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MACROECONOMIC IMPLICATIONS OF REDUCING GREENHOUSE GAS EMISSIONS: A SURVEY OF EMPIRICAL STUDIES

Peter Hoeller. Andrew Dean and Jon Nicolaisen

CONTENTS

The authors were all working in the General Economics Division when this paper was being prepared in **1990.** Jon Nicolaisen has now returned to the Norwegian Ministry of Finance. The authors would like to thank numerous colleagues in the Economics and Statistics Department. the Environment Directorate and the International Energy Agency at OECD for helpful comments and suggestions at various stages of this work. in particular Jean-Marc Burniaux, Jorgen Elmeskov. Robert Ford. John P. Martin and Rudiger Soltwedel. They are also grateful for comments on an earlier version from many of the modellers cited in the survey but take full responsibility for remaining errors and omissions. Special thanks are due to Jackie Gardel for technical assistance.

INTRODUCTION AND CONCLUSIONS

A. The scope of the survey

This survey provides an overview of current estimates of the macroeconomic costs of reducing emissions of greenhouse gases (GHG). These costs have become an important policy question because current levels of GHG emissions seem likely to lead to global warming (see Annex). The costs include both short-run frictional costs and long-run continuing costs. It is important, however, to see the costs of emission reductions in a broader framework which encompasses other responses to climate change'. There are two polar responses to the prospect of climate change; a do-nothing approach, which accepts the risks of damage and the adaptation costs that arise, and a preventive approach which attempts to avoid such damage. Between the two polar cases, all sorts of different combinations of prevention and adaptation are possible.

Even if GHG emissions were curtailed drastically today, warming is likely to occur in the coming decades owing to the lagged effects of past emissions. Hence some adaptation to a warmer climate will have to take place in any case. The damage and adaptation costs that would be incurred in the more distant future are likely to be higher, the lower the level of preventive action. But preventive action itself may well involve rising marginal costs. There is thus an important trade-off which will depend critically on the discounting involved. An optimal policy mix is achieved at the point where the marginal cost of emission reductions is equal to the marginal benefit, as represented by the damage and adaptation costs avoided (Nordhaus, 1990*a*). However, most studies do not attempt to estimate both costs and benefits and hence are unable to identify such an optimal point. The major difficulty lies in quantifying the benefits from cutting emissions. The majority of studies instead focus on the cost side and this survey is limited to such studies.

The survey is further limited to macroeconomic or economy-wide costs, and largely to those associated with reducing emissions of carbon dioxide (CO_2) – the most important greenhouse gas. Thus sectoral issues are not considered, and there is an inevitable bias towards questions with quantifiable answers. It is important, however, at this stage of the work on responses to climate change, to take stock of what quantitative analysis has produced in terms of an answer to the question: what would be the economic costs of reducing CO_2 emissions? The range of answers provided cannot be taken as definitive – this is an increasingly active area for research. Nor has it been possible in this paper to provide a rigorous evaluation of the estimates or a full accounting for differences in them; such work awaits a more detailed comparative review of model properties, an exercise which is currently underway at OECD and elsewhere. The summary of cost estimates contained here is nonetheless a place to begin establishing quantitative foundations in economic terms for the policy debate on climate change.

B. Summary of the main findings

Policies to slow or to halt global warming imply a reduction of GHG emissions from ***current*** levels. Reference scenarios which project trends in the absence of control policies, however, point to a growth in CO_2 emissions in the range of ½ to 1½ per cent per annum in the long run, with increases being somewhat faster in the period up to 2025 and rather slower in later years (as population and output growth slow). Major differences in emission scenarios stem from uncertainties in projecting population growth, technological progress (including the prices of "back-stop technologies"[2]), energy prices and resource availability.

With emissions continuing to increase in reference scenarios, any reduction from ***current*** levels implies very large decreases from the levels projected to occur in the long run. Achieving large reductions of energy-related CO_2 emissions is estimated to lead to a reduction of global GDP ***growth rates*** in the range of close to zero to 0.3 percentage points although there is considerable uncertainty surrounding these cost estimates because of the limitations of such models. Such small reductions in GDP growth rates relative to the baseline would imply large reductions in GDP ***levels*** in the long run.

The size of the reduction in long-run economic growth depends crucially both on the degree of substitutability between the various energy sources and other inputs and on the availability and price of low-carbon, back-stop technologies. The greater the degree of substitutability, the lower the cost will be in terms of growth for any given reduction in energy use. In the same vein, the availability of low-cost, low-carbon, back-stop technologies would allow countries to deal with the run-down of scarce fossil fuels such as oil and natural gas without having to resort to coal, which is in plentiful supply but is the most carbon-intensive of all fossil fuels.

The ***time profile*** of emission reductions is also an important factor. Sharp reductions of CO_2 emissions are likely to be more costly as cheap low-carbon technologies are not yet available and part of existing capital may become unprofitable. The policy instruments used to achieve emission reductions will also influence the size of the costs. A "command-and-control" approach towards limiting CO_2 emissions is likely to increase the macroeconomic cost significantly compared with an approach that operates through economic incentives. On the other hand, if sectoral policies are not optimal at the outset, then changes in, for example, transport or energy policies might provide a relatively cheap means of achieving the initial reductions in CO_2 emissions.

The cost of limiting CO_2 emissions is likely to be much higher in developing countries due to their faster underlying growth rate. Even if they were allowed to double or triple their emissions over the next 100 years, they might still face higher costs than developed countries under much more stringent targets. On the other hand, large reductions in man-made CO_2 emissions are possible on a global scale only if the developing countries also take action.

Regarding other GHGs and other options, international agreement has been reached on cutting CFC emissions sharply. As some substitutes are relatively cheap, a sharp reduction can be achieved at relatively low cost compared with sharp reductions in other greenhouse gases. Stopping further deforestation of tropical areas may also be achieved at low cost. But other forestry options, like reforestation, may be much more costly. A phase-out of CFCs and an end to deforestation would decrease annual GHG emissions considerably. However, a sharp cut in fossil-fuel combustion would still seem to be necessary to achieve the really significant reductions in emissions that would be required to stabilise overall GHG concentration levels.

C. Some lessons for policy

The survey focuses on the presentation and analysis of differences among emission reduction scenarios; these have been summarised in the main findings above. This section goes beyond the direct implications of the cost estimates surveyed here to draw out some general considerations in the setting of policy in this area.

A cost-effective strategy needs to be based on a comprehensive review of policy options including an analysis of both the costs and benefits of policies to limit climate change. This survey focuses on costs. But it is important that the benefits of avoiding climate change, still a poorly researched area, are also taken into account. The narrow focus of the paper nevertheless provides some messages about the relative merits of the range of policies that might be considered for reducing emissions.

First, a cost-effective strategy should look at potential reductions in *all* greenhouse gases, taking into account their relative contribution to climate change. So far, research has focused on CFCs and fossil-fuel related CO_2 emissions because increases in other GHGs are difficult to model.

Second, as noted in the summary, the recently agreed phase-out of major CFCs and halting continuing deforestation of tropical forests would both significantly reduce the warming attributable to GHG emissions and could be achieved at relatively low cost.

Third, "no-regrets" policies, though limited in scope, may have little or no cost. Considerable reductions in CO_2 emissions may be achieved in the course of improving policies in other respects in the areas of transport, energy, forestry and some other sectors.

Fourth, regulatory approaches and policies which tax energy inputs but do not focus on the carbon content of fossil fuels are likely to significantly increase the cost of control strategies.

Finally, the climate change issue is a global problem and requires a policy response which is itself global. In order to minimise free-rider problems, this requires an international agreement which ensures the maximum number of participating countries.

I. THE MODELS COVERED IN THIS SURVEY

The limited scope of the survey has already been mentioned above. The studies examined are those which focus on the cost side of emission reductions and which examine the macroeconomic implications in quantitative terms[3]. This focus reduces the large number of papers concerned with modelling and analysis of the economics of climate change to a more manageable set. The paper surveys just over a dozen models. However, some of these models have been used by more than one author and some authors have used several generations of their model in successive papers. The main features of the models are given in Table 1, beginning with the few global models and then covering the more numerous single-country models.

