OECD Economics Department Working Papers No. 123

New Issues, New Results: The OECD's Second Survey of the Macroeconomic Costs of Reducing CO2 Emissions

Peter Hoeller,

Andrew Dean,

Masahiro Hayafuji

https://dx.doi.org/10.1787/725178447352

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OCDE/GD(92)141

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NEW ISSUES, NEW RESULTS: THE OECD'S SECOND SURVEY OF THE MACROECONOMIC COSTS OF REDUCING CO_2 EMISSIONS

This paper surveys empirical studies of the costs of reducing carbon dioxide emissions. It updates and extends an earlier paper, which focused on baseline emission scenarios and the aggregate cost of emission reductions. It attempts to explain some of the differences in simulation results and highlights some major policy issues.

* * * * *

Ce document passe en revue les études empiriques sur les coûts de réduction des émissions de dioxyde de carbone. Il met à jour et prolonge un document antérieur qui portait essentiellement sur des scénarios de référence concernant les émissions et sur le coût global des réductions des émissions. Il tente d'expliquer quelques unes des différences observées dans les résultats des simulations et met en lumière d'importantes questions de politique économique.

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New Issues, New Results: the OECD'S Second Survey of the Macroeconomic Costs of Reducing CO_2 Emissions

Peter Hoeller, Andrew Dean and Masahiro Hayafuji [1]

I. Introduction and Summary

A. The scope of the survey

Since the OECD's first survey was finished in late 1990 (Hoeller *et al.*, 1991) further research has improved the understanding of the economics of climate change [2]. This new survey provides an update and extension to the estimates of the macroeconomic costs of reducing carbon dioxide (CO_2) emissions and reviews a variety of policy-related topics which have not been covered in previous surveys.

There are two important limitations to the survey. First, the survey is confined to the economic issues and does not consider the scientific background (though the main factors were summarised in an Annex in the previous survey). The most important point to note is that even current levels of greenhouse gas concentrations are likely to lead to some warming and that the further projected increase of emissions might lead to a warming of 0.1°C to 0.5°C per decade over the next hundred years (IPCC, 1990). Second, the survey focuses on CO_2 emissions related to fossil-fuel burning, which are estimated to contribute between 50 and 70 per cent to global warming potential and does not cover sinks for CO_2 and other greenhouse gases. Options to halt deforestation and estimated costs of reforestation were discussed in the previous survey. Concerning other GHGs, the use of most chlorofluorocarbons will be phased out by the end of the century. For other GHGs, like methane and nitrogen oxide, sources of emissions are diverse and emission rates uncertain, so that most models do not include them [3].

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 1 to 2 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 "backstop technologies" [4]), energy prices and resource availability.

With emissions continuing to increase in reference scenarios, reductions from **current** levels imply very large decreases from the levels projected to occur in the long run. Different studies conclude that achieving large reductions of energy-related CO_2 emissions may lead to a reduction in annual growth rates of world GDP in the range of close to zero to 0.2 percentage points. Such small reductions in annual GDP growth rates relative to the no-policy change reference case can nevertheless imply large reductions in the level of GDP in the long run.

For the same constraint, simulations by different models show large differences for the required carbon taxes and for associated welfare losses. Such differences can mainly be explained by variations in assumptions about:

a) the degree of **substitutability** between the various energy sources and other inputs: the greater the degree of substitutability, the lower the cost will be in terms of output or welfare for any given reduction in energy use;

b) the availability of low-cost, low-carbon, **backstop technologies**: in models that include backstops, the price of carbon-free backstop technologies puts an upper cap on carbon taxes and lowers welfare losses as compared to models which do not incorporate them;

c) **capital formation**: the more inertia is assumed in capital stock turnover, the larger the cost will be, especially for sharp reductions in emissions;

d) **expectations formation**: most models assume myopic expectations, but a few models incorporate perfect foresight; for the latter, aggregate cost should be lower as firms and individuals can avoid sunk costs by basing today's decisions on expectations about future relative prices;

e) **trade flows**: few global models treat trade flows consistently; it is only such models which can analyse the income effects of terms-of-trade changes and so-called "carbon leakage" -- the tendency for the production of carbon-intensive products to migrate away from areas where policy aims to control CO_2 emissions;

f) **fossil-fuel supply**: supply is usually modelled in a very crude way, reflecting mainly the difficulties in pinning down OPEC behaviour in the face of demand shocks.

Concerning **issues of policy design**, an important determinant of aggregate cost is the way in which targets are set. Target setting which does not respect differences in abatement cost across sectors or countries, as with equi-proportionate cuts in emissions, is likely to be much more costly than targets which leave flexibility in abatement decisions. Gains due to flexibility in abatement increase disproportionately with the stringency of the target.

The **policy instruments** used to achieve emission reductions will also influence the size of the costs. A "command-and-control" approach or fiscal instruments which do not take account of the carbon content of fuels are likely to increase the macroeconomic cost significantly compared with approaches that operate through economic incentives: carbon taxes and emission trading. Both are likely to achieve emission constraints at least cost. However, the distribution of welfare changes across sectors and regions could differ widely as between the two cases.

Efficient abatement strategies i.e. cost-effective policies which just internalise future damage from warming, have been little researched. What is known about the benefits of avoiding climate change until the end of the next century would argue for only limited abatement in the near future, with the possible use of a slow and steady increase in carbon taxes. Taking account of the projected further build-up of concentrations beyond the next century and adopting a prudent stance concerning risks would argue for much larger abatement now and into the next century.

Most models assess the economic costs of abatement in terms of gross cost, e.g. not taking account of the supply-side effects of using the carbon tax revenue to reduce other distortionary taxes. Recent research points to a significant reduction in estimated costs if **recycling** of **tax revenues** is taken into account. Studies for the United States suggest that carbon taxes should be introduced for efficiency reasons alone, since the offsetting taxes can spur capital formation due to lower user cost of capital. In developing countries, where energy is currently untaxed, reducing distortionary taxes will nearly always lead to a more than complete offset, at least for small carbon taxes. Furthermore, **subsidies** to energy use are currently large in some non-OECD countries such as China, India, the former Soviet Union and the CEECs. Reducing subsidies could reduce emissions substantially and improve allocative efficiency.

II. The Models Covered in this Survey

The limited scope of this survey has already been mentioned above. In the overview tables, the studies covered are restricted to those which can show economy-wide effects [5], while the discussion of policy issues is restricted to papers which deal with the issues in quantitative terms. 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 results of about 25 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 models in terms of modelling the energy sector and its feedback to aggregate output are OECD's GREEN model (Burniaux *et al.*, 1992*c*) and the Global 2100 model of Manne and Richels (Manne, 1991) and a derivative of their model (Rutherford, 1992). OECD's GREEN model is described in more detail in the box overleaf. In Global 2100, the different regions have not been linked so far, so that the income and trade 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

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 coverage
	A. Global models				
Burniaux *et al.* (1992b)	Recursive dynamic general eq.	2050	8	11	12 regions
Manne/Richels (1990)	Dynamic optimising	2100	9	--	5 regions
Whalley/Wigle (1991 and 1992)	Static general equilibrium	2030 & 2100 (3)	2	5	6 regions
Edmonds/Reilly (1983) (4)	Partial optimising	2100	6	--	9 regions
Vouyoukas (1992), IEA	Econometric energy model	2005	5	9	10 regions
Nordhaus (1990)	Dynamic optimising	2100	2	--	World
Perroni/Rutherford (1991)	Static general equilibrium	2020	9	2	5 regions
Rutherford (1992)	Recursive dynamic general eq.	2100	7	2	5 regions
Peck and Teisberg (1990)	Dynamic optimising	2150	7	--	World
	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
Goulder (1991)	Dynamic general equilibrium	2065	4	11	United States
Blitzer *et al.* (1990)	Dynamic general equilibrium	2002	3	10	Egypt
Glomsrød *et al.* (1990)	Dynamic general equilibrium	2010	3	31	Norway
Bye *et al.* (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
Proost/Regemorter (1990)	Static general equilibrium	2005		11	Belgium
Christensen (1991)	Multi-sector macro	2010	10	23	Finland
Ban (1991)	Multi-sector macro	2000			Japan
Nagata *et al.* (1991)	Multi-sector macro	2005			Japan

1. Refers to the end-point of the simulations.
2. Includes electricity.
3. Calibrated on 1990-2030 and 1990-2100 average values, repectively.
4. This model is used by Cline (1989), Mintzer (1987), Edmonds and Barns (1990) and Barns *et al.* (1992).

