progress in pollution control, and $c_i[v_i(t)]$ is assumed to exhibit the usual properties:

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

3. Derivation of the Efficient Solution

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 minimize the present value of aggre-

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

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

[6] An alternative (less demanding) way to cope with this problem is to fix an exogenously determined target path $s(t)=s^*(t)$ that is assumed to satisfy both constraints (see Michaelis, 1992b).

gated abatement cost subject to $s(t) \leq s^\circ$ and $s(t) \leq (1+\gamma)s(t-1)$.[7] Denoting the discount rate by r and differentiating the corresponding Lagrangean,

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

yields the following first order conditions, where an interior solution with $0<v_i(t)<\hat{e}_i(t)$ is guaranteed by (4):

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

Here, the Lagrangean multipliers $\sigma(t)$ and $\mu(t)$ satisfy the Kuhn-Tucker Theorem:

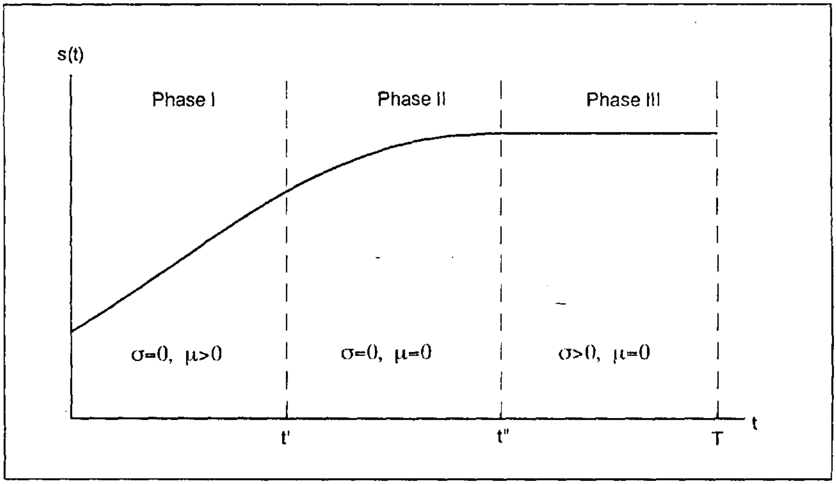
$$\sigma(t) \cdot [s^\circ - s(t)] = 0 \quad \text{and} \quad \mu(t) \cdot [(1+\gamma)s(t-1) - s(t)] = 0. \qquad (6)$$

The interaction of these two multipliers governs the development of s(t) along the optimal time path. Four points should be noted. First, the shadow price $\mu(t)$ is decreasing (or non-increasing, respectively) in the course of time because neglecting the accompanying constraint $s(t) \leq (1+\gamma)s(t-1)$ would lead to a concave time path of s(t). Hence, denoting the period when approaches zero by t', we observe $\mu(t)=0$ for t=t', t'+1, ..., T. Second, due to natural disintegration, it can not be ruled out that s° might be reached *before* period T is reached. A subsequent drop in stock, however, cannot be cost minimising. Hence, denoting the period when s° is reached by t", we observe $\lambda(t)>0$ for t=t", t"+1, t"+2, ..., T. Third, according to the Kuhn-Tucker conditions (6) $\mu(t)>0$ implies $\sigma(t-1)=0$ and $\sigma(t)>0$ implies $\mu(t+1)=0$ sucht that t'≤t". Fourth, there may exist a number of subsequent periods where neither $s(t) \leq (1+\gamma)s(t-1)$ nor $s(t) \leq s^\circ$ are binding, i.e. $\mu(t)=\sigma(t)=0$

Combining together the above results indicates that the optimal time path of s(t) can be divided into three subsequent phases that are distinguished by the respective signs of the Lagrangean multipliers (see Figure 1): During Phase I (t=1,2,..,t'-1), the final stock s° is not yet reached but the constraint $s(t) \leq (1+\gamma)s(t-1)$ 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 Phase II (t=t',t'+1,...,t"-1), none of the two constraints is binding (i.e. $\sigma(t)=\mu(t)=0$)and the accumulation of greenhouse gases is purely governed by dynamic efficiency. During Phase III (t=t",t"+1,t"+2,...T), the final level s° is reached and the remaining greenhouse gas emissions have to be reduced to the level of natural degradation (i.e. $\sigma(t)>0$ and $\mu(t)=0$).

[7] From a theoretical point of view, assuming a finite time horizon can be justified if T is sufficiently large concerning the problem under consideration. The time horizon used in the simulation runs will cover the period of 1990 to 2110, i.e. 120 years (see Section 4).

Figure 1. Optimal Accumulation of Greenhouse Gases.



The actual partitioning of the time horizon - i.e. the location of t' and t'' - 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 Phases I and III and diminishsPhase II. Two polar extremes can be distinguished. For a sufficiently high r, Phase II may completely vanish such that the stock s(t) grows with the maximum permissible rate γ until the final level s° is reached. For a sufficiently low r, the constraint $s(t) \leq (1+\gamma)s(t-1)$ may never bind and s° may be reached just in T such that Phase II 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 $\mu(t)=0$ for t=1, .., T and $\sigma(t)=0$ for t=1,...,T-1, (5) reduces to: $((1+r)(1+\delta_i))^{1-t}\partial c_i(t)/\partial v_i(t) = \sigma(T)\alpha_i(1-q_i)^{T-t}$. This leads to 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 $\{t, t+1\}$:

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

$$\frac{\partial c_i(t+1)/\partial v_i(t+1)}{\partial c_i(t)/\partial v_i(t)} = \frac{(1+r)(1+\delta_i)}{(1-q_i)}. \tag{8}$$

The interpretation of this special case is straightforward (see Michaelis, 1992a): Condition (7) indicates the efficient combination of abatement activities within each period, i.e. the static optimum, and (8) describes the movement of the system over time, i.e. the dynamic efficiency conditions. According to (7) abatement activities have to be combined in such a way that the ratio of marginal abatement cost (corrected for technical progress) equals the ratio of the greenhouse coefficients multiplied by the weighted ratio of the respective disintegration rates.[8] 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 (8) which indicates that marginal abatement cost increase over time with the rate $[(1+r)(1+\delta_i)]/(1-q_i)$.

These results, however, are only valid for the pure Hotelling-case with $\mu(t)=0$ for $t=1,..,T$ and $\sigma(t)=0$ for $t=1,...,T-1$. In the general case, the properties of the efficient time path are less obvious, but it is possible to identify in which direction the general solution deviates from the pure Hotelling case. The generalised versions of (7) and (8) are given by:

$$\frac{\partial c_i(t)/\partial v_i(t)}{\partial c_j(t)/\partial v_j(t)} = \Psi_{ij}(t)\frac{\alpha_i}{\alpha_j}\left[\frac{1-q_i}{1-q_j}\right]^{T-t}\left[\frac{1+\delta_i}{1+\delta_j}\right]^{t-1}, \tag{7'}$$

$$\frac{\partial c_i(t+1)/\partial v_i(t+1)}{\partial c_i(t)/\partial v_i(t)} = \left[1-\Omega_i(t)\right]\frac{(1+r)(1+\delta_i)}{(1-q_i)}, \tag{8'}$$

where the newly added terms $\Psi_{ij}(t)$ and $\Omega_i(t)$ are defined as follows:

$$\Psi_{ij}(t) := \sum_{\tau=t}^{T}[\sigma(\tau)-\mu(\tau)+(1+\gamma)\mu(\tau+1)](1-q_i)^{\tau-T} \Big/ \sum_{\tau=t}^{T}[\sigma(\tau)-\mu(\tau)+(1+\gamma)\mu(\tau+1)](1-q_j)^{\tau-T},$$

$$\Omega_i(t) := \sigma(t)-\mu(t)+(1+\gamma)\mu(t+1) \Big/ \sum_{\tau=t}^{T}[\sigma(\tau)-\mu(\tau)+(1+\gamma)\mu(\tau+1)](1-q_i)^{\tau-t}.$$

Assuming $q_i>q_j$, the above definition of $\Psi_{ij}(t)$ implies $\Psi_{ij}(t)\geq 1$ where the strict inequality holds for $t=1,2,...,T-1$. Hence, compared to the pure Hotelling case, the ratio between marginal abatement cost of G_i and G_j increases, i.e. one observes a shift in abatement ac-