The most complete global model in terms of modelling the energy sector and its feedback to aggregate output is that of Manne and Richels (1990). However, their regional models have not been linked so far, so that the income flows and energy supply reactions between regions are not modelled consistently. Hence no account is taken of feedbacks through international trade, though the latest version of their global 2100 model allows for trade in permits[4]. In addition, the model does not distinguish among different industrial sectors. Models with a sophisticated treatment of the energy sector, but less developed macroeconomic linkages, include those of Edmonds and Reilly (1983), Nordhaus (1990) and the IEA (1990). The model of Whalley and Wigle (1990), though lacking dynamics (it

Table 1. Main features of the models in the survey

	Type of model	Time Horizon[1]	Number of: Energy sources[2]	Number of: Industries	Regional scope[3]
			A. Global models		
Manne/Richels (1990)	Dynamic optimising	2100	9	–	5 regions
Whalley/Wigle (1990)	Static general equilibrium	2030[4]	2	5	6 regions
Edmonds/Reilly (1983)[5]	Dynamic optimising	2100	6	–	9 regions
IEA (1990)	Econometric energy model	2005	5	9	10 regions
Nordhaus (1990)	Dynamic optimising	2100	2	–	No regional detail
			B. Single-country models		
CBO (1990)					
DRI	Multi-sector macro	2000			United States
DGEM	Dynamic general equilibrium	2000	4	9	United States
Jorgenson/Wilcoxen (1990)	Dynamic general equilibrium	2060	3	35	United States
Blitzer et *al.* (1990)	Dynamic general equilibrium	2002	3	10	Egypt
Glomsred et *al.* (1990)	Dynamic general equilibrium	2010	3	31	Norway
SIMEN (1989)	Multi-sector macro	2000			Norway
NEPP (1989)	Multi-sector macro	2010			Netherlands
Bergman (1989)	Dynamic general equilibrium	2000	2	5	Sweden
Dixon et al. (1989)	Dynamic general equilibrium	2005		113	Australia

1. Refers to the end-point of the simulations.
2. Includes electricity.
3. Refers to the regional coverage of the respective studies.
4. Calibrated on 1990-2030 average values.
5. This model is used by Cline (1989). Mintzer (1987) and Edmonds and Barns (1990).

is a comparative-static applied general equilibrium model), does have global consistency and some sectoral disaggregation; it is thus able to give insights into the effects of different types of international agreement to tackle global warming.

There are still relatively few global models, despite the fact that climate change is an inherently global problem. There are many more single-country models, in part because data and computational problems are easier to handle. There is a trade-off between the regional and sectoral scope of the models, as evidenced by the large difference in industry detail between the global and single-country models. A wider regional scope is important for the analysis of the international trade and welfare consequences of different types of international agreement, while sectoral scope is necessary, for instance, in pin-pointing the consequences of policies on the industrial structure. In addition, a certain disaggregation of primary energy sources is important, as the aggregate outcome is dependent on the assumed degree of substitutability between energy sources with different carbon contents.

Greenhouse gas emissions and their effects need to be analysed over an extended time horizon due to the long lags involved in the transition from GHG emissions to, firstly, concentration levels and then to the ultimate effects on climate. It is for these reasons that, as indicated in Table **1,** many projections of global GHG emissions run until the end of the 21st century. Some authors have suggested that even this time horizon is too short, since the major impacts of climate change would not be felt until the centuries beyond. Many country models, on the other hand, focus on the short and medium term, perhaps because unilateral reductions in the long run would change concentration levels little and would be extremely costly relative to the benefit for the country. Most of the studies focus exclusively on fossil-fuel related CO_2 emissions as they are responsible for a large part of GHG emissions and are the easiest to link to economic behaviour. Only three of the studies cover other than fossil-fuel CO_2 emissions (Mintzer, **1987;** Nordhaus, **1990;** and Edmonds and Barns, **1990).**

Different types of model answer different questions. The short-run macro-models are able to quantify short-run transitional or frictional costs such as additional expenditures on pollution control plus foregone output from existing capital that becomes unprofitable or has to be prematurely scrapped. They also include costs that arise because of problems of adjustment in the labour market or the effects of alternative macroeconomic policy responses to tax-induced price changes. In the short run, it is probably not critical that they are poor in modelling substitution possibilities as short-run substitution elasticities are typically low. Long-run models, while sometimes incorporating such frictional costs are better capable of modelling substitution possibilities and reallocation of resources in a realistic way. Short-run frictions are likely to play only a minor role in shaping long-run growth trajectories. In addition, modelling of capital formation and technical change and assessing the deadweight loss of taxation are important considerations for the analysis. Applied general equilibrium and dynamic optimising models are the best vehicles to address these long-run issues.

This survey reviews the results of the models specified in Table 1 and provides some preliminary analysis of some of the apparent reasons for the range of results presented. However, it needs to be stressed that a satisfactory accounting for differences in baseline and emission reduction scenarios among the studies covered has not been attempted here, as important parameter values are not available for many studies and sensitivity analysis with respect to changes in parameters is reported only in a few cases. The more intensive work necessary for a full evaluation of the different models requires the more detailed analysis of the sort currently being attempted in a comparative exercise being carried out by the Energy Modelling Forum at Stanford University and a more modest exercise covering only global models which is currently underway at the OECD.

II. BASELINE SCENARIOS

A. Key determinants of baseline CO_2 emissions[5]

In order to understand the differences between various baseline CO_2 emission scenarios, it is useful to focus on the key determinants of the growth of emissions (as shown in Table 2).

Output growth. Most of the long-term, global studies assume an annual GDP growth of around 2 per cent over the next century, usually with stronger growth in the next few decades. The subsequent slowdown mainly reflects a lowering of population growth in developing countries. A common feature is also the assumption of much faster average growth in developing than in developed countries. None of the baseline projections of future growth includes an estimate of the potential cost and benefits of climate change, however, the baselines being run off models which do not include climatic feedback (positive or negative).

Energy efficiency. This is a key exogenous parameter in the models. Estimates of the baseline growth in autonomous energy efficiency range from 0 to 2 per cent per annum for different regions in Manne and Richels (1990). The average for the world as a whole in Manne and Richels is close to the assumptions of Mintzer (1987) and Reilly *et al.* (1987), who assume long-term average growth rates of energy efficiency of 0.8 and 1 per cent, respectively.

Energy prices. Most studies incorporate a rise in relative energy prices throughout the next century, reflecting depletion and increasing exploration and mining costs, with an especially sharp rise in fossil-fuel prices[6]. Most baseline

Table 2. Baseline projections of key variables

	Projection period	GDP	Energy efficiency	Final energy demand		Energy prices		CO_2 equiv. emissions	Absolute levels, end-year	
				Total	Fossil	Total	Fossil		GHG concentration[1]	Warming (°C)
Global studies										
Manne/Richels (1990)	1990-2100							1.4		
USA		1.6	0.5	0.9				1.1		
Other OECD		1.6	0.5	0.9				1.1		
Eastern Europe (including USSR)		1.6	0.3	0.9				0.7		
China		3.5	2.0	2.6				2.1		
Rest of world		3.0	0.0	2.3				2.0		
IEA (1990)	1987-2005			2.2			3.1	2.2		
Cline (1989)	1975-2075			1.0	0.9			0.8	>600	1.5-4.2[2]
Reilly *et al.* (1987)	1975-2075		1.0					0.5	430-590	3
Mintzer (1987)	1975-2075	2.0	0.8	1.3				1.5	825	
Nordhaus/Yohe (1983)	1975-2100	2.1		1.4	0.9	0.2	1.0	1.2	780	
Nordhaus (1990)		1.1						1.1	600	3[2]
Nordhaus (1977)	1980-2100			1.4				1.6		
Edmonds/Barns (1990)	1988-2025	3.0	1.0	2.0				1.2		
National studies										
SIMEN (1989) (Norway)	1988-2000	1.5		1.1				1.6		
Glomsred *et al.* (1990) (Norway)	2000-2010	2.7					1.0	3.9		
Blitzer *et al.* (1990) (Egypt)	1987-2002	3.5						2.2		
Bergman (1989) (Sweden)	1985-2000	2.0		0.7				5.3		
Dixon *et al.* (1989) (Australia)	1989-2005	3.4		2.6[3]				2.7[3]		
CBO (1990) (USA)	1988-2000				1.1			1.1		