The OECD's GREEN model

The OECD Secretariat has developed a multi-country, multi-sector, dynamic applied general equilibrium (AGE) model with the explicit aim of quantifying the economy-wide and global costs of policies to curb CO_2 emissions. There are several vintages of the model. The version mainly discussed here, is the one used for OECD's Model Comparisons Project. It has a medium-term focus in terms of the CO_2 issue: it runs over a 65-year time horizon from 1985 to 2050.

There are twelve detailed **regional** sub-models: four OECD regions (the United States, Japan, the EC and other OECD) and eight non-OECD regions (the former Soviet Union, Eastern Europe, China, India, the energy-exporting LDCs, the Dynamic Asian Economies, Brazil and a Rest-of-the-World grouping). Because of the global nature of the GHG problem, it was decided to pay specific attention to modelling some key non-OECD regions.

There are eleven **producing** sectors in GREEN, chosen to highlight the relationships between resource depletion, energy production, energy use and CO_2 emissions. Since the main source of manmade CO_2 emissions arises from the burning of fossil fuels, the key focus is on the energy sector. Three sources of conventional fossil-fuel energy -- oil, natural gas and coal -- and one source of conventional non-fossil (so-called "carbon-free") energy are distinguished. The carbon-free energy source includes nuclear, solar and hydro power. Both carbon-based and carbon-free backstop technologies are available for all conventional energy sources at given costs and introduction dates. The production side of each regional model describes in a detailed way the supply of fossil fuels and the use of fossil and non-fossil energy inputs in the productive process. Some allowance is also made for shifts in the composition of production by treating agriculture as a separate sector, and by distinguishing between two broad aggregates, energy-intensive industries and other industries and services.

Consumer demand is split between four broad aggregates: food and beverages, fuel and power, transport and communication and other goods and services, and saving -- which is treated implicitly as a "fifth good". Thus, shifts in energy prices affect the structure of consumer demands directly and the consumption/saving mix through changes in real income.

The current version of GREEN has a simple recursive dynamic structure, in which saving decisions affect future economic outcomes through the accumulation of productive capital. In the version mainly discussed here, capital accumulation is modelled in a putty/semi-putty fashion.

An earlier version of the model and preliminary simulation results are documented in Burniaux *et al.*, 1991. The new version and simulation results are discussed in Burniaux *et al.*, 1992*b* and 1992*c*. A forthcoming special issue of the OECD Economic Studies will include a variety of policy-relevant simulations.

Global 2100 allows for trade in permits. In addition, the model does not distinguish among different industrial sectors. Rutherford's Carbon Rights Trade Model (CRTM) modifies Global 2100 to include consistent trade links, though at the expense of departing from the assumption of perfect foresight to myopic expectations. In this respect, CRTM is therefore like GREEN, with regions being linked by trade and myopic behaviour being assumed.

The model of Whalley and Wigle (1991 and 1992), though lacking dynamics (it is a comparative-static applied general equilibrium model), does have global consistency, with trade links and some sectoral disaggregation. It is thus also able to give insights into the effects of different types of international agreement to tackle global warming. Models with a sophisticated treatment of the energy sector, but less developed macroeconomic linkages, include those of Edmonds and Reilly (1983), Nordhaus (1991) and the IEA (1990).

The models of Nordhaus (1991*b*) and Peck and Teisberg (1990) are also global in nature, but treat the world as one entity, with little sectoral detail. On the other hand, their models relate CO_2 emissions to atmospheric concentrations and concentration levels to climate change and the economic impacts of warming. As both cost and benefits are dealt with in these models, they can answer questions about efficient intertemporal climate change policies which the other more partial, cost-oriented models cannot.

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 in a single-country framework. There is also a trade-off between the regional and sectoral coverage of the models, as evidenced by the large difference in industry detail between the global and single-country models. A wider regional coverage is important for the analysis of the international trade and welfare consequences of different types of international agreement, while greater sectoral disaggregation 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 many projections of global GHG emissions run until the end of the 21st century (see Table 1). Many country models, on the other hand, focus on the short and medium term, reflecting the policy-maker's time horizon and perhaps the realisation that unilateral reductions would change global concentration levels little over the long run and would be extremely costly relative to the benefit for the country.

Different types of model are designed to 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 able to model 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.

III. Baseline Scenarios

A. Key determinants of baseline CO_2 emissions [6]

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 projected slowing of population growth in developing countries. A common feature is the assumption of much faster average growth rates in developing than in developed countries. Except for Nordhaus (1991*b*) and Peck and Teisberg (1990), none of the baseline projections of future growth include an estimate of the potential cost and benefits of climate change, the baselines being run off models which do not include climatic feedback (positive or negative). The results quoted for the costs of policies to slow climate change are therefore often presented as partial estimates with reference to a baseline which is implicitly not affected by the damage that climate change is expected to cause. This is an apparent contradiction which is insufficiently stressed in such research.

Energy efficiency. This is a key exogenous parameter in the models. Estimates of the baseline growth in autonomous energy efficiency range from zero to 1 per cent per annum for different regions in Manne (1992), though converging to a common 1/2 per cent increase for all regions by 2050. Mintzer (1987), Barns *et al.* (1992), the OECD's GREEN model (Oliveira Martins *et al.*, 1992) and the latest IPCC scenarios assume long-term average growth rates of 1 per cent or close to 1 per cent, while Whalley and Wigle (1992) assume no improvement in energy efficiency.

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 oil and gas prices. Most baseline scenarios suggest that the use of oil and gas will be subject to supply-side constraints even in the absence of specific policies to limit GHG emissions.

Table 2. **Baseline projections of key variables** (1)

	Projection period	Annual growth rates						
		GDP	Energy efficiency	Final energy demand		Energy prices		CO_2 equiv. emissions
				Total	Fossil	Total	Fossil	
<u>**Global studies**</u>								
Burniaux ***et al.*** (1992b)	1985-2050	2.5	1.0					2.0
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
Reilly ***et al.*** (1987)	1975-2075		1.0					0.5
Mintzer (1987)	1975-2075	2.0	0.8	1.3				1.5
Nordhaus/Yohe (1983)	1975-2100	2.1		1.4	0.9	0.2	1.0	1.2
Nordhaus (1990)		1.1						1.1
Edmonds/Barns (1990)	1988-2025	3.0	1.0	2.0				1.2
Peck and Teisberg (1990)	1990-2150							1.6
<u>**National studies**</u>								
Bye ***et al.***(1989) (Norway)	1988-2000	1.5		1.1				1.6
Glomsrød ***et al.*** (1990) (Norway)	2000-2010	2.7					1.0	3.9
Blitzer ***et al.*** (1990) (Egypt)	1987-2002	3.5						2.2
Bergman (1990) (Sweden)	1985-2000	2.0		0.7				5.3
Dixon ***et al.*** (1989) (Australia)	1989-2005	3.4		2.6 (2)				2.7 (2)
CBO (1990) (USA)	1988-2000				1.1			1.1
Goulder (1991) (USA)	1990-2065	2.0						1.8
Christensen (1991) (Finland)	1991-2000	2.6	1.0					1.4
	2000-2010	2.3	1.0					1.4
Ban (1991) (Japan)	1990-2000	3.8						1.6
Nagata ***et al.*** (1991) (Japan)	1988-2000	3.9						2.2
	2000-2005	3.1						0.9

1. **Emission paths for the six global models in OECD's Model Comparisons Exercise are shown in Chart 1 and discussed in detail in Dean and Hoeller (1992).**

2. For electricity and road transport.

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.