[8] In the special case of equal disintegration rates condition (7) 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).

tivities towards greenhouse gases with comparatively high disintegration rates. Recalling the impact of the discount rate discussed above, this result does not come as a surprise. In contrast to the always positive $\Psi_{ij}(t)$, the sign of $\Omega_i(t)$ depends on t:

1. For Phase I ($1 \leq t < t'$) with $\sigma(t)=0$ and $\mu(t)>0$ only little can be said about the behaviour of $\Omega_i(t)$. Due to $\mu(t+1)<\mu(t)$ the numerator of $\Omega_i(t)$ is likely to become negative for a sufficiently small γ. The sign of the denominator, however, can not readily be determined such that $\Omega_i(t)$ may be either positive or negative. Hence, compared to the pure Hotelling case the increase in marginal abatement cost between t and t+1 may be either slowed down or accelerated.
2. For Phase II ($t' \leq t \leq t''-1$), $\sigma(t)=\mu(t)=\bar{0}$ implies $\Omega_i(t)=0$. Consequently, marginal abatement cost evolve according to the pure Hotelling case as described by (8).
3. For Phase III ($t'' \leq t \leq T$), $\sigma(t)>0$ and $\mu(t)=0$ implies $0<\Omega_i(t)\leq 1$ where the strict inequality holds for all t except t=T. Hence, the increase in marginal abatement cost between t and t+1 is slowed down compared to the pure Hotelling case. It even cannot be ruled out that marginal abatement cost decline over time.

All these effects can be found in the simulation results that will be presented in the subsequent sections.

3. A Simulation Approach

Two sets of information 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, and second, an appropriate specification of abatement cost functions, of the discount rate and of 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 will be restricted to the five major greenhouse gases which together contribute about 90% to the man-made greenhouse effect: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and the chlorofluorocarbons CFC11 and CFC12.[9] The 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

[9] Tropospheric ozone (O_3), which also contributes significantly to global warming, cannot readily be included into the simulation model because O_3 is not directly emitted from anthropogenic sources. Instead, O_3 is created by highly complex and non-linear atmospheric processes that involve nitrogen oxides, methane, carbon monoxide and other trace gases.

Table 1. Basic Data on Greenhouse Gases.

	CO_2 (i=1)	CH_4 (i=2)	N_2O (i=3)	CFC11 (i=4)	CFC12 (i=5)
Greenhouse warming potential α_i	1	58	206	3,970	5,750
Atmospheric lifetime c_i [years]	180	10	140	65	130
Disintegration rate q_i	0.0055	0.0952	0.0071	0.0153	0.0077
Initial stock $s_i(0)$ [10^6 tons]	2,752,500	4,900	2,350	2.17	3.75
Basic emissions $\hat{e}_i(0)$ [10^6 tons]	28,901	503.2	22.6	0.12	0.07
Growth in basic emissions γ_i	0.011	0.002	0.006	0.005	0.005

Source: IPCC (1990); Enquete (1990, 1992); own calculations.

IPCC, 1990). The second line shows the gases' atmospheric lifetimes c_i that have been used to calculate the disintegration rates q_i indicated in the third line of Table 1.[10] The fourth line shows the initial stocks of greenhouse gases in the earth's atmosphere 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). 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 0.5% per year under status quo-conditions, i.e. without the provisions of the *Montreal Protocol on Substances that Deplete the Ozone Layer* (see, e.g., Markandya, 1991).

According to the UNEP Advisory Group on Greenhouse Gases, two temperature targets have to be pursued in order to "*...limit the risk of rapid, unpredictable, and non-linear responses that could lead to extensive ecosystem damages*": First, the absolute rise in global mean temperature should not exceed 1-2°C above preindustrial levels; and second, the rate of change in temperature should not exceed 0.1°C per decade (see Swart/Hootsmans,

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[10] As shown in Michaelis (1992a), 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 180 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.

1991, p.131). To translate these targets into the model's constraint, the well known relationship between global mean temperature and greenhouse gas concentrations can be used (see, e.g., Cline, 1992):

$$\Delta T = 6.3\lambda\beta \ln(C/C_0). \tag{9}$$

Here, ΔT is the increase in global mean temperature compared to preindustrial levels (in °C), λ and β are climate parameters, and C/C_0 indicates the ratio between the actual atmospheric concentration of greenhouse gases and the respective preindustrial concentration (both figures measured in terms of CO_2-equivalents). Assuming an absolute temperature target of $\Delta T \leq 1.5$°C, equation (9) can be reformulated as: $C/C_0 \leq e^{0.254/\lambda\beta}$. Accounting for $\lambda=0.3$ and $\beta=1.9$ (see, e.g., Cline, 1992) this condition requires that the increase in the concentration of greenhouse gases compared to preindustrial levels should be limited to approximately 56.15%.[11] A large part of this global greenhouse budget, however, has already been used up. For 1990 - the model's base year - it can be calculated that the concentration of greenhouse gases was already about 35.2% above preindustrial levels (see Enquete, 1992). Hence, with 1990 as base year the further increase in the concentration of greenhouse gases has to be limited to about 15.5%. Since there exists a constant relationship between the stock of greenhouse gases and their atmospheric concentration this limitation implies for the above model that the stock s(t) should not exceed the upper bound of $1.155 \cdot s(0)$. Similarly, it can be calculated that the growth in s(t) should not exceed 2.8 % per decade in order to restrict the rate of change in global mean temperature to 0.1°C per decade. It should be stressed again, however, that all these figures are subject to considerable uncertainties. The same reservation applies to the cost data discussed in the following subsection.

Abatement Cost, Discount Rate and Time Horizon

A simple functional form of $c_i[v_i(t)]$ that satisfies all requirements formulated in (4) is given by:

$$c_i[v_i(t)] = \frac{a_i v_i(t)^2}{[\hat{e}_i(t) - v_i(t)]^{1/2}} . \tag{10}$$

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.

[11] Whereas the magnitude of $\lambda=0.3$ is a widely agreed figure, the magnitude of β, the so-called 'feedback multiplier', has caused considerable controversy. The estimates range from a lower bound of 1.1 to an upper bound of 3.4. According to Cline (1992), the figure employed above, 1.9, has to be viewed as the 'best guess' of β. Using instead the lower or upper bound of β would lead to $C/C_0 \leq 2.16$ or $C/C_0 \leq 1.28$, respectively.

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 coefficients a_i can be calculated from the first derivative of (10):

$$a_i = \frac{MC_i}{\left[0.2^{1/2}+0.02/0.8^{3/2}\right]\hat{e}_i(0)^{1/2}}. \tag{11}$$

In quantifying the magnitude of MC_i it should be recognised that the present model deals with *global* emissions such that (10) 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 (see Nordhaus, 1991). However, only about 80-85% of global CO_2 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 \$ 6 per ton of carbon. 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 \$ 30 at a 20% reduction level. Accounting for a conversion rate of 3.7 tons of CO_2 per ton of carbon implies marginal cost of about \$ 8 per ton of CO_2. The resulting marginal cost curve shown in Figure 2 is roughly in line with the "consensus" estimate calculated by Nordhaus (1991).

Concerning the other greenhouse gases under consideration, only sketchy information on abatement cost is available. In the case of CFCs, the *UNEP Economic Assessment Panel on Substances that Deplete the Ozone Layer* has estimated marginal substitution cost between 0 and 15 \$/kg for reduction levels up to 30% (see UNEP, 1989). Similar results have been obtained by Smith/Vodden (1990) within the framework of detailed cost engineering studies. Based on these findings and accounting for the likely impact of technical progress within the last few years it seems reasonable to assume that marginal abatement cost at a 20% reduction level amount to 5,000 \$ per ton of CFC.