1. In ppm-CO_2 equivalents.
2. Effect of CO_2 doubling.
3. For electricity and road transport.

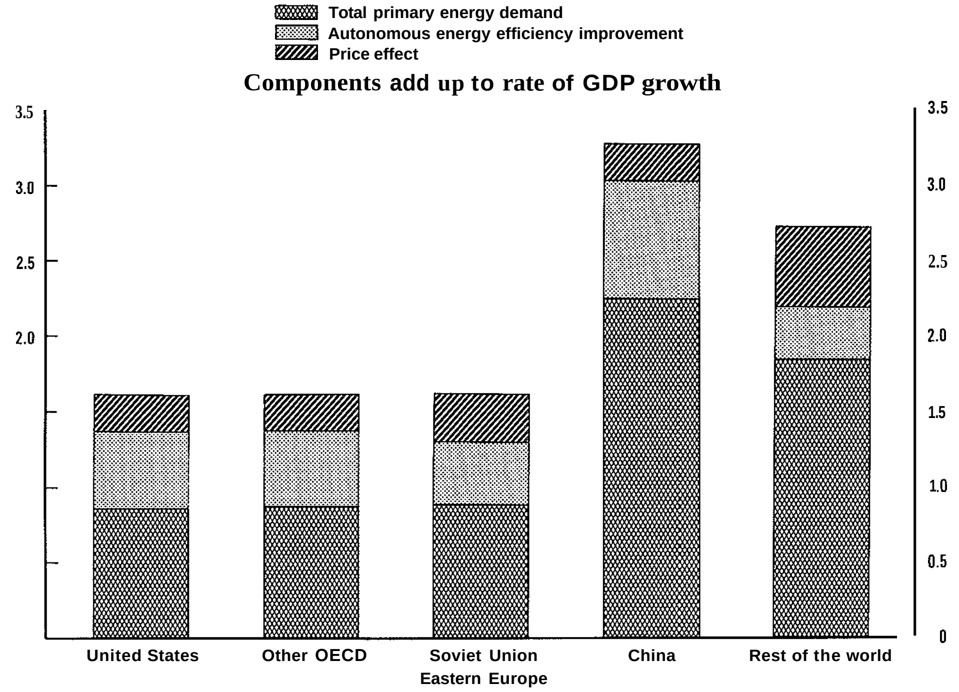
scenarios suggest that the use of fossil fuels will be subject to supply-side constraints even in the absence of specific policies to limit GHG emissions[7].

Rising energy prices and energy efficiency gains lead to slower growth of aggregate energy demand than output growth. For instance, Nordhaus and Yohe **(1983)** estimate a growth rate in total final energy demand and fossil-fuel demand of only around 1.4 and **0.9** per cent a year, respectively, in spite of output growing at over 2 per cent per year.

The decomposition of the differences between output and energy demand growth into its autonomous energy efficiency and energy substitution components for the baseline scenario of Manne and Richels **(1990*a*)** is shown in Chart **1.** Slower growth in energy inputs than in output growth is due more to autonomous energy efficiency gains than to substitution except for the developing countries, excluding China where energy efficiency gains are the largest. The substitution elasticity of total energy requirements with respect to the bundle of labour and capital inputs is usually set at close to 0.5.

CHART 1

DECOUPLING BETWEEN TOTAL PRIMARY ENERGY CONSUMPTION AND GDP GROWTH, 1990-2100



Source : Manne and Richels (1990)

Back-stop technologies. Most analyses include an exogenous reduction in back-stop energy prices due to technical progress. For instance, Reilly ***et al.*** (1987) estimate that the supply prices of solar energy and "safe" nuclear energy will fall at annual rates of 2.5 and 0.6 per cent, respectively. In addition, if other fuel prices rise, back-stop technologies gain in competitiveness relative to traditional (mainly fossil) fuels. Manne and Richels (1990) specify upper bounds on growth rates of investment in back-stop energies and also assume a set of specific introduction dates at which back-stop technologies become competitive. For example, the cost of producing electricity from solar energy is estimated to range between 5.1 and 11.1 cents per kwh in 2010. Torrens (1989) and Hubbard (1989) estimate solar energy back-stop prices at or below 10 cents per kwh by 2000, roughly in line with the Manne and Richels estimates, and the estimates of Dixon ***et al.*** (1989) are somewhat below 10 cents at the turn of the century for Australia[8].

B. The range of growth rates for CO_2 emissions

Global CO_2 emissions increased from an estimated 1.5 billion tons per year in 1950 to more than 6 billion tons per year in 1990. The average annual growth rate more than halved between 1950-70 (4.8 per cent) and 1970-88 (2.0 per cent) (Edmonds and Barns, 1990), reflecting slower output growth as well as the important impact of energy price changes in the latter period.

Despite large uncertainties, there is agreement among the different studies that CO_2 emissions are also likely to grow substantially over the next century. The annual growth rate of fossil-fuel CO_2 emissions is generally estimated to be in the range of ½ to 1½ per cent for the world as a whole for the period to 2075. All scenarios point to faster growth of emissions over the next decades and a considerable slowdown thereafter. The IEA, for instance, projects that emissions could grow by more than 2 per cent annually over the next 20 years. Even the low central projection of Reilly ***et al.*** (1987) implies that CO_2 emissions will be more than 50 per cent higher than today by 2075[9]. The projections in other studies imply that CO_2 emissions will more than double by 2075, with the IPCC's business-as-usual case pointing to the possibility of a quadrupling of emissions by the end of the next century (IPCC, 1990).

Differences in the various projections of man-made CO_2 emissions shown in Table 2 reflect primarily:

- Different estimates of output growth and energy efficiency gains; the higher the growth in energy efficiency, the lower is the growth in final fuel demand relative to output growth.
- Different estimates of growth in real energy prices and the dates when suitable carbon-free back-stop technologies come on-stream. In the study

by the IEA (1990), for instance, energy prices rise rapidly, but there is assumed to be only very limited scope for substitution to non-fossil fuels in the next decade, while final energy demand grows by more than 2 per cent a year. Taking a long-term view, Manne and Richels (1990*a*) explicitly introduce back-stop technologies that bring down the demand for fossil fuels.

Most long-term models suggest that a key issue is when substitutes for existing fuels become competitive and are going to be introduced on a large scale. It is likely that oil and especially natural gas reserves will diminish quickly over the next century, while coal reserves are much more abundant. But coal is the fossil fuel with the highest carbon content. Price increases for fossil fuels currently used are likely to lead to the introduction of fossil-fuel back-stop technologies as well as improvement of non-fossil-fuel technologies.

C. Other greenhouse gases

Most countries have agreed to reduce the use of CFCs drastically by the end of this century. Increases in other greenhouse gas emissions are difficult to model as the sources of methane and nitrous oxide, for instance, are diverse and emission rates uncertain. As noted previously, nearly all of the models surveyed focus only on man-made CO_2 emissions although the latter part of the following section briefly considers some options for reducing other greenhouse gases.

III. EMISSION REDUCTION SCENARIOS[10]

A. Reducing CO_2 emissions related to fossil-fuel combustion

Reduction targets. Since the pioneering work of Nordhaus (1977), several attempts have been made to estimate the macroeconomic implications of CO_2 reductions on a national or global basis. CO_2 reduction targets in the studies reviewed here are often specified with respect to the base-year. In the study of Manne and Richels (1990*a*), for instance, the target is to lower emissions by 20 per cent from the base-year level by 2020 and to keep emissions at this lower level until the year 2100. Similarly, Dixon *et al.* simulate the implications of the Toronto goal of reducing CO_2 emissions by 20 per cent below the 1988 level by 2005. This implies a reduction of CO_2 emissions in the year 2005 of nearly 50 per cent below the then baseline level. The study by the IPCC (1990) suggests that a drastic cut in CO_2 emissions of more than 60 per cent from the levels in

1990 is needed in order to stabilise atmospheric concentration levels by the middle of the next century.

The mechanisms for reducing emissions. The main policy instruments considered are taxes differentiated by the carbon content of the different types of fossil fuels. Taxes are differentiated because carbon emissions are lower for the use of oil than for coal, while they are lower still for natural gas (Table 3). On the other hand, coal is the fossil fuel in greatest supply and exhaustion of natural gas and oil reserves is likely to increase both coal use and demand for synthetic fuels (which have twice the emission factor of oil).