Backstop technologies. Few models introduce backstop technologies explicitly. This is of little importance for baselines spanning only the next thirty years. However, they may play an important role afterwards in shaping emission scenarios. On the one hand, lower oil and gas reserves may lead to the introduction of synfuels with a high carbon content. On the other hand, increasing fossil-fuel prices may make carbon-free backstop technologies competitive. The assumptions used by the Energy Modelling Forum 12 (EMF12) and OECD's Model Comparisons Project about backstop prices and a comparison with current end-use prices is shown in Table 3. On these assumptions, coal-based or shale-based liquid synthetic fuels would be close to being competitive in a few countries, while the prices of conventional fossil fuels would still need to increase considerably in order to reach the backstop price for the carbon-free liquid fuel. However, the backstop price for a carbon-free electric option is close to the current after-tax price for electricity in some countries.

The backstop technologies shown in Table 3 are assumed to come on-stream in all countries only from 2010 onwards [7]. Using the EMF12 assumptions about backstop prices and introduction dates leads to a virtual phase-out of carbon-based energy in the electricity generating sector between 2030 and 2060 in the baseline scenarios of Manne (1992) and Rutherford (1992). Carbon intensity in the non-electric sector would increase sharply, on the other hand, with the introduction of the "dirty" synfuels. Fossil-fuel based energy prices in the non-electric sector do not increase to the level of the carbon-free backstop technology until the end of the next century.

Policy assumptions. None of the emission scenarios take account of the repercussions of possible further increases in the cost of environmental policies on energy use. Given the severe air pollution problems in many developing countries and ambitious policies in most OECD countries to further curb emissions other than CO_2, emission scenarios as shown in the table may exaggerate future emission growth. Bergman (1990), for instance, shows in a simulation exercise for Sweden that the current commitments of the Swedish Government to sharply reduce sulphur and nitrogen emissions may stabilise CO_2 emissions between the early 1980s and mid-1990s. In the absence of these policies, CO_2 emissions would have increased at an annual rate of 3 per cent. Japanese emission scenarios show that the official commitment to a stabilisation of CO_2 emissions in per-capita terms could be achieved by expansion of nuclear and other non-fossil fuel sources (MITI, 1991).

The recent political and economic changes in central and Eastern Europe are not yet reflected in the baseline scenarios discussed here. Output may be depressed for a considerable time, which would tend to lower emissions in the near term. An allowance for this has been made in the most recent IPCC scenarios. More importantly, most of these countries have embarked on energy price reforms which will increase their energy prices to world market levels. Calculations with a simple energy demand model suggest, that such moves could reduce emissions in Poland, Hungary and the CSFR by approximately 30 per cent

Table 3. **Backstop prices** (1)

Coal or shale-based liquid synthetic fuel	$314 per toe (2)
Carbon-free liquid fuel	$629 per toe (2)
Carbon-free electric option	7.5 cents per kWh
<u>Memorandum items</u>:	
Price band for heavy fuel oil in industry in OECD countries	$114-386 per toe (3)
Price band for electricity in industry in OECD countries	3.2-13.3 cents per kWh (4)

1. Assumption for EMF12 project and OECD's Model Comparisons Project. Backstop technologies are assumed to come on-stream in 2010.
2. Ton of oil equivalent.
3. 1990 average prices after tax.
4. 1989 average prices after tax; includes distribution cost.

Sources: EMF12 and IEA, *Energy Prices and Taxes.*

(Unterwurzacher and Wirl, 1991). Simulations of the removal of price distortions in energy markets with the GREEN model are reported below (Burniaux, 1992*b*).

B. The range of growth rates for CO_2 emissions

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 1 to 2 per cent for the world as a whole for the period to 2100. All scenarios point to faster growth of emissions over the next decades and some slowdown thereafter. They also suggest that emissions will grow much faster in developing than in developed countries.

Differences in the various projections of man-made CO_2 emissions shown in Table 2 reflect differences in assumptions about output growth, real energy price developments and energy efficiency improvements. As an important input to the OECD's Model Comparisons Project (see box overleaf), the six modelling teams which participated in the exercise were asked to run emission scenarios using the same key assumptions on output and population growth, the energy resource base and prices for backstop technologies. Even after standardisation, emission scenarios differed by substantial amounts (Chart 1). The model of Manne and Richels, for instance, projected emissions in 2100 almost double those projected by the Edmonds-Reilly model. Sensitivity analysis showed, however, that imposing the same assumption for autonomous energy efficiency improvement would lead to rather similar emissions in 2100 in these two models. The difference between the two models in the assumption about autonomous energy efficiency improvements is only 1/2 per cent per year and shows the importance of small differences in the growth rate of key variables leading to large differences in emission levels in the long run.

IV. CO_2 Emission Reduction Scenarios: an Update [8]

A. Aggregate effects of CO_2 emission reductions

Reduction targets. CO_2 reduction targets in the studies reviewed here are usually specified with respect to the base-year. As emissions are increasing over time, any reduction of emissions from current levels implies very large reductions from the business-as-usual scenarios in the long-run. If reduction targets are set relative to the base-year and are the same across regions, then planned reductions across regions for future target dates will differ by large amounts. Because the growth dynamics would make it very difficult for developing countries to adhere to an absolute cap in emissions, many studies assume less stringent targets for them.

The mechanisms for reducing emissions. The main policy instruments considered in almost all models are taxes differentiated by the carbon content of the different types of fossil fuels. Taxes are differentiated because carbon emissions from oil are lower than for coal, and are lower still for natural gas. Emission factors and mechanical fuel-price implications of a

OECD's Model Comparisons Project

Surveys of the economic costs of reducing CO_2 emissions have highlighted large differences in model results, without being able to explain such differences in a satisfactory way. The OECD's model comparisons project is an attempt to better understand the way various **global** models work by standardising key assumptions and emission reduction targets and conducting some limited sensitivity analysis. The OECD project has proceeded in close co-operation with a more comprehensive exercise by the Energy Modelling Forum of Stanford University (EMF12). The latter exercise involves more models and has a stronger focus on detailed energy sector results. Results of the EMF12 exercise will be released during 1992.

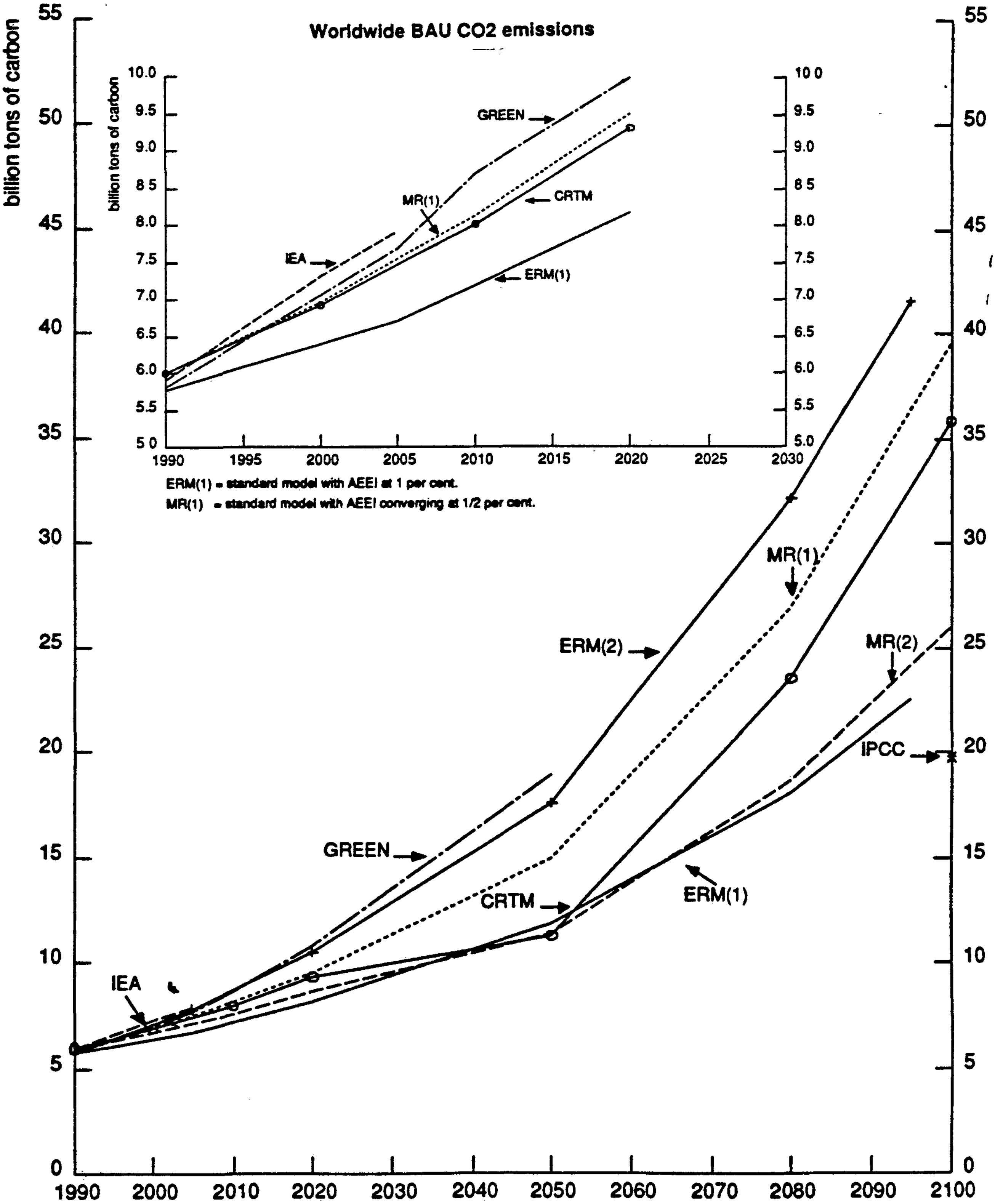
Six global models participated in the OECD project: the models of Edmonds and Reilly, Manne and Richels, Rutherford, Whalley and Wigle, the IEA model and the OECD's GREEN model. The main features of these models are shown in Table 1.