According to the IPCC (1992), the use of nitrogen fertiliser has to be regarded as the main source of global anthropogenic N_2O emissions.[13] Empirical evidence suggests that an average of about 3.2% of the utilised nitrogen is converted into N_2O and emitted the to

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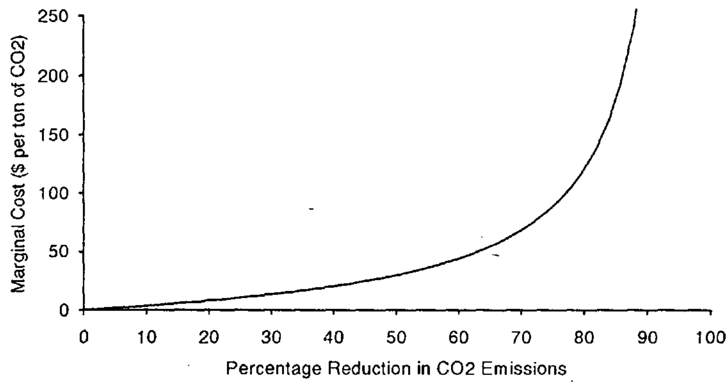
[12] It should carefully be noted that the use of *global* cost functions implies the assumption that it is possible to ensure an efficient international allocation of abatement activities by multilateral negotiations between the involved countries (see, e.g., Barrett, 1991; Stähler, 1993).

[13] Until the beginning of the nineties, it was falsely believed that also the combustion of fossil fuels is a significant source of nitrous oxide (see, e.g., Enquete, 1992).

Figure 2. Assumed Marginal Cost of CO_2 Reduction in t=1990 ($ per ton of CO_2).



Source: Own calculations based on Table 2 and equation (10).

atmosphere (ibd).[14] Accounting for the relative molecular mass of nitrogen and oxygen leads to an average emission coefficient of about 0.05 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 20 tons. Assuming that prices remain unchanged, the social cost of reducing nitrogen input can be approximated by the farmers' loss in income corrected for possible subsidies. For example, in West Germany the annual input of nitrogen amounts to about 1,500,000 tons at a price of $ 650 per ton (see Statistisches Bundesamt, 1991). Assuming 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 (see Andréasson, 1989), marginal loss in income at a 20% reduction level amounts to $ 260 per ton of nitrogen or $ 5,200 per ton of N_2O, respectively. This figure, however, is only a rough guess. On the one hand, it may overestimate the true social cost of reducing nitrogen consumption since it is not corrected for subsidies. But on the other hand, from a *global* point of view it may underestimate social cost because the above calculation can not readily be applied to the developing countries of the southern hemisphere. In view of these uncertainties, it seems reasonable to assume marginal cost of $ 8,000 per of N_2O in the base run and to calculate additionally a low-cost and a high-cost scenario with $ 4,000 and $ 12,000 respectively.

[14] This figure includes also the indirect effects caused by leaching of nitrogen into ground water.

Table 2. Assumed Marginal Cost at 20% Reduction Level ($/ton of Greenhouse Gas).

	CO_2	CH_4	N_2O	CFC11	CFC12
Low-cost scenario	8	2,000	4,000	5,000	5,000
Base run scenario	8	6,000	8,000	5,000	5,000
High-cost scenario	8	10,000	12,000	5,000	5,000

Source: Cline (1992); Nordhaus (1991); own calculations.

In the case of methane, the variety of emission sources makes any cost estimate very difficult. Six different economic activities contribute significantly to global emissions (see, e.g., Enquete, 1992): Cultivation of rice, coal mining, landfill tipping, distribution of natural gas, deforestation and intensive livestock (ruminants). However, due to nutritional problems in many developing countries, reducing the cultivation of rice would involve tremendous opportunity cost. Similarly, installing capital-intensive gas insulation equipment at coal mines and landfills or overhauling leaky gas distribution systems can hardly be viewed as low-cost options for reducing CH_4 emissions. As a consequence, it seems reasonable to suppose that any least-cost strategy for reducing CH_4 emissions should first of all focus on limiting deforestation and intensive livestock. This assumption, however, implies a 'joint abatement'-problem since limiting deforestation has already been identified as a low-cost option for reducing anthropogenous CO_2 emissions.[15] In order to capture this effect it is assumed that the least-cost strategy for reducing CO_2 involves a strict ranking of policies: The first 10% in emission reductions are achieved solely by limiting deforestation, whereas further reductions are achieved by energy-related policies. Moreover, it is assumed that each percentage of CO_2 reduction via limiting deforestation yields as extra benefit another percentage of emission reduction in CH_4.[16] This implies that the origin of the abatement cost curve for CH_4 is shifted to the right, such that the first $\bar{p}$ percent of reductions are obtained at zero cost, where $\bar{p}$ equals the percentage reduction in CO_2 emissions up to the assumed limit of 10%.

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15 Energy-related policies for reducing CO_2 emissions may also have an impact on CH_4 emissions. These interdependencies, however, are neglected in the present analysis since their magnitude and even their direction is not clear: Whereas improvements in energy efficiency would probably lead to a decrease in CH_4 emissions from coal mining and gas distribution, it cannot be ruled out that switching from high-carbon fuels (coal, oil) to low-carbon fuels (natural gas) may lead to an increase in CH_4 emissions (see, e.g., Jackson, 1991).

16 Based on an average carbon content of 50 tons per hectare of mature tropical rain forest (see e.g., Brown, 1992) and assuming the emission factors estimated by Lobert et al. (1993), the burning of one hectar of rain forest leads to about 185 tons of CO_2 and 3 tons of CH_4. This ratio of 185:3 roughly equals the ratio of basic emission levels (see Table 1) such that reducing CO_2 emission by one percent via limiting deforestation implies that CH_4 emissions are also reduced by about one percent.

In addition to forestry policies, limiting intensive livestock is another low-cost option for reducing CH_4 emissions.[17] Among all ruminants, milk cows exhibit by far the highest 'emission coefficient' - about 0.1 tons of CH_4 per year and cow (see, e.g., Sauerbeck/ Brunnert, 1990). In a perfectly competitive environment, the social cost 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 most countries the market for milk is regulated by quotas and price floors such that there is considerable scope for reducing the number of milk cows without significantly increasing milk prices. Hence up to a certain degree social cost can be approximated solely by the farmers' loss in income. For example, in West Germany the farmers' average net income from milk production amounts to about \$ 600 per cow and year or \$ 6,000 per ton of CH_4, respectively (see Bundesregierung, 1992). For several reasons, however, this figure is only a very crude guess of abatement cost. First, it includes a certain amount of indirect subsidies caused by the regulations mentioned. Second, it indicates *average* and not *marginal* cost as required by equation (11). And third, it applies only to *milk cows* but not to other types of ruminants that exhibit smaller emission coefficients and consequently higher unit cost. Therefore, the base run which assumes marginal cost of \$ 6,000 per ton of CH_4 is supplemented by a low-cost scenario and a high-cost scenario which assume marginal cost of \$ 2,000 and \$ 10,000, respectively (see Table 2).

The coefficients a_i derived from (11) establish the *initial* position of the abatement cost curves, whereas the likely impact of technical progress is captured by the shift parameters δ_i (see Section 2). Empirical estimates on the long-run development of abatement cost are not available, but it seems reasonable to adopt a not too optimistic view of the future cost saving potentials. Therefore, technical progress is assumed to diminish abatement cost of CO_2 by 0.25% per year (i.e. $\delta_1 = 0.0025$). Concerning CFCs higher (but still moderate) shift parameters $\delta_4=\delta_5=0.005$ are employed, and for N_2O and CH_4 no cost saving progress at all is assumed (i.e. $\delta_2=\delta_3=0$).

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 $r=3.5\%$. It should carefully be noted, however, that the impact of discounting is less dramatic in the

[17] Methane production per unit of livestock can hardly be influenced by measures like changes in feeding, and low-cost technologies to prevent the ruminants' digestive gases from escaping to the atmosphere are not available (see Sauerbeck/Brunnert, 1990). Consequently, the only practicable way to reduce emissions caused by livestock is a reduction in livestock itself.

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 120 years (1990 to 2110) 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 70 to 80 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: The Base Run Scenario

The main simulation results[18] for the base run scenario are summarised in Figures 3 to 6. Figure 3 shows the development of the total stock of greenhouse gases, s(t), along the efficient time path. Moreover, the dashed line marked as 'unrestricted path' indicates the development of s(t) that would result from cost minimisation *without* taking into account the additional constraint $s(t) \leq (1+\gamma)s(t-1)$. Two conclusions can be drawn from this figure. Firstly, even with moderate discounting (r=3.5%), economic efficiency and ecological stability cannot be brought into line during the first decades (see 'Phase I'): In order to avoid the risk of a breakdown of vulnerable ecosystems, the accumulation of greenhouse gases has to be slowed down compared to the unrestricted path which is purely driven by dynamic efficiency. Secondly, the maximum permissible stock of greenhouse gases will already be reached in 2060, i.e. half a century before the end of the planning horizon is reached (see 'Phase III'). Hence, even with moderate discounting and only slow technical progress, the existence of comparatively large natural disintegration capacities justifies a policy that exhausts the remaining 'greenhouse budget' within the first 70 years, such that after 2060 emissions have to be reduced to the level of natural degradation.