Table 3. Fossil-fuel carbon emission factors and fuel prices

	Carbon emission coefficient, tons of carbon per million BTU of crude oil equivalent[1]	Unit fuel cost 1988 $ per million BTU of crude oil eauivalent
Coal – direct uses	0.0251	2.00
Oil	0.0203	2.50–6.00
Natural gas	0.0145	1.50–5.00[2]
Synthetic fuels	0.0408	10.00
Non-electric back-stop	0.0000	20.00

1. BTU equals British Thermal Unit. Source of carbon emission coefficients: Edmonds and Reilly (1985).
2. To allow for burner-tip equivalence, an additional $1.25 per million BTU is added to allow for gas distribution costs.
Source: Manne and Richels (1990).

The effects on growth of CO_2 emission reductions are summarised in Tables 4 and 5 for the models under review. Column *2* in Tables 4 and 5 gives the difference in average growth rates in percentage points between the baseline and reduction scenarios. Column 3 shows the simulated change to end-year GDP as a per cent of baseline GDP (which obviously depends on the length of the simulation period). With the exception of the Egyptian study by Blitzer ***et al.,*** which shows much larger effects on average growth rates, and of one NEPP scenario, which shows an output increase, most simulation results indicate long-run reductions in growth rates arising from large emission reductions of between close to zero and 0.3 per cent annually. This would imply a simulated global long-term average growth rate of about 1.8 per cent per year, as compared to about *2* per cent in the baseline scenarios. As noted above, comparisons of GDP growth trajectories hinge on the assumption that climate change does not affect the baseline growth rates.

Table 4. **Growth effect of CO_2 emission reductions: global models**

	(1) Emission reduction from end-year baseline levels (%)	(2) Change in the growth rate of GDP	(3) End-year GDP as a per cent of baseline	(4) Carbon tax ($ per ton of carbon)	
				Peak	End-year
Manne/Richels (1990)					
USA		-0.0	-2.5	400	
Other OECD		-0.0	-1.8	250	
Eastern Europe	-75	-0.0	-2.5	700	250
China	(2100)	-0.1	-10.5	250	
Rest of world		-0.0	-4.0	250	
Whalley/Wigle (1990)[1]					
National producer taxes	-50		-4.4[2]		462.8
National consumer taxes	-50		-2.1[2]		463.1
Global tax	-50		-4.22		459.7
Ceiling on per capita emissions	-50		-8.5[2]	..	..
Cline (1989)	-65.5 (2075)	-0.1	-7.4	..	..
Mintzer (1987)	-88 (2100)	-0.0	-3.0	..	..
IEA (1990)[3]					
Carbon tax scenario	-12 (2005)	-0.2			72
70% nuclear plus carbon tax scenario	-25 (2005)	-0.2			72
Nordhaus (1990 and 1990b)					
Low	-30	-0.0			48.5[4]
Middle	-50	-0.0			119.0[4]
High	-80	-0.1		..	..
Nordhaus (1990*b*)					
Rapid phase-in scenario	-60	-0.3[5]			
Rapid phase-in using regulation	-60	-0.5[5]			
Edmonds/Barns (1990)	-75 (2025)	-0.2	-8.0		436.5

1. Target and results apply to average values over 1990 to 2030.
2. Welfare effect measured by Hicksian equivalent variation.
3. Policy and results apply only to the OECD countries.
4. Includes sharp reduction in CFCs. The carbon tax per CO2 equivalent without a reduction of CFCs would be about $90 and $200 for the two scenarios.
5. For the industrialised countries.

Table 5. Growth effect of CO_2 emission reductions: country-specific results

	(1) Emission reduction from end-year baseline levels (%)	(2) Change in the growth rate of GDP	(3) End-year GDP as a per cent of baseline	(4) Carbon tax ($ per ton of carbon)	
				Peak	End-year
Manne/Richels (1989, USA)					
a) technology pessimistic case	–88 (2100)	–0.1	-4.0	600 (2020)	250 (2100)
b) technology intermediate case	–77 (2100)	-0.0	–2.5		
c) technology optimistic case	–50 (2100)	–0.0	-0.8		
CBO (1990, USA)					
DRI model	–16 (2000)	-0.2	–2.0	100	100
DGEM	–36 (2000)	-0.1	-0.6	100	100
Jorgenson/Wilcoxen (1990, USA)	–20 (2060)	-0.0	-0.5	17 (2020)	15 (2060)
	-36 (2060)	-0.0	–1.1	46 (2020)	42 (2060)
Blitzer et *al.* (1990, Egypt)					
Scenario 1	–15[1] (2002)	-0.1	–2.1		
Scenario 3	–35[1] (2002)	–1.0	–15.0		
Scenario 5	-40[1] (2002)	–1.5	–19.0		
Glomsrød et *al.*[2] (1990, Norway)	–26 (2010)	-0.4	–2.7		
SIMEN[2] (1989, Norway)	–16 (2000)	-0.1 to -0.2	–1 to –2		
NEPP (1989, Netherlands)[2]					
National policy scenario	–25 (2010)	-0.2	-4.2		
Global policy scenario	–25 (2010)	0.0	0.6		
Bergman (1990, Sweden)	–51 (2000)	-0.4	–5.6		
Dixon et *al.* (1989, Australia)	-41[3] (2005)	-0.1	–2.4		

1. End-year for emission targets is 2012, at which date reductions are –30%. –35% and –55%, respectively.
2. Includes reductions in other pollutants.
3. Reductions apply to the electricity and road transport sector.

Table 6. Emission reductions and carbon taxes

Percentage reduction in CO_2 from baseline path for different levels of CO_2 tax or cost

Tax (1989 $ per ton of carbon)	N-Y (1)	Revised N-Y (2)	Bodlund *et* al. (3)	Kram-Okken (4)	Edmonds-Reilly (5)	Manne-Richels (6)	Nordhaus model (7)	Argonne model (8)
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10		3.5					5.0	
20	5.9	6.7					9.3	
30		9.8			40.0		16.8	
40		12.7		27.9				20.0
50		15.4						
60								
70								
80								
90							42.8	
100		27.0						
150		36.0					59.9	
160			63.2					
170								
180								
190							92.3	
200		43.2						
210								
220	38.5							
230								
240							78.1	
250			73.9					
260						82.2		
210							94.0	
300		53.9						
350								
430							97.5	

1. Nordhaus and Yohe (1983).
2. Simplified version of the Nordhaus-Yohe model.
3. Bodlund *et* al. (1989). Converted to marginal cost by W. Nordhaus.
4. Kram and Okken (1989). Converted to marginal cost by W. Nordhaus.
5. Edmonds and Reilly (1983).
6. Manne and *Richels* (1989).
7. Nordhaus (1977) and (1979). The observations are for different years and different constraints.
8. Daly *et* al. (19851. All prices are converted into 1989 prices from earlier prices using the U.S. GNP deflator.

Source: Nordhaus (1990).

The size of tax changes. The marginal tax rate per unit of carbon indicates the marginal cost of emission reductions. If the tax rate is large, there is a large gain from relaxing the CO_2 constraint. If the tax rate is small, so is the marginal cost of a more ambitious policy. The last columns in Tables 4 and 5 show carbon taxes – defined in US dollar per ton of carbon – for the peak and end-years of the emissions reduction scenarios. Table 6 shows tax rates in relation to different amounts of emission reduction. While there is significant variation in tax rates for the same amount of emission reduction among models, two messages are clear: small amounts of emission reduction might cost little, while large reductions can be achieved only at high tax rates, i.e. at high marginal costs. Hence, marginal reduction costs rise with the amount of emission reductions. Tax rates of about $250 per ton of carbon for large reductions (Manne and Richels, 1990 and Nordhaus, 1990) imply a more than five-fold increase in the price of coal, a more than doubling in gasoline prices and a large increase in natural gas prices[11].

Timing of tax increases. A sharp reduction in emissions in the short run may be much more costly because of high short-run adjustment costs and the absence of low-cost back-stop technologies. In the simulations by Manne and Richels (1990), for instance, the carbon tax in eastern Europe and the Soviet Union rises to more than $600 per ton until 2020, but falls back thereafter to equal the price differential between traditional fuels and the low-carbon energy technologies, which are assumed to become available after this date. The effect on annual growth rates, which would be about 0.3 percentage points in the period up to 2020, would diminish thereafter. A simulation by Nordhaus (1990*b*) suggests that a rapid phase-in of emission reductions would be much more costly in terms of output growth as a large part of the existing capital stock would need to be scrapped prematurely. Single-country simulations, which usually do not go beyond 2020, also show higher growth effects than the long-run global models. However, part of these output losses are due to losses in competitiveness[12].