As regards the baseline, the modellers were asked to follow the EMF12 project's assumptions for output and population growth, for the cost of backstop technologies, for the world oil price and for the size of oil and gas reserves. In order to reduce the dependence of simulation outcomes on baseline emission paths, reduction targets are specified in terms of changes in the baseline growth rate of emissions of 1, 2 and 3 percentage points, respectively. In addition, each modeller was asked to provide a simulation in which emissions were stabilised at 1990 levels.

In order to achieve those reduction targets, modellers were asked to use a carbon tax as the policy instrument. Where possible, they were also asked to report results of using tradeable permits, the initial allocation of permits being based on the targeted emission levels by region. The modellers were also requested to provide sensitivity analysis of their results, mainly for changes in autonomous energy efficiency improvements and inter-fuel substitution elasticities.

Results of the model comparisons project have been published in a series of Economics Department Working Papers together with an overview paper (Dean and Hoeller, 1992).

Chart 1. Business-as-usual scenarios for five global models



Sources:

ERM(1) = standard model with AEEI at 1 per cent; Barns et al., 1992.
ERM(2) = model with AEEI at 1/2 per cent; Barns et al., 1992.
MR(1) = standard model with AEEI converging at 1/2 per cent; Manne, 1992.
MR(2) = model with AEEI at 1 per cent; Manne, 1992.
IPCC = the new (1992) IPCC reference case.
GREEN = Oliveira Martins et al., 1992.
IEA = Vouyoukas, 1992.
CRTM = Rutherford, 1992.

$100 carbon tax are shown in Table 4. While the price of coal would go up most after the imposition of a carbon tax and that of gas the least in absolute terms, changes in end-use prices critically depend on the taxes already in place. Because existing taxes on these fuels differ widely, both within and across countries, the proportionate increases in energy prices arising from a carbon tax would therefore differ considerably between countries and fuels. Apart from taxes, some models can also simulate permit trading systems, but only a few studies consider a regulatory approach to emission reductions.

Key determinants of aggregate costs have been discussed in some detail in the previous survey (see also Boero *et al.*, 1991). Aggregate costs are influenced by the ease with which producers and consumers can switch from high-carbon content fuels to low-carbon content fuels. In addition, an increase in aggregate energy prices will lead to substitution between energy and other factors of production and change consumption patterns away from energy-intensive products. The greater the substitution possibilities, the lower the aggregate cost will be. Aggregate cost may also be lowered if higher energy prices spur investment in, and greater diffusion of, energy-saving technical progress.

The few models with endogenous trade highlight the importance of terms-of-trade effects on income flows. An increase in fossil-fuel prices in energy-importing countries, for instance, is likely to strongly affect the revenues of energy producers. Similarly, permit trading could lead to large income transfers between countries and thereby affect aggregate welfare outcomes.

In the following overview table and remainder of the text, aggregate costs are equated with output losses. This choice is largely dictated by the availability of the relevant variables in the different models. Focusing on a welfare measure such as the Hicksian equivalent or compensating variation would be a better choice. For example, Burniaux *et al.* (1992*b*) and Whalley and Wigle (1992) calculate welfare losses using a static version of the Hicksian equivalent variation. In addition, it is often assumed that there is a diminishing marginal utility of income and that people value current consumption higher than future consumption. The latter is captured in intertemporal utility functions in the models of Manne and Richels (1990), Jorgenson and Wilcoxen (1991), Goulder (1991) and Blitzer *et al.* (1990).

The ***effects on growth*** of CO_2 emission reductions are summarised in Tables 5 and 6 for the models under review. Column 2 in Tables 5 and 6 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 depends on the length of the simulation period). Most simulations of large emission abatement indicate long-run reductions in growth rates of between zero and 0.2 per cent annually. As noted above, these comparisons of GDP growth trajectories hinge on the assumption that climate change does not affect the baseline growth rates so that the results are partial, being confined to cost estimates.

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 would be a significant 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

Table 4. **Emission factors and fuel price effects of a $100 carbon tax**

$US, 1988

A. Price effect on primary energy sources

	Crude Oil	Coal	Natural Gas
Unit of measure	Barrel	Metric ton	Ton of oil equivalent
Tons of carbon/unit of fuel	0.12	0.61	0.60
World market price ($)	14.9 (1)	44.0 (2)	95.0 (3)
Absolute tax ($)	12.0	60.5	60.0
Price increases, per cent	81%	138%	63%

B. Price effect on end-use prices (per ton of oil equivalent)

	Gasoline			Steam coal			Gas price for households		
	United States	Japan	Germany	United States	Japan	Germany	United States	Japan	Germany
End-use price, ($)	299.5	1 084.5	720.4	58.4	110.7	252.3	234.2	1 086.7	353.2
Price increase, per cent	26.0	7.2	10.8	167.8	88.5	38.8	25.6	5.5	17.0

1. IEA country average import price.
2. OECD average steam coal import price.
3. EC average import price by pipeline.

Source: IEA, *Energy Prices and Taxes;* IEA (1991), *Greenhouse Gas Emissions: the Energy Dimension*, Paris.

Table 5. Growth effect of CO_2 emission reductions: global models (1)

	[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) End-year
Oliveira Martins *et al.* (1992)	-70 (2050)	-0.0	-2.6	230
Manne/Richels (1990)				
USA	-75 (2100)	-0.0	-2.5	-250 (2)
Other OECD		-0.0	-1.8	
Eastern Europe		-0.0	-2.5	
China		-0.1	-10.5	
Rest of world		-0.0	-4.0	
Whalley/Wigle (1991) (3)				
National producer taxes	-50	..	-4.4 (4)	462.8
National consumer taxes	-50	..	-2.1 (4)	463.1
Global tax	-50	..	-4.2 (4)	459.7
Ceiling on per-capita emissions	-50	..	-8.5 (4)	..
Cline (1989)	-65.5 (2075)	-0.1	-7.4	..
Mintzer (1987)	-88 (2100)	-0.0	-3.0	..
IEA (1990) (5)				
Carbon tax scenario	-12 (2005)	-0.2	..	72
70% nuclear plus carbon tax scenario	-25 (2005)	-0.2	..	72
Nordhaus (1990 and 1991)				
Low	-30	-0.0	..	48.5 (6)
Middle	-50	-0.0	..	119.0 (6)
High	-80	-0.1	..	..
Nordhaus (1990)				
Rapid phase-in scenario	-60	-0.3 (7)	..	..
Rapid phase-in using regulation	-60	-0.5 (7)	..	..
Edmonds/Barns (1990)	-75 (2025)	-0.2	-8.0	436.5
Perroni/Rutherford (1991)	-23 (2010)		-1.0	

1. Some results for the six global models participating in the OECD's Model Comparisons Exercise are shown in Charts 2 and 3 and Table 7. Detailed results can be found in Dean and Hoeller (1992).
2. Tax rates differ across region before the introduction of back-stop technologies.
3. Target and results apply to average values over 1990 to 2030.
4. Welfare effect measured by Hicksian equivalent variation.
5. Policy and results apply only to the OECD countries.
6. Includes sharp reduction in CFCs. The carbon tax per CO_2 equivalent without a reduction of CFCs would be about $90 and $200 for the two scenarios.
7. For the industrialised countries.