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[18] All simulation runs have been calculated using the professional 2.05 version of GAMS-MINOS (see Brooke et al., 1988) on a VAX/VMS. 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.

Figure 3. Base Run Scenario: Accumulation of Greenhouse Gases.

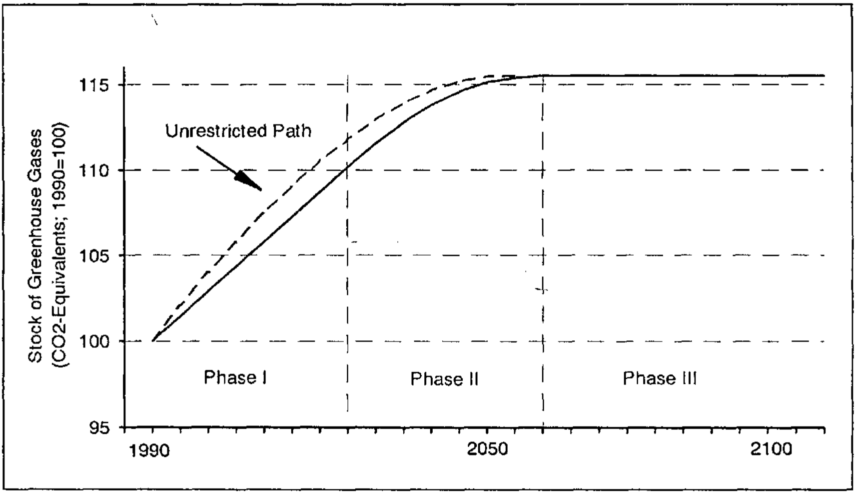

Figure 4 shows the percentage reduction in greenhouse gas emissions - i.e. the ratio between $v_i(t)$ and $\hat{e}_i(t)$ - along the efficient time path. Concerning CFCs the model predicts reduction rates that start that at 70-80% and converge to a final level of about 96-98%. These results suggest that an almost complete phasing out of CFCs - as laid down in the Montreal Protocol and its London amendments - could already be justified by global warming without taking into account the additional damages caused to the earth's ozone layer.[19] A second important implication of Figure 4 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.[20] Hence, a 'piecemeal approach' which ignores reduction possibilities related to CH_4 and N_2O could lead to an allocation far from efficiency. The possible amount of excessive abatement cost imposed on society by such an approach will be discussed in Section 5.

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[19] Recently, the role of CFCs has become subject to controversy because new scientific evidence indicates that their direct effect on global warming may partly be compensated by their ozone stripping impact (see Cline, 1992). To check the sensitivity of the above results, an additional run with ten times smaller warming potentials (α_4=397, α_5=575) has been calculated. The resulting reallocation of abatement effort, however, turned out to be only of minor significance: The long-term reduction in CFC11 (CFC12) decreases from 96% (98%) to 83% (88%), whereas the other reduction rates remain almost constant (see Figure A.7 in the Appendix).

[20] Note, however, that during the *first half* of the time horizon the percentage reduction in CH_4 emissions does not significantly exceed the zero cost (joint abatement) level of 10 %.

Figure 4. Base Run Scenario: Percentage Reduction in Greenhouse Gas Emissions.

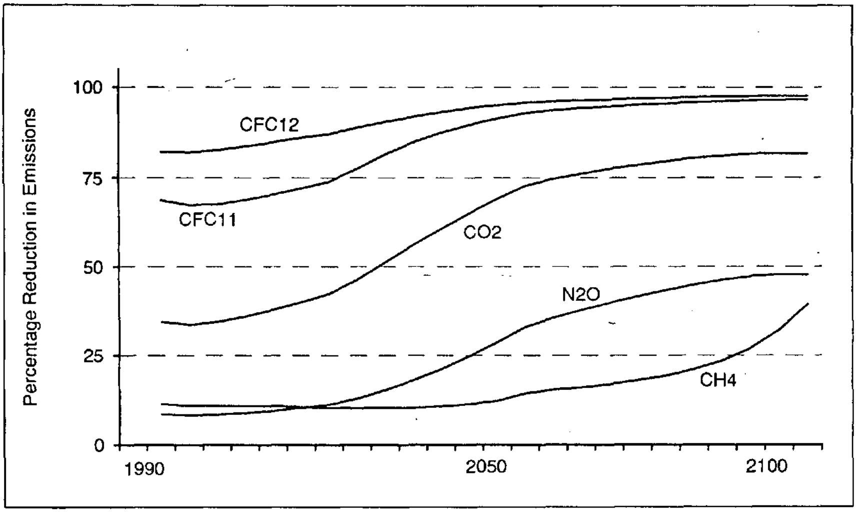
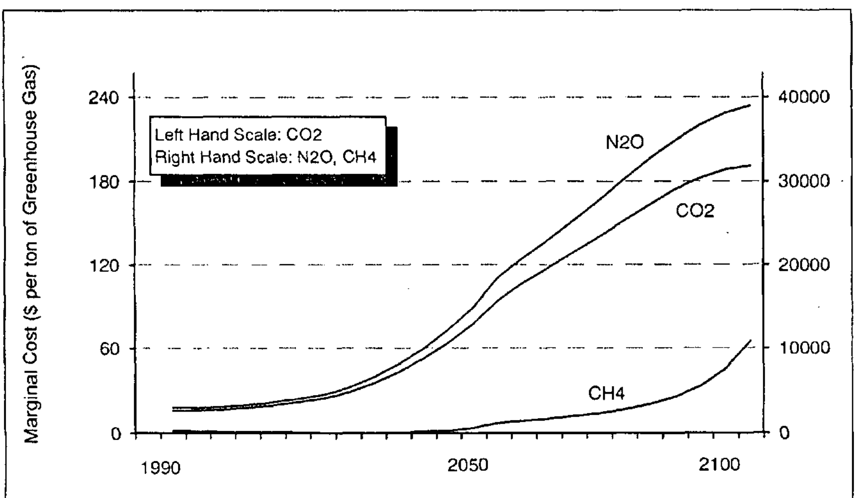


Figure 5. Base Run Scenario: Marginal Cost of Greenhouse Gas Reduction ($/ton).



The most striking implications of Figure 4, however, are related to CO_2. Here, the percentage reduction in emissions starts at 34.3 % and increases up to a final level of 81.5 % in 2110. These percentages are much higher than the reduction targets of 20 or 25% that are presently discussed at the political level (see, e.g., Schmidt, 1992). Consequently, a reorientation towards the ecologically more ambitious stabilisation approach 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. Figure 5 shows the development of marginal cost concerning CO_2, CH_4 and N_2O calculated in terms of $ per ton of gas.[21] These figures can also be interpreted as the tax rates that would be necessary to decentralise the efficient solution (see Michaelis, 1992a). Hence, the tax rate necessary to induce the required reductions in CO_2 emissions starts at about $ 16 per ton of CO_2 (or $ 60/t carbon, respectively) and gradually increases up to a final level of almost $ 190 per ton of CO_2. In order to give a first clue to the likely impact of a such a tax, it may be noted that the initial rate of $ 16/ton CO_2 would increase the current U.S. coal prices by a factor of about 2½.

As pointed out in Section 3, however, the present analysis relies on cost data concerning CH_4 and N_2O that are highly uncertain. Hence, it might be asked how the above results will change when switching to one of the other cost scenarios shown in Table 2. The consequences of such an alteration are clear in principle: Switching to the low cost (high cost) scenario leads to an reallocation in abatement effort that 1) accelerates (slows down) the percentage reduction in CH_4 and N_2O emissions and 2) slows down (accelerates) the percentage reduction in CO_2 and CFC emissions. These reallocations, however, turned out to have only a moderate effect on the taxation of CO_2 (see Figures A.2 to A.5 in the Appendix): Switching to the high cost (low cost) scenario shifts the initial tax rate from $ 16 to $ 16.5 ($ 14.5) and the final tax rate from $ 190 to $ 210 ($ 155) per ton of CO_2.