B. Key determinants of aggregate costs

Inter-fuel substitution. The effect of a tax differentiated by the carbon content of different fuels would depend primarily on the share of fossil fuels in aggregate output and substitution possibilities for primary energy sources. Substitution can take several forms: there is first the possibility to substitute from high-carbon (e.g. coal) to low-carbon (e.g. gas) fossil fuels. Then, there is the possibility to substitute non-fossil (nuclear power, solar energy) for fossil fuels. Such substitution is limited at present because the major non-fossil fuels are either in limited supply (as with hydropower) or pose environmental risks (as with nuclear energy).

However, a large increase in fossil-fuel prices could make the use of non-carbon based energy substitutes, such as solar energy, attractive and provide an incentive to search more actively for alternative clean energies. If available abundantly, the price of back-stop technologies would put a cap on the cost of CO_2 emission reductions. An increase of fossil-fuel prices beyond the price of non-fossil, back-stop technology would reduce fossil-fuel use substantially in the long run. On the other hand, if substitution possibilities are limited and a cheap back-stop technology is unavailable, reductions of CO_2 emissions will mainly occur via the costly route of policy-induced reductions in energy use.

The model of Blitzer et al. (1990) is restricted to two fossil fuels, gas and oil, so that emission reductions are primarily achieved by income reductions. This partly explains the large effects on Egyptian growth estimated in their study. The other models are richer in their treatment of the energy sector and allow more extensive substitution, so that large reductions in carbon emissions can be achieved at lower cost. In the long run, the availability of an abundant low-cost, low-carbon energy technology substantially reduces carbon emissions per unit of energy. Chart *2* and Table **7** show changes in the fuel mix and aggregate energy inputs from the studies of Manne and Richels (1990*a*) and Cline (1989), respectively.

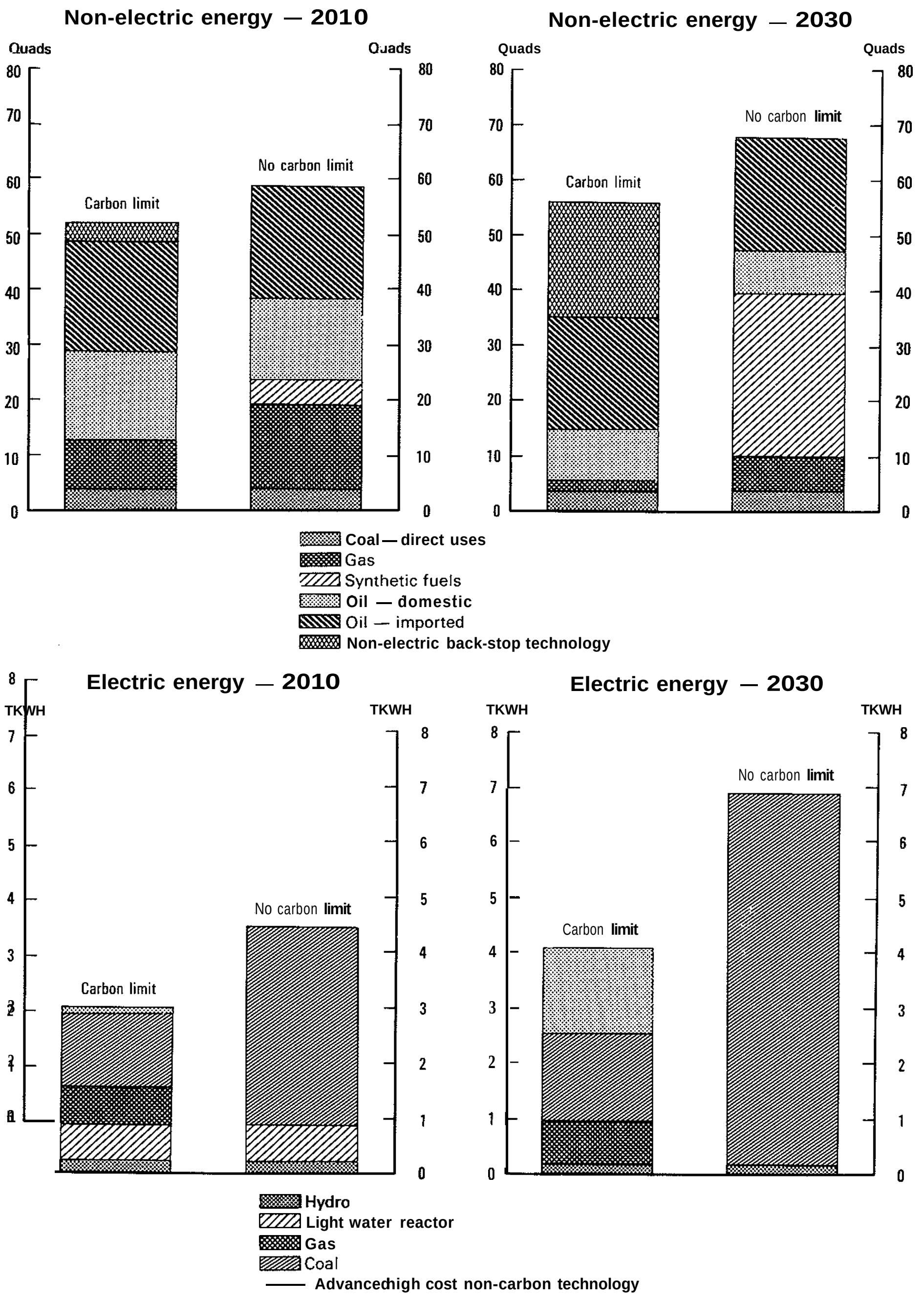
The aggregate *energy/output* link. The ratio of aggregate energy input to aggregate output is not fixed, as evidenced by the more than 20 per cent fall in OECD countries' aggregate energy intensity between 1970 and the late 1980s. An increase in the relative price of the aggregate energy bundle will induce substitution between energy and other inputs, such as capital, labour and other materials. However, it is fairly likely that other inputs, capital in particular, would be less profitable due to limited substitution possibilities. Many studies point to the possibility that energy and capital are complements in production, at least in some sectors. In that case, an energy price increase will reduce the rate of return on capital and saving so that capital accumulation and growth will be lower. Most models under review work with long-run substitution elasticities of about 0.5 between energy and the bundle of other inputs[13].

Another route taken by some modellers is to assume an "energy-feedback" effect on aggregate growth from energy price increases. The feedback effect is thought to capture all effects of energy price changes on aggregate GNP and is negative for net energy importers and positive for energy-exporting countries. Reilly et al. (1987) and the IEA (1990), for instance, assume that a 10 per cent increase in the relative price of energy reduces GDP in QECD countries by about 1.5 percentage points below baseline in the long run.

For sharp increases in fossil fuel prices, adjustmdnt costs are likely to be higher in the short run as capital is largely sector-specific and retrofitting of installed capital is costly. Studies which model capital accumulation explicitly

CHART 2

IMPACT OF FOSSIL-FUEL TAXES ON THE FUEL MIX



Source: Manne and Richels (1990a)

Table 7. Impact of fossil-fuel taxes on carbon dioxide emissions[1]

	Primary energy supply (10**18 joules per year)						
	Oil	Gas	Solids	Nuclear	Solar	Hydro	Total
Base case							
2000	141.5	49.2	141.3	15.3	0.1	51.2	410.6
2025	141.1	95.1	119.3	32.4	13.0	93.0	560.5
2050	169.8	126.1	248.8	49.1	25.8	120.3	140.4
2015	118.2	120.1	352.2	92.4	35.1	121.4	899.4
High tax case							
2000	11.1	35.1	10.1	26.9	0.1	51.5	268.0
2025	56.5	66.5	69.9	48.7	19.5	92.8	353.8
2050	10.4	84.0	82.8	61.1	35.0	103.9	443.2
2015	15.6	90.1	110.1	111.0	45.0	122.9	561.9
	Carbon dioxide emissions (10**6 tons of carbon per year)						
	Conv. oil	Shale oil	Synoil	Coal	Syngas	Gas	Total
Base case							
2000	2 544.1	0.0	14.4	3 081.0	0.1	668.2	6 301.9
2025	2 663.8	5.5	218.9	3 394.5	2.2	1 284.3	7 569.1
2050	3 003.1	21.3	568.6	4 301.5	31.8	1 102.6	9 634.8
2015	3 023.5	40.1	1051.4	5 186.6	211.1	1 622.1	11 141.9
High tax case							
2000	1 394.6	0.0	25.2	1 301.1	0.1	485.6	3 206.6
2025	994.3	0.0	220.9	830.3	0.4	891.8	2 943.7
2050	1 263.2	0.0	241.7	805.2	4.1	1 134.1	3 448.2
2015	1 361.0	4.9	365.2	1 089.2	10.8	1 225.5	4 056.6

1. Consumer tax of 50 per cent on gas, 100 per cent on oil and 150 per cent on coal, imposed in year 2000.
Source: Cline (1989).

assume either putty-clay production functions or sector-specificity of capital in the short run (Nordhaus, 1990*b*).