Table 6. 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) End-year
Manne/Richels (1990a, USA)				
a) technology pessimistic case	-88 (2100)	-0.1	-4.0	-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
DGEM	-36 (2000)	-0.1	-0.6	100
Jorgenson/Wilcoxen (1991, USA)	-8 (2020)	..	-0.3	7 (2020)
	-14 (2020)	..	-0.5	17 (2020)
	-32 (2020)	..	-1.6	60 (2020)
Goulder (1991, USA)	-13 (2050)	..	-1.0	25
	-18 (2050)	..	-2.2	50
	-27 (2050)	..	-4.5	100
Blitzer *et al.* (1990, Egypt)				
Scenario 1	-15 (1) (2002)	-0.1	-2.7	..
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	..
Bye *et al.* (2) (1989, Norway) (2000)	-16	-0.1 to -0.2	-1 to -2	..
NEPP (1989, Netherlands) (2)				
National policy scenario (2010)	-25	-0.2	-4.2	..
Global policy scenario (2010)	-25	0.0	0.6	..
Bergman (1990, Sweden) (2000)	-51	-0.4	-5.6	..
Dixon *et al.* (1989, Australia)	-47 (3) (2005)	-0.1	-2.4	..

Table 6 (continued). 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) End-year
Proost/Regemorter(1990, Belgium)	-28 (2010)	..	-1.8	315 (2010)
Christensen (1991, Finland)				
Unilateral action	-23 (2010)	-0.4	-6.9	..
Global action	-21 (2010)	-0.3	-4.8	..
DRI (1991, EC) (4)	-12 (2005)	-0.1	-0.8	80 (2005)
Nagata *et. al* (1991, Japan)	-26 (2005)	-0.3	-4.9	492 (2005)
Ban (1991, Japan)				
Tax case	-18 (2000)	..	-0.4 (5)	..
Regulation case	-18 (2000)	..	-1.7 (5)	..

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.
4. EC policy package, which is a mix of regulation and taxation.
5. Consumption change.

column in Tables 5 and 6 shows carbon taxes -- defined in $ per ton of carbon -- for the end-years of the emission reduction scenarios. While there is significant variation in tax rates for the same amount of emission reduction among models, three messages emerge:

a) small amounts of emissions reduction can probably be achieved at low cost;

b) large reductions can only be achieved at high tax rates, i.e. marginal reduction costs rise with emission reductions; and

c) backstop technologies are likely to slow the rise of the carbon tax or halt it all together, if they are available at constant marginal cost.

Simulation results from the OECD's Model Comparisons Project for the United States and China are shown in Chart 2 and an overview for one of the scenarios in Table 7 (more detail is provided by Dean and Hoeller, 1992). There is broad agreement about output losses among models for the United States up to a reduction of about 50 per cent. Afterwards, results diverge significantly, mainly because the models of Manne-Richels, Rutherford and Oliveira Martins *et al.* incorporate backstop technologies, while the other models do not. For the other regions, results differ considerably, with costs being large for some developing countries (Table 7 and Chart 2 for China). The same is true for carbon taxes, where results among models differ considerably for developing countries (see Table 7 and Chart 3 for the United States and China).

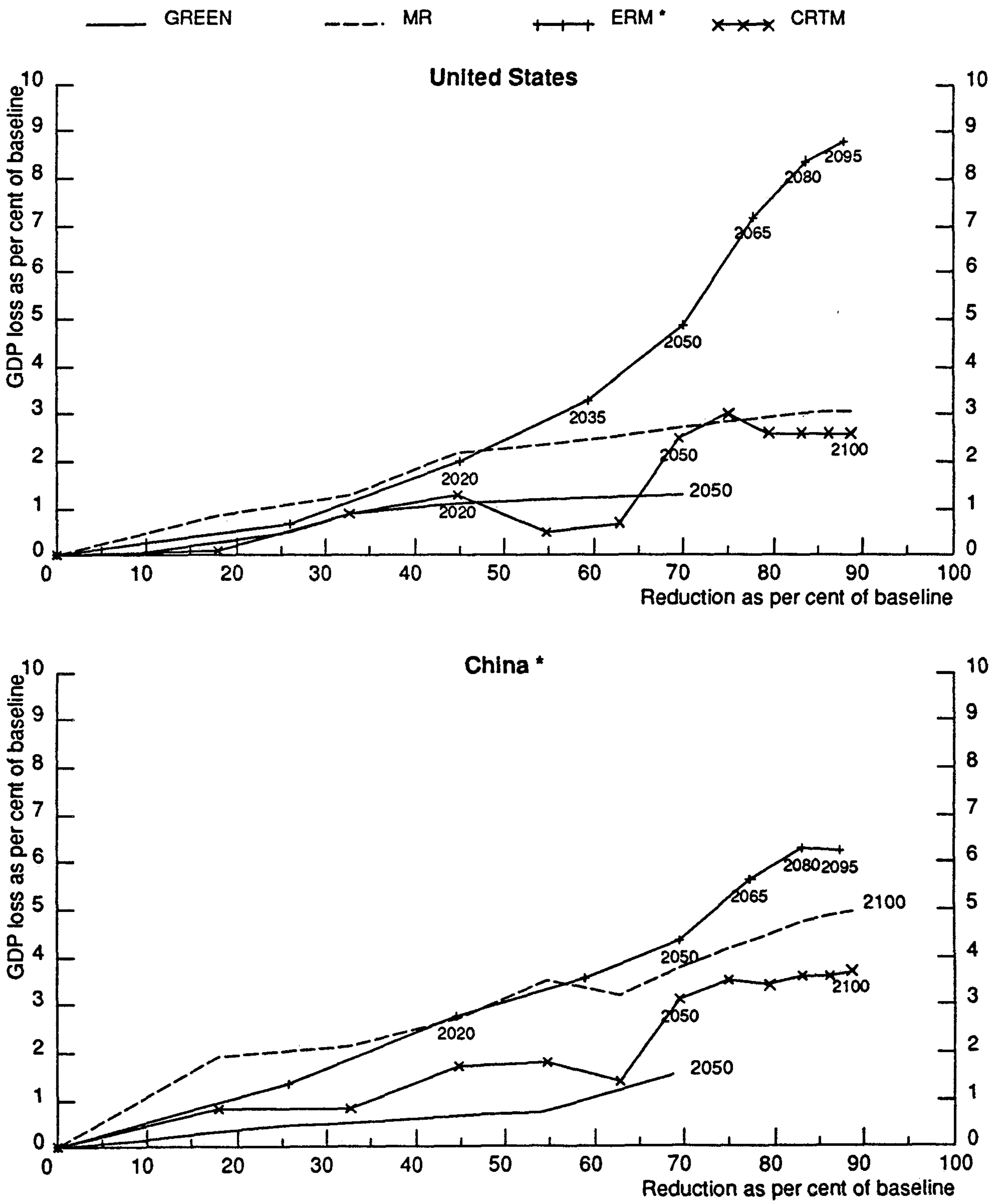
Oliveira Martins *et al.* (1992) show large regional differences in GDP and household real income changes for some regions. The difference is especially large for the energy-exporting LDCs, reflecting a large fall in their terms-of-trade.