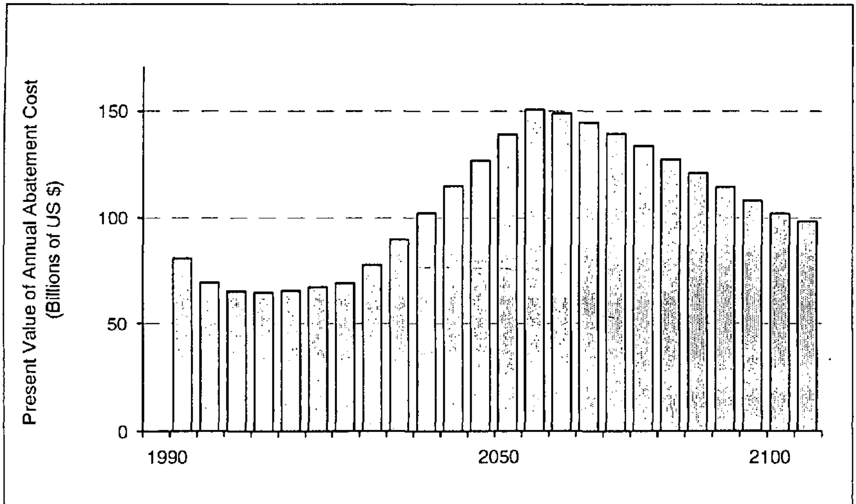
Finally, Figure 6 indicates that the present value of aggregated annual abatement cost[22] starts at a level of about $ 80 billion and gradually declines to about $ 65 billion at the beginning of the next century. Subsequently, annual cost rise to a maximum level of about $ 150 billion in 2060 and then start to decline again until a final level of about $ 100 billion is reached.[23] These cost figures are enormous in absolute terms, but they are

[21] For diagrammatic reasons the respective figures concerning CFCs are not shown above. Marginal cost start at about $ 40,000 ($ 85,000) and increase up to a final level of about $ 900,000 ($ 1,500,000) per ton of CFC11 (CFC12).

[22] The numbers above are averages of the respective five-year periods calculated by the model.

[23] The peak in cost is reached just when the stock of greenhouse gases reaches it's maximum. The subsequent decline of cost is due to a reallocation in abatement activities motivated by the closer coming end of the time horizon: The smaller the number of years ahead, the less important is the *long-term* impact of the different gases and the more long-lived gases will be emitted. Consequently, the percentage reduction ratios shown in Figure 3 imply decreasing emissions of CH_4 and increasing emissions of the other gases during the last decades.

Figure 6. Base Run Scenario: The Cost of Stabilising the Global Greenhouse.



not too dramatic compared to the total size of the world economy. Assuming an initial base-line world GNP of $ 22,500 billion (see World Bank, 1992) and a growth rate of 2% p.a., leads to the estimate that the cost of 'stabilising the global greenhouse' would start at about 0.36% of world GNP in 1990 and rise to a maximum of about 2.4% of world GNP in the year 2110.[24]

5. The Cost of a Piecemeal Approach

The above analysis was based on the assumption of a comprehensive policy approach that tackles all major greenhouse gases simultaneously. In contrast to this, today's greenhouse policies concentrate almost exclusively on CO_2 emissions. There are virtually no regulations aiming at CH_4 or N_2O, and the current regulations concerning CFCs are motivated solely by protecting the ozone layer. In order to quantify the possible amount of excessive abatement cost caused by such a piecemeal approach, an additional scenario based on the following two assumptions has been calculated: 1) The reductions in CFC emissions follow an exogenously determined 'Montreal Path' that is assumed to start at

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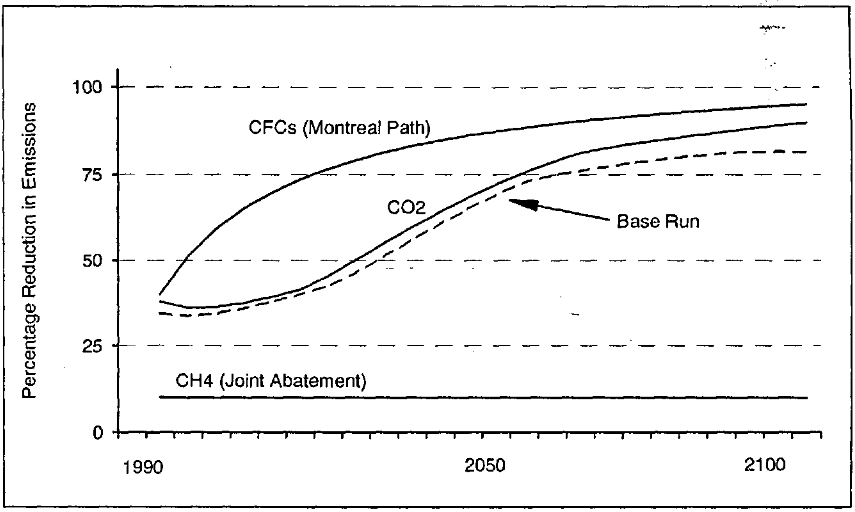
[24] The latter figure, of course, depends crucially on the employed growth rate of world GNP. Assuming a growth rate of only 1.5% increases the long-term cost of sustainable greenhouse policies from 2.4% to about 4.1 % of world GNP.

Figure 7. Piecemeal Approach: Percentage Reduction in Greenhouse Gas Emissions.



40% and to increase to a final level of 95%.[25] 2) The reductions in CH_4 emissions are restricted to the joint abatement level caused by CO_2 policies and N_2O emissions completely are unrestricted.

Figure 7 shows the resulting percentage reductions in greenhouse gas emissions. Additionally, the dashed line marked as 'base run' replicates the percentage reduction in CO_2 calculated for the comprehensive approach (compare Figure 4). Comparing the two time paths concerning CO_2 indicates that switching from the comprehensive to the piecemeal approach increases the reduction in CO_2 emissions by about 3 to 8.5 percentages. At first glance, this difference might appear surprisingly small. It should be recognised, however, 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, a comparatively small expansion of abatement effort starting from an *already high* abatement level may have considerable economic consequences. This is illustrated by Figure 8 which displays

[25] It should be noted that the quantification of a 'Montreal Path' is subject to considerable uncertainties (see, e.g., OTA, 1989). In particular, the number of countries that ultimately will ratify the protocol and the extent to which the parties will comply with the protocol is unknown yet. The above assumed time path implies a rather optimistic view of the Montreal Protocol. However, due to the small absolute contribution of CFCs to the total stock of greenhouse gases, a variation in the assumed time path has only minor impacts on the overall results.

Figure 8. Piecemeal Approach versus Comprehensive Approach: Marginal Cost of CO_2 Reduction (\$/ton of CO_2).

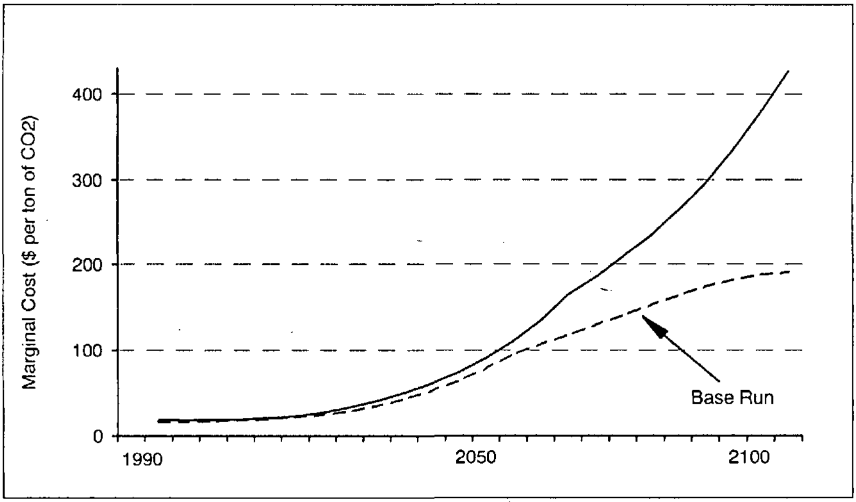
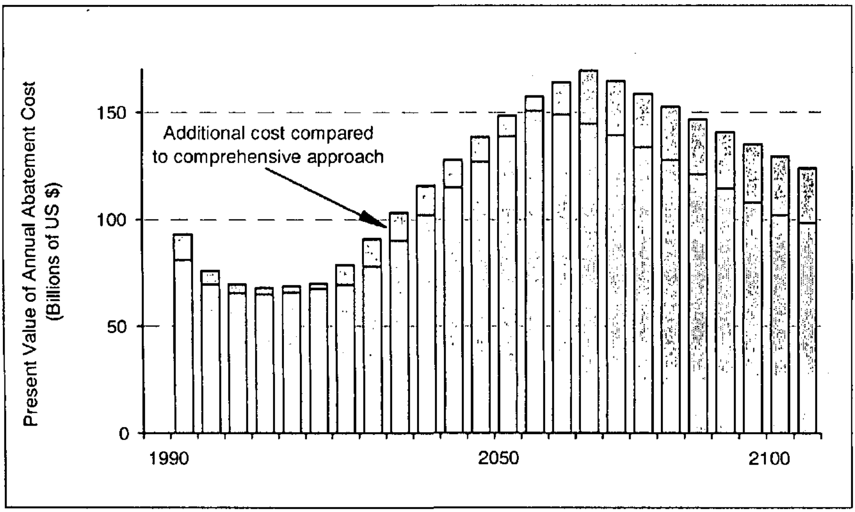