What also matter for the energy-output link are improvements in energy efficiency. The energy efficiency parameter is exogenous in almost all models. One could, however, argue that energy efficiency gains are partly endogenous, i.e. reacting to changes in relative prices. Mintzer (1987), for instance, assumes that energy-related technical progress will be greater the higher relative fossil fuel prices (raising the assumed growth in energy efficiency from 0.8 to 1.5 per cent per year).

Moreover, the dynamics of the overall adjustment depend on the formation of expectations. Assuming optimising behaviour by producers and consumers under perfect foresight about future energy end-use prices will lead to lower aggregate long-run costs as compared with a model assuming myopia, as economic agents plan purchases taking into account announced future policy. Also the simulated path of private consumption will depend on the specific path of emission reductions in models which assume optimising behaviour under perfect foresight (Blitzer et al., 1990).

*Terms-of-*trade effects could importantly influence aggregate income flows. Unilateral action to reduce emissions in energy-importing countries could lead to a deterioration in their balance of payments with any attempt to move towards balance implying a real resource transfer to other countries. Global action, on the other hand, is likely to induce a large redistribution of income between regions, especially as fossil-fuel resources are unevenly distributed across the globe and rates of usage and exhaustion of different fuels will be affected. Fossil-fuel producer prices, for instance, could fall substantially and permanently below baseline in the case of global action, thereby improving the terms of trade in fossil-fuel importing countries.

The simulations of Whalley and Wigle (1990) highlight the importance of the terms-of-trade effects and changes in trade patterns which may occur under different policies: they simulate the effects of a global 50 per cent emission reduction via:

i) a production-based carbon tax collected by national governments;
ii) a consumption-based carbon tax collected by national governments;
iii) a global carbon tax collected by an international body and redistributed according to population; and
iv) national consumption taxes aimed at a 50 per cent global reduction and the same per capita consumption of fossil fuels at the same time.

Global welfare losses as well as regional losses would differ by large amounts. In the case of a tax levied by fossil-fuel producers, oil-exporting countries would gain a large amount, while developing countries would be significant losers (Table 8). If the tax was levied in consuming countries, oil-exporting countries would lose most while the EC and Japan could even gain. In the case where emission rights are tradeable, with redistribution of the tax revenues by an international agency under a formula that favoured low-income countries, welfare losses of oil-exporting countries and the United States would be steep, while there would be some loss in other high-income countries and some gain in low-income countries. Finally, in the case of a per capita emission ceiling which aims at equalising per capita emission levels across countries, there could be a small

Table 8. Regional welfare changes under different policies

Global emission reduction by 50 per cent on average over 1990-2030

	Change in welfare[1] (%)	Revenue generated over 1990-2030 ($ trillion, 1990 prices)
1. ***National production taxes***		
EC	–4.0	3.3
North America	-4.3	11.0
Japan	–3.7	0.1
Oil exporters	4.5	9.4
Developing countries	–7.1	21.7
World	-4.4	46.6
2. ***National consumption taxes***		
EC	1.4	6.7
North America	–1.2	12.4
Japan	3.0	2.0
Oil exporters	–16.7	2.5
Developing countries	-4.5	21.9
World	–2.1	46.7
3. ***Global production tax; redistribution proportional to each region's population***		
EC	–3.8	–3.2[2]
North America	–9.8	–9.1[2]
Japan	–0.9	–0.6[2]
Oil exporters	–13.0	–1.5[2]
Developing countries	1.8	12.0[2]
World	-4.2	[2]
4. ***Per capita emission ceiling***		
EC	-6.4	
North America	–18.6	
Japan	–2.5	
Oil exporters	–15.1	
Developing countries	–1.2	
World	–8.5	

1. Hicksian equivalent variation over the period 1990-2030 in 1990 prices as a per cent of GDP in present value terms.
2. Net transfer between regions; the total tax revenues raised amount to $46.3 trillion.

Source: Whalley and Wigle (1990).

welfare loss for low-income countries, a sizeable loss in high-income countries and again a steep fall in welfare for oil exporters. The loss for North America could be 15 times larger than in the case of the national consumption tax and the global welfare loss four times larger. The large difference in global welfare mainly reflects the fact that such a reduction mechanism would diverge most from an efficient solution, in which every user would face the same tax on carbon for using fossil fuels. While the (implicit) carbon tax would be lowest and equal across regions in the case of emission trading, it would be somewhat higher and show a small variation in the cases of the consumption and producer tax case. It would be much higher and vary significantly across regions in the case of a common per capita emissions ceiling.

Regional aspects. While Manne and Richels (1990) do not present a fully-consistent global solution, because their regions are not linked by trade, their model gives rich insights into the growth problems which developing countries could face in the wake of sharp emission reductions. Assuming fast growth in output and emissions in developing countries, it would be virtually impossible to put an absolute ceiling on annual emissions. Even a doubling of emissions above base-year for China and other developing countries by 2100 could lead to a much larger loss in output than in the developed countries, where a 20 per cent reduction of emissions from the base-year is assumed to apply. The output loss for China would be sizeable (6 per cent of GDP in 2100) even if its emissions were allowed to quintuple. Large output losses for another developing country (Egypt) are also shown in the study by Blitzer ***et al.*** (1990). Given the small amount of empirical research, long-run parameter values for these countries are more uncertain than those for developed countries. Inefficient use of energy resources, especially in the centrally-planned economies, may provide considerable scope for fossil-fuel reductions per unit of output.

The study by Edmonds and Barns (1990) highlights the fact that it would be impossible for OECD countries alone to reduce ***global*** CO_2 emissions by 20 per cent below 1988 levels by 2005 (the Toronto target) and 50 per cent by 2025. Even eliminating all fossil-fuel use in the OECD countries would not be sufficient to outweigh the increases in other countries above the specified CO_2 emission targets.

Contrasting results depending on model type. The CBO (1990) study uses two different models to highlight the effects of a $100 per ton carbon charge on the U.S. economy: a multi-sector macro-model (DRI) and a dynamic general equilibrium model (DGEM). The DRI model, with only limited possibilities of substitution in production processes, shows larger macroeconomic effects. Substitution is due mainly to a shift in final demand away from energy-intensive goods. The DGEM model, on the other hand, assumes much greater flexibility in adjusting to higher energy prices, ignores some of the costs during the transition period and arrives at much larger emission reductions for the same tax.

Carbon taxes versus other policy instruments. The scenarios included in the official Dutch environmental plan (NEPP, 1989), comprise a variety of non-tax policies. In the first scenario, rather sharp unilateral CO_2 reductions up to 2010 lead to a negative growth-rate effect of 0.2 percentage points. If similar action were to be taken in competitor countries (the second scenario), the situation would be very different and the NEPP study argues that there could even be a positive impact on growth. Emission reductions in the NEPP study are not achieved by a carbon tax, but by a package of measures, including regulation concerning energy conservation in homes and businesses, expanding the share of cogeneration, maximum use of renewable energy sources, reductions in coal and oil use, a sweeping change from private car use to public transport and bicycles and measures like reductions in subsidies to commuters and road pricing. It is obviously difficult to model the effects of regulations on aggregate output and, in the absence of sensitivity analysis, it is difficult to judge the reliability of such estimates. There may still be an important lesson: emission reductions could initially be achieved at little cost if existing sectoral policies are not optimal. Changes in transport and energy policies could provide a "cheap lunch" for a first set of cuts in CO2 emissions.