B. Why do model results differ?

Baseline energy prices. Reported simulation results of most global models are rich in detail on quantities but much less so on prices. Baseline prices for energy vary considerably across country and region; they have a considerable influence on model outcomes. In GREEN and the IEA model, where data bases on prices have been built up from primary sources, the ranking of regional levels of carbon taxes to reach certain emission targets largely reflects the ranking of levels of initial prices. Where prices are low initially, as in the former Soviet Union and China, carbon taxes to achieve the same given amount of reduction across countries are relatively low, while they are high in countries with higher initial prices, for instance, Japan. In general the carbon tax needs to be higher in "high-price" countries because they are already much more efficient in their use of energy, while countries with low prices use more energy per unit of output.

Substitution elasticities. Apart from baseline prices and initial fuel proportions, elasticities of substitution between fuels and aggregate inputs are of crucial importance for model outcomes. Table 8 summarises critical parameters for the models participating in OECD's Model Comparisons Project [9].

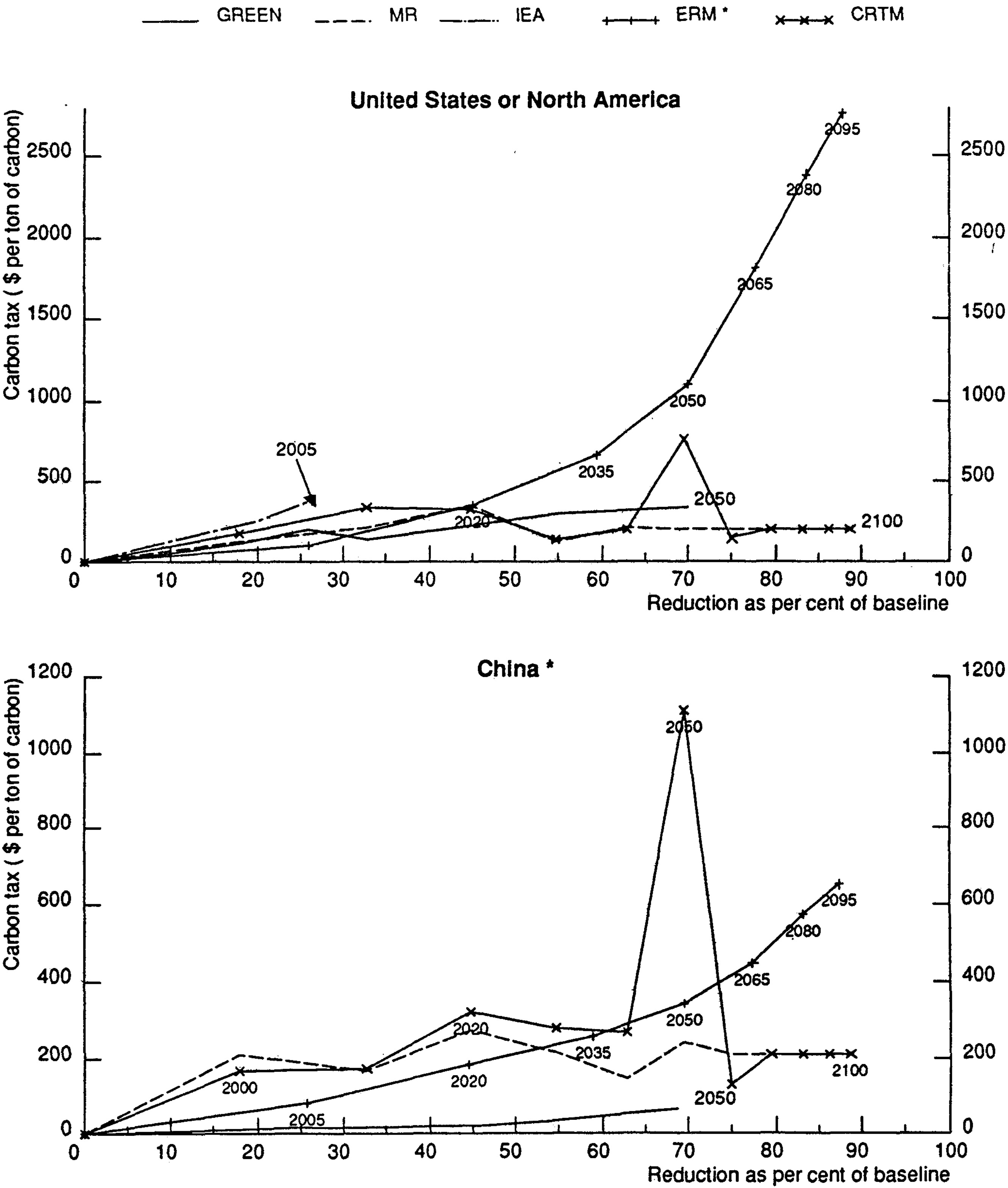
Chart 2. **Output losses for the United States and China**



* ERM includes Asian CPE's.

Sources: GREEN(Oliveira Martins et al., 1992); MR(Manne, 1992); ERM(Barns et al., 1992); CRTM(Rutherford, 1992).

Chart 3. **Carbon taxes for the United States and China**



* ERM includes Asian CPE's.

Sources:GREEN(Oliveira Martins et al., 1992); MR(Manne, 1992); ERM(Barns et al., 1992); CRTM(Rutherford, 1992).

Table 7. **A summary of results from OECD's Model Comparisons Project**

Simulation results for a 2 percentage point
reduction in baseline emission growth

A. Carbon taxes ($/ton of carbon) (1)

	Barns *et al.* (1992)			Oliveira Martins *et al.* (1992)		Manne (1992)			Rutherford (1992)		
Year	2020	2050	2095	2020	2050	2020	2050	2100	2020	2050	2100
United States	351	1 095	2 754	223	340	354	208	208	324	754	208
Other OECD	342	734	1 240	239	299	241	208	208	233	365	208
China	182	341	651	26	67	271	240	208	320	1 109	208
Former USSR	104	325	719	69	180	301	990	758	322	2 245	758
RoW	430	1 012	2 021	184	329	399	727	208	409	763	208
Total	283	680	1 304	149	230	171	448	242	325	884	235

B. Change in GDP relative to baseline (% loss)

	Barns *et al.* (1992)			Oliveira Martins *et al.* (1992)		Manne (1992)			Rutherford (1992)		
Year	2020	2050	2095	2020	2050	2020	2050	2100	2020	2050	2100
United States	2.0	4.9	8.8	1.1	1.3	2.2	2.7	3.1	1.3	2.5	2.6
Other OECD	1.9	3.4	4.8	1.2	1.6	1.1	1.6	1.9	0.4	1.1	1.5
China	2.8	4.3	6.2	0.7	1.5	2.7	3.8	5.0	2.0	3.1	3.6
Former USSR	0.9	2.3	3.7	1.7	3.7	3.1	6.4	5.6	1.5	5.8	4.1
RoW	2.0	3.5	5.1	3.8	4.4	4.9	5.1	5.6	2.3	2.1	4.5
Total	1.9	3.8	5.8	1.9	2.6	2.9	3.7	4.7	1.5	2.4	3.6

1. Carbon taxes for the United States and the Other OECD are $376 and $548, respectively, for the IEA's model in 2005.

Note: The 2 percentage point reduction in the growth rate of emissions corresponds to a cut from the BaU emissions path of about 45 per cent in 2020, 70 per cent in 2050, and 88 per cent in 2095/2100.