Figure 9. Piecemeal Approach versus Comprehensive Approach: Present Value of Annual Abatement Cost.



the development of marginal cost of CO_2 abatement along the two different time paths: Switching from the comprehensive to the piecemeal approach leads to a sharp increase in tax rates during the second half of the time horizon.

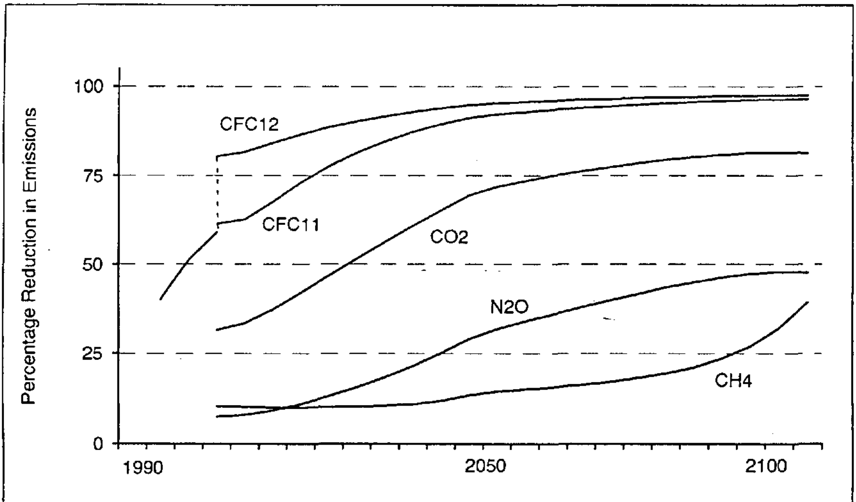
Figure 9 shows the present value of annual abatement cost under piecemeal assumptions, where the dark shaded areas indicate the *additional* cost compared to the comprehensive approach. Over the whole time horizon, the additional cost sum up to about $ 1,800 billion that equal 14,5% of the total cost implied by the comprehensive approach. These additional cost, however, are not evenly distributed over time. Instead, about ¾ of them ac-crue during the last 50 years. Hence, excessive abatement cost caused by the piecemeal approach may be of moderate size for the first decades. However, in the course of time they will grow up to a considerable burden on future generations.

Of course, the amount of excessive abatement cost indicating the relative inefficiency of the piecemeal approach depends crucially on the reference case that determines the efficient (comprehensive) solution. Here, the assumed cost of reducing CH_4 and N_2O emissions are of particular importance. The higher these cost, the lower are the losses in efficiency associated with the piecemeal approach. However, in an additional simulation run, it turned out that switching to the high cost scenario (see Table 2) decreases excessive cost only by about $ 400 billion, i.e. the remaining losses in efficiency still amount to about $ 1,400 billion (see Figure A.7 in the Appendix). This result suggests that even under favourable conditions - i.e. comparatively high abatement cost concerning CH_4 and N_2O - the piecemeal approach would lead to an allocation far from efficiency.

6. The Cost and Benefits of 'Waiting for Good News'

The analysis in Sections 4 and 5 was based on the hypothesis that there *really exists* a severe greenhouse problem that warrants aggressive abatement measures. However, up to now scientific evidence does not allow to draw definite conclusions concerning the extent and the likely consequences of global warming. In order to cope with these uncertainties, Manne/Richels (1991) propose to spent only moderate abatement effort during a learning phase of three decades and thereafter to switch to a tightened 'catch up'-policy if new scientific evidence reveals that greenhouse damage would really be severe. They estimate that this 'wait and learn'-strategy could save the United States about $ 90 billion compared to immediately introducing far-reaching abatement measures. These optimistic results did not remain unchallenged in the literature (see Cline, 1992). But nevertheless, the basic idea of reducing cost by postponing part of the abatement effort until further scientific evidence will emerge, might be an appropriate response to the present uncertainties surrounding global warming.

Figure 10. Ten-year Moratorium: Percentage Reduction in Greenhouse Gas Emissions.



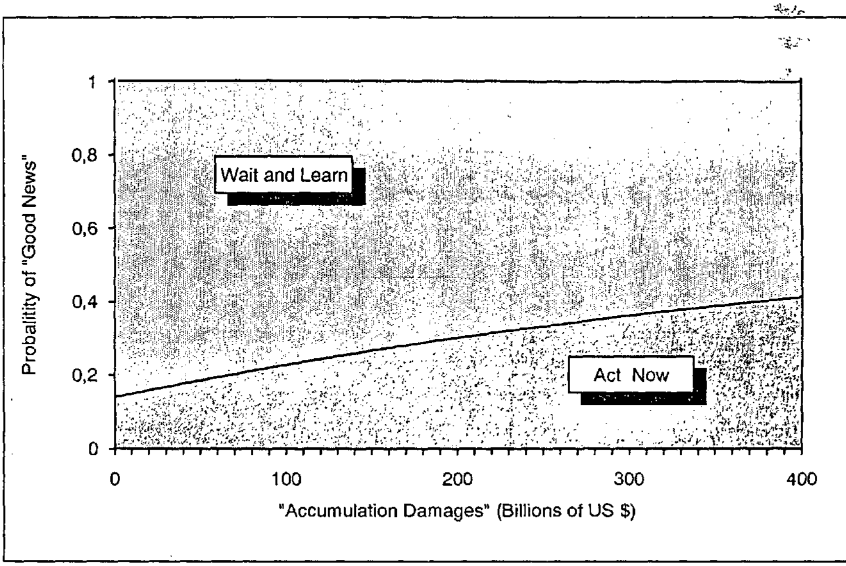
In order to explore the implications of such a 'wait and learn'-strategy for the model under consideration, an additional simulation run with a ten-year moratorium has been calculated. Specifically, it has been assumed that during the first decade no reduction measures concerning CO_2, N_2O and CH_4 are taken, whereas the reductions in CFC emissions follow the 'Montreal Path' introduced in the last Section (see Figure 10).[26] Comparing the resulting time path shown in Figure 10 with the original path shown in Figure 2 reveals that the ten-year moratorium necessitates a considerable tightening of abatement measures during the following decades. Denoting the present value of abatement cost saved during the first decade by ΔC_1 = \$ 747 billion and denoting the present value of additional abatement cost accruing during the following decades by ΔC_2 = \$ 865 billion leads to a net increase in abatement cost of $|\Delta C_1 - \Delta C_2|$ = \$ 118 billion.

This figure, however, does not reflect the complete cost of waiting since it neglects those damages $D \geq 0$ that might be caused by violating the constraint $s(t) \leq (1+\gamma)s(t-1)$ during the first decade.[27] But there are also potential benefits from waiting since the learning phase

[26] As pointed out by Cline (1992), due to the risk of irreversible damages during the learning phase a moratorium of only 10 years seems to be more appropriate than 30 years as assumed by Manne/Richels (1991).

[27] The growth in stock s(t) during the first decade amounts to about 6% compared to a maximum permissible growth of only 2.8% (see Section 4).