Other studies show that use of regulations instead of carbon taxes could be an expensive route towards achieving a cut in emissions. For example, Nordhaus (1990*b*) suggests that the use of regulatory mechanisms could reduce output growth by an additional ¼ percentage point for a 60 per cent reduction in emissions. Blitzer *et* al. (1990) present simulation results where emission targets do not apply to the economy as a whole, but are applied on a sector-by-sector basis. The loss in flexibility leads to a significant increase in economic costs as compared to an economy-wide emissions target.

Jorgenson and Wilcoxen (1990) also simulate reduction scenarios using taxes other than carbon taxes. A tax on the energy content (BTU tax) would increase the aggregate cost of achieving a given target slightly, while an ***ad valorem*** tax on primary fuels would increase it considerably (double it in the case of a 20 per cent emission reduction). The aggregate costs are higher because such taxes are less well focused on the carbon content of the different fuels.

Other policy considerations. The aggregate cost in terms of reduced output may depend crucially on the way the increased tax revenue is redistributed within countries. This issue is only addressed in the Norwegian SIMEN study (Bye *et* al., 1989), which considers the question of a rechannelling of tax receipts. A fiscally neutral policy is achieved by a cut in taxes on labour and capital. As no data or sensitivity analysis are provided, the labour and capital supply effects are unknown.

Glomsrød *et* al. (1990) also provide estimates of the benefits of reduced fossil-fuel use stemming from reductions in other pollutants, such as sulphur dioxide, nitrogen oxides, carbon monoxide and particulates. These emissions would fall roughly in line with emissions of CO_2. While unilateral action on COs would have virtually no benefit in terms of reduced warming globally, reductions in other pollutants would reduce local environmental damage. Calculations in this study indicate that the benefits from reducing other pollutants, as well as the benefits from cutting the number of traffic accidents and the level of traffic noise, would offset roughly two-thirds of the GDP loss due to the CO_2 emission ceiling.

C. Forestry options

Deforestation of tropical forests, especially of the Amazon rain forest, is contributing significantly to CO_2 emissions: estimates of carbon released range from *0.5* to *3* billion tons of carbon per year (Nordhaus, 1990*a*) relative to the *6* billion tons associated with current fossil-fuel use. Many observers argue that forest clearing is to a large extent uneconomic and mainly due to the absence of property rights for rain forests. If so, a significant reduction of emissions might therefore be achieved at low economic cost through a cessation of forest clearing.

Nordhaus *(1990* and 1990*a*) argues that reforestation – as opposed to merely arresting deforestation – is likely to be expensive. He presents estimates for three different schemes:

i) A subsidy to lumbering and forestry operations, which would reduce the input price of wood and expand its use. The subsidy could be as much as *$100* per ton of carbon and would absorb up to 0.28 billion tons of carbon per year.

ii) Reforestation of open areas, an option which could absorb 0.20 billion tons per year. The cost would range from $40 for low-cost tropical land to *$1 15* per ton of carbon for marginal land in the United States.

iii) A "tree set-aside programme", which would consist of the purchase and storage of trees. This is the most unattractive of the three schemes as it could cost *$500* per ton of carbon for low levels of absorption.

Blok *et al. (1989)* estimate that the cost of reforestation would be only $0.7 per ton of carbon, much less than Nordhaus's estimate. Differences arise because Nordhaus's estimate also includes land and management costs. In addition, the carbon removal rate per hectare and year is set at only *1.6* tons per year in Nordhaus's estimate but is four times higher in the estimate of Blok *et al.* Dutch utilities recently announced a scheme to reforest 10 000 hectares of tropical land in South America per year. They estimate the annual cost at Gld 40 million and reckon that a similar programme in the Netherlands would cost eight times as much *(Het Financiele Dagblad,* 1990). Applying the low removal rate of Nordhaus, the cost estimate of the Dutch utilities would just coincide with his estimate of about $40 per ton of carbon for low-cost tropical land. Dixon *et al. (1990)* estimate a cost of $4-8 per ton of carbon, based on a planting cost of *$1* 600 and an absorption rate of 20-40 tons per hectare per year.

Sedjo (1990) argues that, at an absorption rate of about 6 tons of carbon per hectare, the estimated current 3 billion tons of net "man-made" CO_2 emissions would require replanting an area of 465 million hectares. At current land and plantation costs, plantation of such an area would be $186 billion in the tropics and $372 billion in the United States.

The range of estimates concerning the reforestation option is very wide. The estimates are also all partial in nature and do not take into account the effects of large reforestation programmes on land and timber prices.

D. The cost of reducing CFC emissions

Curbing emissions of CFCs is of particular importance because they are the most powerful greenhouse gas and also affect the ozone layer. CFC production has increased rapidly in recent decades. In the absence of policy action it would most likely have continued to do *so* in the future (Mintzer, 1987).

In a follow-up to the Montreal agreement, about 100 countries, including the Soviet Union, India and China, signed a commitment to reduce emissions of ozone-depleting chemicals in the London agreement, which came into force in July 1990. The London agreement establishes a schedule for the phase-out of the most damaging CFCs by 2000. Some countries have announced an earlier phase-out by 1997.

Reductions in CFC emissions can be achieved by the use of substitutes, some of which have less or no radiative power. As some substitutes are relatively cheap, a sharp reduction can be achieved at relatively low cost compared with sharp reductions in other greenhouse gases. The official economic assessment following the Montreal agreement was of a partial nature, but indicated that available substitutes are cheap for most applications (UNEP, 1989). Nordhaus (1990) estimates that at a modest tax rate of $5 per ton of CO_2 equivalent, the greenhouse warming effect from CFC emissions would fall by more than two-thirds. Beyond that, the tax rate would rise rapidly. Recently, Smith and Vodden (1989) estimated the cost of fulfilling the Montreal agreement for Canada. Based on cost-curve estimates made by the U.S. Environmental Protection Agency, they calculated a present discounted value for the social cost of Canadian $0.2 billion for the period 1989 to 2075. Bailey (1982) calculated earlier that the discounted present value (over the period 1979 to 2100) of cutting CFC emissions in the United States by 50 per cent would be in the order of $0.2 to $2.2 billion (1978 dollars). The central estimate is $0.6 billion, a trivial amount as a per cent of GDP. But Bailey also showed a rapid increase in cost beyond a cut-back of more than two-thirds. The cost of reducing CFC emissions is nevertheless of a different order of magnitude from the cost of reducing CO_2 emissions *so* that, even in the absence of the effects of CFCs on the ozone layer, action on CFCs would be a prime candidate in any policy to reduce greenhouse gas emissions.

NOTES

1. All studies use the term "cost" in characterising GDP or consumption losses from the reference scenarios due to preventive action. However, none of the baseline scenarios includes estimates of the costs and benefits of climate change or other externalities due to increased fossil-fuel consumption. The term "cost" is inappropriate if such externalities exist or widen in the future. Furthermore, up to a certain point preventive action may be welfare improving. The economic dimension of environmental externalities is discussed in a broad context in Nicolaisen, Dean and Hoeller (1991) which appears in this volume.
2. A "back-stop technology" is a new or unproven technology which will be available in the future in abundant quantity (with no natural resource constraint), hence providing a ceiling to the eventual movement of the prices of existing resources.
3. For partial equilibrium analyses see, for instance, Chandler (1990), who surveys energy policy responses for eight countries, a similar study by Capros *er al*. (1990), a Report for the European Commission (1990) or Ingham and Ulph (1990). who concentrate on the U.K. manufacturing sector.
4. The OECD is just finalising a dynamic applied general equilibrium model, the so-called GREEN project. Having sufficient regional and sectoral detail, it can address most issues discussed below and aims specifically at the clarification of issues concerning cost-effective international agreements.
5. The number of fossil-fuel related CO_2 emission scenarios has become large (for an early survey, see Nordhaus and Yohe, 1983). The scenarios reviewed here are those for which reduction scenarios are also available as well as studies by Reilly *et al*. (1987) and Nordhaus and Yohe (1983) which focus on the probability distribution of emission scenarios.
6. Some modellers also present "green" baselines, which assume a continuing tightening of environmental standards for reasons other than the greenhouse effect (Bergman, 1989) and lead to policy-induced price rises. As policy measures in such scenarios aim mainly at a reduced use of coal and less traffic density or higher energy prices more generally, CO_2 emissions are lower.
7. Depletion of oil and gas reserves may, however, lead to development of other fossil-fuel sources with a high carbon content.
8. Barbier *et al*. (1990) survey available back-stop technologies and prices.
9. The estimate of an increase of only 50 per cent by 2075 by Reilly *er al*. (1987) is particularly interesting, as it is the result of an approach which allows the calculation of the probability distribution of future emissions (Monte Carlo analysis).
10. One response to the threat of climate change, which will not be discussed here, is climate engineering. Several ingenious schemes have been suggested, for instance to float latex in the oceans, paint roofs white or increase nutrients for algae in the ocean, which is likely to

speed up the uptake of carbon in the oceans. So far, the feasibility and effectiveness of these options is in doubt and cost estimates are shaky. The option of CO_2 scrubbing is technically feasible, but may be expensive. Blok et al. (1989) estimate that removal and disposal of CO_2 from stack gases would cost Gld 30-62 per ton of carbon dioxide. Disposal costs are likely to rise significantly after low-cost CO_2 storage facilities have been used up.