Table 8. **Key parameters in five global models** (1)

	United States	Other OECD	Former Soviet Union	China	RoW
Autonomous energy efficiency improvement (AEEI):					
Barns *et al.*	1.0	1.0	1.0	1.0	1.0
Manne (2)	0.5	0.5	0.25	1.0	0.0
Whalley/Wigle	0.0	0.0	0.0	0.0	0.0
Vouyoukas (3)	~1.1	~1.1	..	..	..
Burniaux *et al.*	1.0	1.0	1.0	1.0	1.0
Elasticity of substitution between energy and other factors of production:					
Barns *et al.*	..	..	..	..	..
Manne	0.4	0.4	0.3	0.3	0.3
Whalley/Wigle (4)	0.7	0.7	0.7	0.7	0.7
Vouyoukas	..	..	..	..	..
Burniaux	E-K L-KE	E-K L-KE	E-K L-KE	E-K L-KE	E-K L-KE
et al. (5)	0.6 1.0	0.6 1.0	0.6 1.0	0.6 1.0	0.6 1.0
Interfuel substitution elasticities in production:					
Barns *et al.*	..	..	..	..	..
Manne	..	..	..	..	..
Whalley/Wigle (6)	5.0	5.0	5.0	5.0	5.0
Vouyoukas (3)	~0.5	~0.5	..	..	..
Burniaux *et al.*	2.0	2.0	2.0	2.0	2.0
Interfuel substitution elasticities in final demand:					
Barns *et al.*	..	..	..	..	..
Manne	..	..	..	..	..
Whalley/Wigle	5.0	5.0	5.0	5.0	5.0
Vouyoukas	..	..	..	..	..
Burniaux *et al.*	1.2	1.2	1.2	1.2	1.2

Energy supply elasticities:

Barns *et al.*	Oil	1.0
	Coal	1.0
Whalley/Wigle	Carbon-based	1.0
	Carbon-free	1.0
Burniaux *et al.*	Carbon-free	0.2
	Coal	5.0
	Oil	between 1 and 3

---

1. Regional disaggregation is not the same for all models.
2. AEEI is the same across regions from 2050 at 0.5.
3. Numbers are approximate averages over a variety of parameter values for different fuels and sectors.
4. For the production of energy, the elasticity is 1.0.
5. Elasticities shown are long-run values; in the short run, they are about one-tenth of the long-run values.
6. No substitution between fossil fuels; elasticity applies to substitution between fossil and non-fossil energy sources.

Source: Barns *et al.* (1992); Manne (1992); Whalley and Wigle (1992); Vouyoukas (1992); and Burniaux *et al.* (1992*c*).

The regional variation of substitution elasticities within each model is minor, so that differences in substitution elasticities do not seem to be responsible for the large dispersion of carbon taxes across regions within each model. Elasticities, however, vary significantly across models. The IEA model uses much lower substitution elasticities and shows much higher carbon taxes than the other models. Hence, emission reductions in the IEA model are mainly achieved by reductions in aggregate energy. In the other models participating in the Model Comparisons Project, substitution between fossil fuels and between fossil and non-fossil fuels contributes about half or even more to the emission reductions in most regions. Reductions in aggregate energy are less important, and carbon taxes and aggregate costs are lower.

The importance of differences in substitution elasticities is also highlighted by a study by the Congressional Budget Office (CBO, 1990), which 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 and lower emission reductions. 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 and arrives at much larger emission reductions for the same tax.

Technical progress is another important determinant of aggregate cost. If energy efficiency improvements were to be spurred by the introduction of a carbon tax, emissions would be lower without necessarily incurring higher cost. An increase in the rate of autonomous energy efficiency improvements would lower the cost of emission reductions considerably.

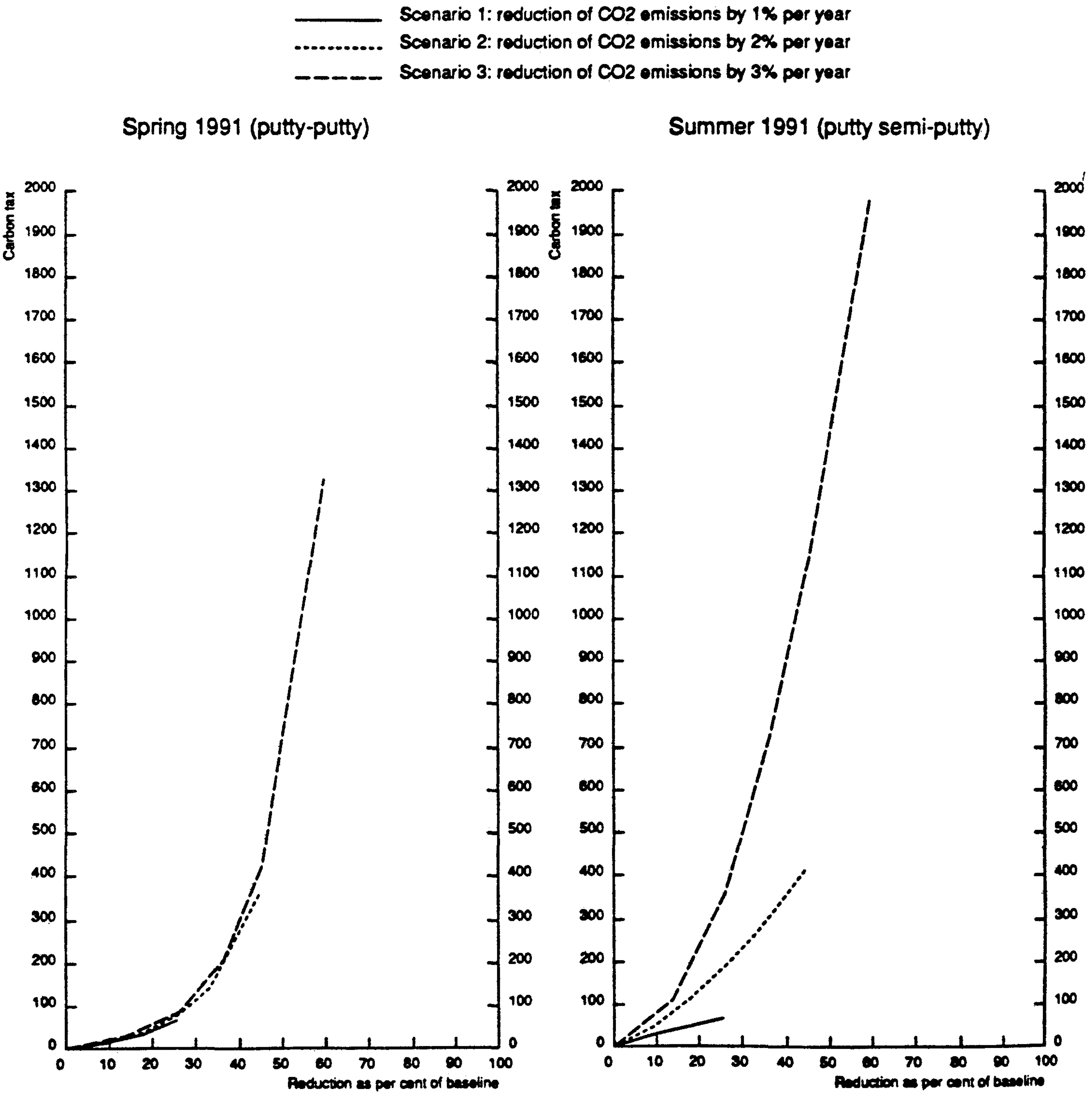
Apart from autonomous energy efficiency improvements, technical progress matters for the date of introduction and price of ***backstop technologies***. Among the models included in the OECD's Model Comparisons Project, those of Manne and Richels (Manne, 1992), Rutherford (1992) and Oliveira Martins *et al.* (1992) include backstop technologies. In these models, such technologies come on-stream in 2010, are available at the same constant marginal cost in all regions and can be phased in at a certain speed. The price of carbon-free backstop technologies puts an upper cap on carbon taxes, so that low carbon taxes in later periods as compared with other models are a direct consequence of the introduction of backstop technologies.

Adjustment speed. In the absence of low-cost carbon-free backstop technologies, a sharp reduction in emissions in the short run may be much more costly because of high short-run adjustment costs. Models either distinguish between lower short-run and higher long-run elasticities or model the turn-over of the capital stock explicitly.

The building of GREEN in stages to reach greater sophistication gives the rare opportunity to show the sensitivity of outcomes between the preliminary version which assumed that the capital stock could be completely renewed in every period (putty-putty technology), and the more recent version which treats capital as being only partly malleable in the short to medium run. Using the earlier putty-putty version, the speed of reduction hardly mattered (Chart 4). In the later version, using a putty/semi-putty assumption,

Chart 4. **Carbon taxes under different capital stock models**

(GREEN model)



carbon taxes can differ by large amounts depending on the speed of phase-in of the carbon constraint. If the carbon constraint were less ambitious later on, carbon taxes would fall again, giving a hump-shaped carbon tax profile[10].