Figure 11. Ten-year Moratorium: Comparing the Cost and Benefit of Waiting.



the greenhouse effect may qualify as a mere chimera. Denoting the probability of this 'good news' by π and assuming risk neutrality, the expected net benefit from waiting is positive if the condition $\pi > 1 - [\Delta C_1/(\Delta C_2+D)]$ holds. Hence, for given cost differences ΔC_1 and ΔC_2 the profitability of waiting depends on the relationship between the probability of 'good news' on the one hand and the accumulation damages eventually caused during the learning phase on the other hand. Accounting for ΔC_1 = $ 747 billion and ΔC_2 = $ 865 billion. condition (12) implies that a probability of 'good news' of 20% - as suggested by Cline (1992) - suffices to justify a ten-year moratorium if the accumulation damages do not exceed a magnitude of about $ 68 billion. And even with accumulation damages as high as $ 300 billion, a probability of only 35% would be required in order to generate a positive expected net benefit (see Figure 11). Hence, even with a comparatively low probability of 'good news' it might pay to wait and learn.

Finally, it should be emphasised that these calculations are only intended to give a first clue to the likely profitability of a moratorium. At least two shortcomings of the above analysis warrant further research. First, the oversimplified 'bang bang'-structure of the employed probability distribution is clearly inadequate. In particular, it might turn out during the learning phase that global warming is in fact a problem but it is less severe than previously suspected. And second, there may exist technological irreversibilities particularly associated with the reduction of CO_2 may (see Stähler, 1993) such that switching between different reduction paths is costly. An inclusion of this latter aspect would induce an additional bias in favour of waiting.

7. Summary and Conclusion

The present study has investigated the economic implications of a comprehensive policy approach that strives to stabilise the atmospheric concentration of greenhouse gases at an ecologically determined threshold level that restricts the rise in global mean temperature to about 1.5°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 with the corresponding tax schemes, the model has been empirically specified and adapted to a dynamic GAMS-algorithm that covers the period of 1990 to 2110. Given the input data and cost parameters assumed in this paper, the model predicts that the stabilisation target will be reached by the year 2060 such that for the remaining time horizon emissions have to be reduced to the level of natural degradation. The corresponding tax scheme[28] implies a price per ton of CO_2 that starts at about \$ 16 and increases up to a final level of almost \$ 190 in 2110. The respective tax rates on CH_4, N_2O and CFCs are considerably higher due to the higher dynamic greenhouse potential of these gases. In particular, the tax rates on CFCs can be considered as prohibitive, such that a total ban of these substances could already be justified by their impact on global warming.

The present value of total abatement cost associated with the above stabilisation target is estimated to range from about \$ 80 billion p.a. at the beginning of the time horizon to a maximum level of \$ 150 billion p.a. in the year 2060. These 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 this case, the model predicts excessive abatement cost that sum up to a present value of about \$ 1,800 billion. Although these empirical results are subject to several uncertainties, their basic policy implication can hardly be doubted: An efficient solution to global warming requires a comprehensive approach that would not only affect forestry policies and fossile fuel consumption but also modern agriculture which contributes significantly to the atmospheric accumulation of methane and nitrous oxide.

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[28] On the practical properties of such a tex scheme, like, e.g., the definition of the assessment base, see Michaelis (1992a).

However, in view of the substantial cost burden quoted above and accounting for the vast uncertainties surrounding climate change, a 'wait and learn'-strategy as originally proposed by Manne/Richels (1991) might be considered as a reasonable alternative compared to immediately introducing far reaching abatement measures. In principle, the evaluation of such a strategy depends on the relationship between the probability of 'good news' and the additional cost caused during the learning phase. Given the input data and cost parameters assumed in this paper, the model predicts that a 10-year moratorium might be reasonable even if the probability of 'good news' is comparatively low.

Finally, it is instructive to compare the above results with those obtained by other authors applying explicit cost-benefit-analysis to the problem of global warming. The most comprehensive studies in this field are those of Cline (1992) and Nordhaus (1993). Nordhaus calculates an optimal transition path for controlling CO_2 and CFCs *together* that starts at a reduction level of about 10% and increases up to about 15% in 2105. As claimed by Nordhaus, within the next 120 years this time path implies an increase in global mean temperature of about 3.2°C compared to preindustrial levels. This calculation, however, does not account for the impact of uncontrolled CH_4 and N_2O emissions. Hence, the true increase in temperature might be considerably higher. In the light of long-term risk management, as proposed by the UNEP Advisory Group on Greenhouse Gases, such an outcome has to be viewed as unacceptable.

Cline (1992) assumes an 'aggressive' approach to climate change that aims at reducing global CO_2 emissions to an annual level of 4 GtC (which implies an initial reduction in emissions of about 40%). He calculates the corresponding benefit-cost-ratio for a number of scenarios that differ by the assumed key parameters: discount rate, climate sensitivity and warming damages. In contrast to Nordhaus (1993), the results obtained by Cline (1992) suggest that aggressive abatement measures can be justified for a wide range of reasonable key parameters.[29] These findings are of particular interest with respect to the present study because the emission target assumed by Cline (1992) is roughly in line with the stabilisation target assumed in the above simulations.[30] Hence, there is evidence that the above stabilisation scenario can be justified in terms of cost and benefits although the present study did not explicitly deal with quantifying warming damages.

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[29] The differences between the results of Cline (1992) and Nordhaus (1993) are due to a number of differing assumptions among which the employed discount rates play a key role.

[30] The long term reduction rates calculated for the base run scenario (see Figure 3) imply annual net emissions of greenhouse gases in the order of magnitude of 4-5 GtC.

Acknowledgements

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Appendix

Figure A.1. Percentage Reduction in Greenhouse Gas Emissions: The Case of Reduced Greenhouse Warming Potentials of CFCs (α_4=397 and α_4=575).

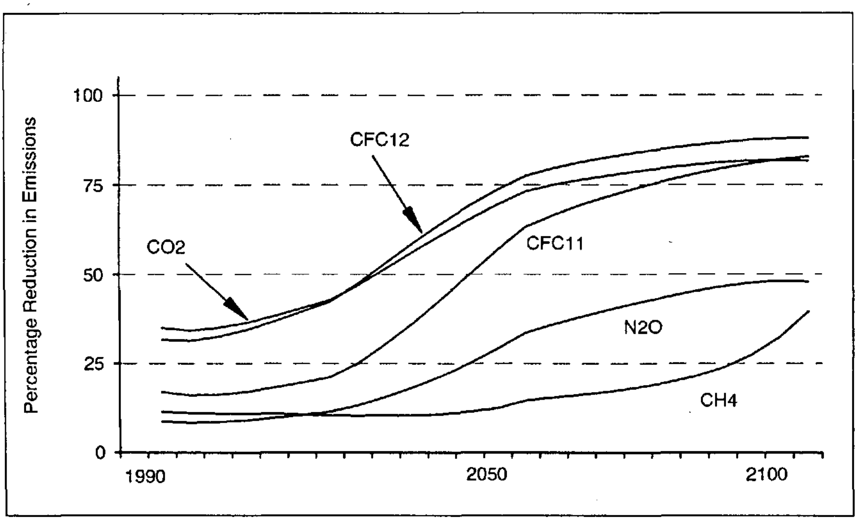


Figure A.2. Low Cost Scenario: Percentage Reduction in Greenhouse Gas Emissions.

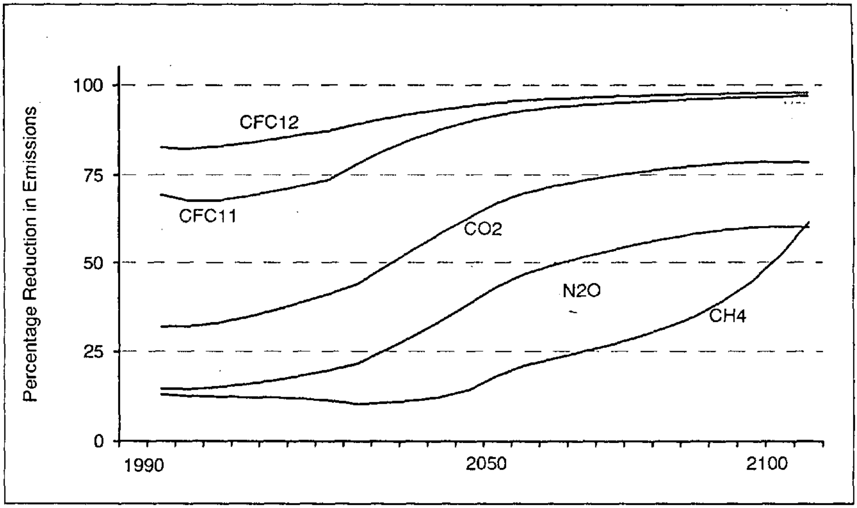


Figure A.3. High Cost Scenario: Percentage Reduction in Greenhouse Gas Emissions.