11. Sweden, Finland and the Netherlands have recently adopted carbon taxes at rates per ton of carbon of $1 1, $6.5 and $1.5, respectively.
12. The cuts in CO_2 emissions shown in single-country results may be deceptive as it is likely that energy-intensive products will be imported.
13. Changes in aggregate energy intensity (i.e. total or fossil-fuel requirements per unit of GDP) are a rough gauge of the assumptions of different models about the adaptability of the aggregate energy/GDP relationship. Bergman (1988) provides sensitivity analysis of the link for aggregate energy price shocks, but not for carbon taxes.

Annex

THE GREENHOUSE EFFECT

The Earth's climate is determined by a complex array of factors. One key factor is the so-called "greenhouse effect" which is due to the presence of heat-trapping gases in the lower atmosphere. The expression itself stems from the fact that "greenhouse gases" (GHGs) act as a jacket that keeps warmth (infrared rays) from escaping the Earth's atmosphere, in much the same way as glass traps heat in a greenhouse. The fact that the Earth is already as warm as it is, is due to the effect of naturally occurring GHGs. Even at relatively low atmospheric concentrations – the atmosphere consists of less than 0.05 per cent GHGs – the amount of heat that escapes the atmosphere decreases significantly and surface temperatures tend to rise (Schneider, 1989). Although intensely studied over the last few years, there are still many scientific uncertainties so that the exact extent and impact of "greenhouse warming" that seems to be due to increases in man-made GHGs is still undetermined.

The main GHG is carbon dioxide (CO_2). Other important GHGs are chlorofluorocarbons (CFCs), methane (CH_4) and nitrous oxide (N_2O). The main source of man-made GHG emissions is fossil-fuel combustion, which is estimated to be responsible for about 55-80 per cent of net "man-made" CO_2 emissions to the atmosphere (the rest stemming largely from deforestation); it is also a major source of N_2O and possibly methane emissions (IEA, 1989). Among GHGs, only CFCs are entirely independent of fossil-fuel use.

CO_2 emissions arising from fossil-fuel combustion are small compared to the natural cycle of carbon through and between natural sinks: the oceans, the biosphere and the atmosphere. Globally, the amount of carbon released annually through fossil-fuel burning is approximately 6 billion tons, which compares with gross emissions of 200 billion tons and a total atmospheric stock of carbon of about 700 billion tons. The fraction of "man-made" carbon emissions that remains in the atmosphere, rather than being absorbed in sinks, is believed to be around 60 per cent (Darmstadter and Edmonds, 1989).

For other GHGs, the relationship between emissions and greenhouse gas concentration levels is even more complex and relatively little is known about it. In the case of chemically unstable GHGs like CFCs, N_2O, ozone and water vapour, an essential feature of these relationships is the time period involved in disintegration of the gas into a non-GHG. CFC concentrations, for instance, are likely to increase only as long as the net emissions of CFCs exceed the net chemical transformation of airborne CFCs to non-GHGs. Annex Table A1 summarises the current concentration level of different GHGs as compared to the pre-industrial level. CO_2 concentration levels, for instance, have increased by 26 per cent since the late 18th century. As the lifetime and radiative power of GHG emissions differs, a greenhouse warming potential index can be constructed, which takes into account the different characteristics of GHGs. Annex Table A2 shows these characteristics in relation to a 1 kilogram emission of carbon dioxide over

Table A1. **Summary of major greenhouse gases affected by human activities**

	Carbon Dioxide	Methane	CFC-11	CFC-12	Nitrous Oxide
Atmospheric concentration	ppmv	ppmv	pptv	pptv	ppbv
Preindustrial (1750-1800)	280	0.8	0	0	288
Present day (1990)	353	1.72	280	484	310
Current rate of change per year	1.8 (0.5%)	0.015 (0.9%)	9.5 (4%)	17 (4%)	0.8 (0.25%)
Average atmospheric lifetime (years)	50-200'	10	65	130	150

ppmv equals parts per million by volume:
ppbv equals parts per billion by volume:
pptv equals parts per trillion by volume.
1. The way in which CO_2 is absorbed by the oceans and biosphere is not simple and a single value cannot be given.
Source: IPCC (1990).

Table A2. **Global warming potential'**

	Time horizon 20 yr.	100 yr.	Source of emission
Carbon dioxide	1	1	Largely from combustion of fossil fuels. Deforestation.
Methane (incl. indirect)	63	21	From fossil fuel combustion and a wide variety of biological and agricultural activities.
Nitrous oxide	270	290	From fertilisers and energy use.
CFC-11	4 500	3 500	Wholly industrial, from both aerosols and non-aerosols.
CFC-12	7 100	7 300	
HCFC-22	4 100	1 500	

1. The warming effect of an emission of 1 kg. of each gas relative to that of CO_2. These figures are best estimates calculated on the basis of the present-day atmospheric composition.
Source: IPCC (1990).

several time periods and Annex Table A3 shows the relative cumulated climate effect of 1990 man-made emissions. While the relative radiative power of CO_2 is much lower than that of the other gases, the quantities emitted are much larger, so that its relative contribution to greenhouse warming is close to 60 per cent.

Table **A3. The relative cumulative climate effect of 1990 man-made emissions**

	Greenhouse warming potential (100 yr. horizon)	1990 emissions (Tg)	Relative contribution over 100 yr.
Carbon dioxide	1	26 000[1]	61 %
Methane[2]	21	300	15 %
Nitrous oxide	290	6	4 %
CFCs	Various	0.9	11 %
HCFC-22	1 500	0.1	0.5 %
Others[2]	Various		8.5 %

1. 26 000 Tg (teragrams) of carbon dioxide equals 7 000 Tg (equals 7 Gigatons) of carbon.
2. These values include the indirect effect of these emissions on other greenhouse gases via chemical reactions in the atmosphere. Such estimates are highly modeldependent and should be considered preliminary and subject to change. The estimated effect of ozone is included under "others".

Source; IPCC (1990).

The IPCC (1990) argues that average global temperatures could rise from current levels by 1°C by 2025, in the absence of control policies, and continue to increase by an additional 2°C before the end of the next century – although it stresses that there is a great deal of uncertainty around these estimates. The range of potential warming from pre-industrial levels is usually estimated at 1.5°C to 4.5°C by the end of the next century. The wide range reflects uncertainties concerning future emissions and feedback effects from oceans, clouds and other ecosystems. The dates in the future at which GHG concentrations are likely to double vary in the studies examined in this survey, ranging from 2030 (Mintzer, 1987) to around 2060 (IPCC, 1990) to beyond 2075 (Edmonds and Reilly, 1987). To put estimated temperature increases in perspective, average global temperatures have fluctuated by as much as 10°C over the last 160 000 years and have increased by 0.3°C to 0.7°C over the last century. While this latter increase cannot be definitively attributed to the greenhouse effect, it is consistent with model simulations of climate changes caused by GHGs, given the uncertain delay arising from ocean absorption of GHGs and heat intake and from the uncertain effect of changes in the cloud cover (Houghton and Woodwell, 1989; EPA, 1989; Solow, 1990; and IPCC, 1990).

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