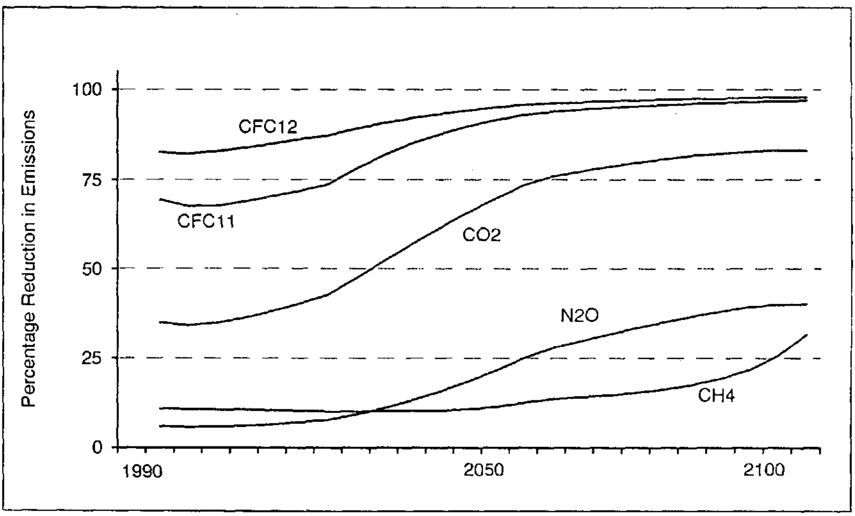


Figure A.4. Low Cost Scenario: Marginal Cost of Greenhouse Gas Reduction ($/ton).

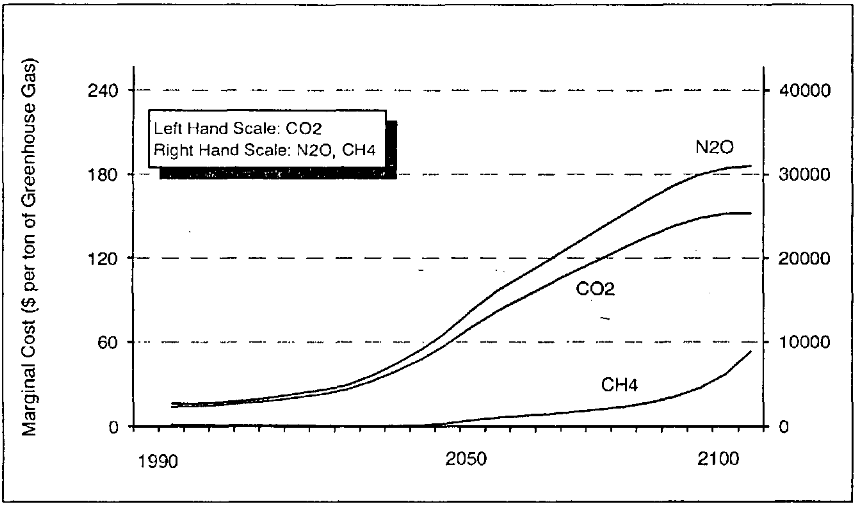


Figure A.5. High Cost Scenario: Marginal Cost of Greenhouse Gas Reduction ($/ton).

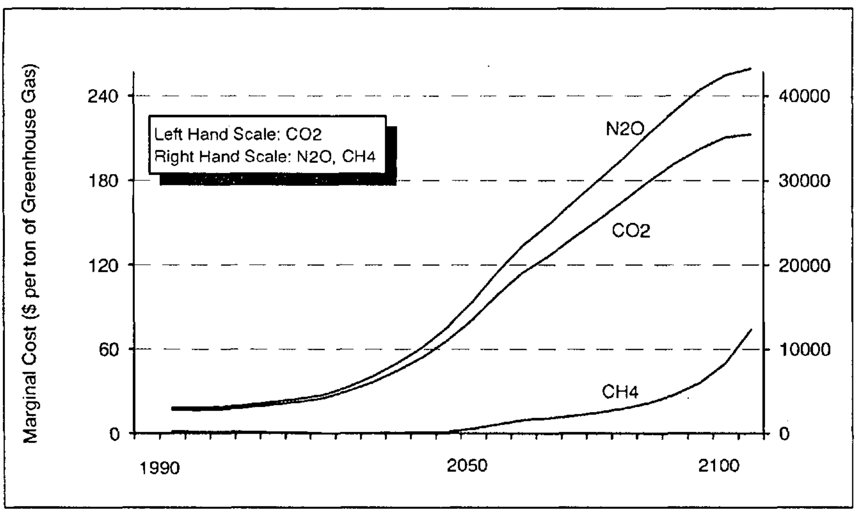


Figure A.6. Piecemeal Approach versus Comprehensive Approach (Low Cost Scenario): Present Value of Annual Abatement Cost.

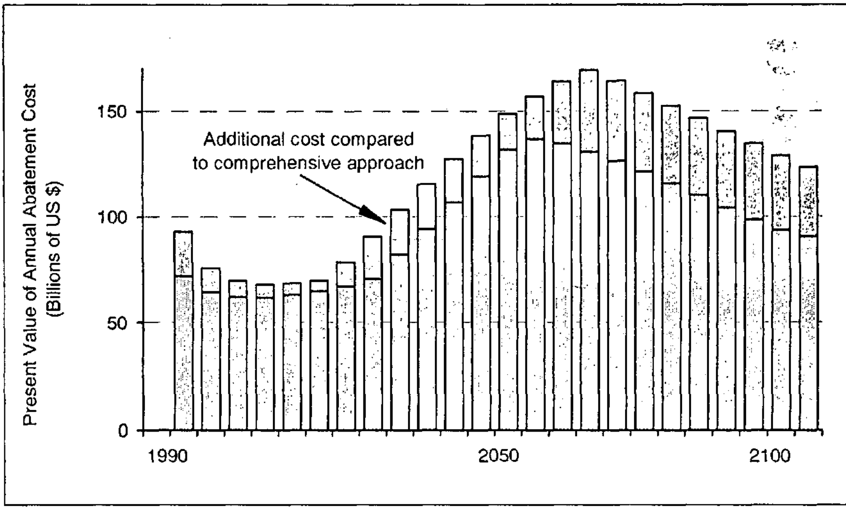
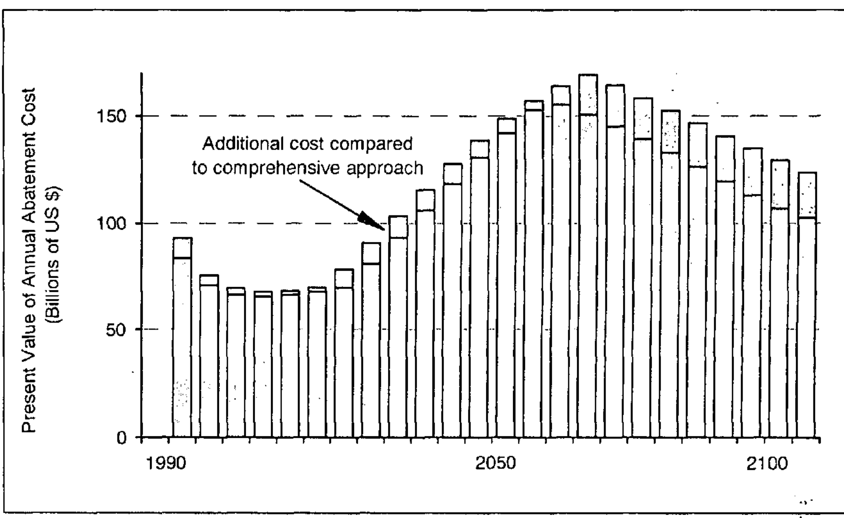


Figure A.7. Piecemeal Approach versus Comprehensive Approach (High Cost Scenario): Present Value of Annual Abatement Cost.



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