A simulation by Nordhaus (1990) also 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.

Modelling expectations formation. Expectations about the future course of carbon taxes and energy prices will affect the energy efficiency of capital installed. They will also alter the path of consumption, saving and capital formation. Most models assume myopic expectations, which is an extreme assumption. However, a few models use an assumption at the other extreme -- perfect foresight (Manne, 1991; Jorgenson and Wilcoxen, 1991; Goulder, 1991; and Blitzer *et al.*, 1990).

In the case of forward-looking behaviour based on perfect foresight, aggregate costs are likely to be lower and carbon tax profiles smoother than under the assumption of myopic expectations as firms and individuals can avoid the sunk cost of making decisions based only on a knowledge of current prices. With forward-looking behaviour, firms and individuals will also base their decisions on future prices. Differences in outcomes for the same constraint are illustrated by comparing model simulations of Manne (1992) and Rutherford (1992). Rutherford's model is a general equilibrium clone of the Manne-Richels model but it assumes myopic behaviour (so as to be able to model trade flows), while Manne and Richels use perfect foresight but trade flows are not consistently modelled across region[11]. Output losses and carbon tax rates show much larger swings in Rutherford's model than in Global 2100 (Charts 2 and 3). At the same time, Rutherford's model seems to generate some extreme results. Most models with myopic expectations do not generate such a volatile profile for carbon taxes and output losses for the same regional carbon constraint.

The consumption profile will also be different between models incorporating myopic or forward-looking expectations. In the case of forward-looking expectations, consumption will be affected by expectations about future income and prices. As a carbon tax will reduce future income, consumption is likely to drop off immediately by a large amount. As carbon taxes are often low at the start of the simulation period, changing current income rather little, savings will increase as well as capital formation (Jorgenson and Wilcoxen, 1991; and Blitzer *et al.*, 1990).

Modelling trade flows. Only the GREEN model, the models of Whalley and Wigle (1991 and 1992) and Rutherford (1992) treat global trade flows consistently. The importance of terms-of-trade changes following the imposition of a carbon constraint is likely to influence simulation results significantly as there are large differences between regions in the endowment of fossil fuels. Moreover, the way in which trade is modelled also varies. While trade flows are modelled as imperfect substitutes (Armington assumption) in GREEN, the models of Whalley and Wigle and Rutherford allow for full substitutability (Heckscher-Ohlin model). In the latter case trade flows are much more responsive to relative price changes (see below for an example).

Fossil-fuel supply. Oil price formation is currently dominated by the OPEC countries. In such a situation, assumptions need to be made about the future of the cartel and its response to a falling demand for oil. In the IEA model oil prices are unchanged in real terms in simulation runs, with the energy-exporting LDCs acting as residual suppliers. Manne and Richels assume that the rest-of-the-world group (which includes OPEC) sets an international oil price, while Rutherford and Whalley-Wigle model the oil market as perfectly competitive. With OECD's GREEN model, simulations can be carried out assuming either a fixed real oil price or competitive behaviour.

V. Policy-related Aspects

A. Costs and benefits from reducing emissions

The course of emission reductions with respect to the amount and timing of eventual benefits from avoiding climate change is an optimisation problem facing policy makers. Peck and Teisberg (1990), Nordhaus (1991*b*) and Cline (1992) explore this optimisation problem [12]. In order to tackle this issue, models need to be enhanced by a climate sector relating emissions, concentrations and warming and a damage function which relates the degree of warming to economic costs. Given the complexity of the issues to be modelled, the studies treat the world as a single economic entity. This modelling strategy makes it impossible to distinguish differences in regional cost and to identify potential losers and winners from climate change. However, these studies are concerned with efficient intertemporal policies and not with the distribution of income across regions.

While the link running from emissions to warming is already uncertain, any damage from warming is even more so. Nordhaus assumes that a warming of 3°C would reduce global output by 1.3 per cent and that output losses increase sharply as the temperature increases further. Peck and Teisberg experiment with a damage function which is linear in warming and another one which increases steeply (3°C causes a 2 per cent reduction in output and 4°C a 10 per cent reduction).

In the studies by Nordhaus and Peck and Teisberg, increases in emissions in the reference scenario lead to a temperature increase of about 3°C by the end of the next century. In the Nordhaus study the discounted value of consumption in the absence of any abatement is 1/2 per cent lower than in the optimal policy scenario. In both studies, damage associated with the temperature increase in the no-mitigation scenario would call for only a limited amount of abatement. The carbon tax would increase slowly towards $100 per ton of carbon in the Nordhaus study, emissions would be reduced by 20 per cent below baseline by 2100 and temperature would be lowered from the level it would otherwise have attained by only 1/2°C. Even using the extreme damage function of Peck and Teisberg would allow increases in emissions from 1990 levels. Nordhaus also estimates that the cost of delaying the implementation of policies by ten years would be small.

The small amount of abatement identified as efficient policy in the studies by Nordhaus and Peck and Teisberg hinges on the assumption of a limited temperature increase by the end of the next century and low damage associated with it. However, the limited amount of warming is largely a function of the lags involved between the build-up of atmospheric concentrations and the increase in global temperatures. Cline (1992) argues that concentrations could increase further sharply throughout the 23rd century. Cline's estimates of the cost and benefits suggest that damage increases sharply beyond the end of the next century, while the cost of abatement would peak at the middle of the next century at 3 1/2 per cent of global GDP before falling back to 2 1/2 per cent of GDP. In his calculations, the present discounted value of benefits from stabilising emissions at 4 billion tons per year would still not outweigh the cost. However, if a modest amount of risk aversion is assumed, they would.

B. Setting targets

Targets for emission reductions can be formulated in many different ways: equi-proportionate cuts from a certain base-year in every region; reductions fixed in terms of per-capita levels; and reductions in the form of a global constraint, with the price of emissions being established by emission trading or via a common global carbon tax. A system of emission trading between countries or regions or a global carbon tax would allow cuts in emissions to be concentrated where abatement is cheapest, thereby minimising global welfare losses. Differences between carbon taxes and emission trading are discussed in more detail below (see also OECD, 1992 and UNCTAD, 1992).

Several studies highlight the differences between cost-effective schemes (global carbon tax or emission trading) and equi-proportionate regional cuts or targets fixed in per-capita terms. Oliveira Martins *et al.* (1992), for instance, find a global output loss of 2.3 per cent by 2020 in the case of a CO_2 emission reduction of 45 per cent by 2020 in all regions. In such a scenario, carbon taxes would vary considerably across region, reflecting large differences in the marginal cost of abatement (Table 9). If the same global constraint were imposed, but emissions were tradeable among regions, a common price would be established. With larger cuts in the regions where abatement is cheapest and lower reductions elsewhere, the global output loss would nearly halve to 1.3 per cent in 2020. Table 9 reports results from different models comparing cost-effective policies with equi-proportionate cuts across region. All of them point to gains from a cost-effective approach. Gains are small in the models with little regional dispersion in carbon taxes in the no-trade case, e.g. Manne (1992) and Barns *et al.* (1992), and sizeable in models with a large dispersion, for instance with OECD's GREEN model (Oliveira Martins *et al.*, 1992).

Whalley and Wigle (1991) find that a per-capita emission ceiling would increase global welfare losses four times over a national carbon tax in the case of a global emission reduction by 50 per cent on average over 1990 to 2030. The high cost reflects the wide variation in current emissions per capita, which is largely unrelated to the marginal cost of abatement.

Table 9. **Cost differences for various target-setting procedures**

Numbers refer to a 2 percentage point reduction in emissions from the baseline and are global aggregates

		Manne (1992)		Oliveira Martins *et al.* (1992)		Barns *et al.* (1992) (1)	
		Tax ($/tC)	Welfare loss (2)	Tax ($/tC)	GDP loss (%)	Tax ($/tC)	GDP loss (%)
2020	No trade	325	..	332	2.3	283	1.9
	Trade	308	..	166	1.3	238	1.6
2100 (1)	No trade	242	8.0	..	..	1 304	5.7
	Trade	208	7.5	..	..	919	5.0

1. End-year is 2095 for Barns *et al.* (1992).

2. Consumption losses through 2100 -- discounted to 1990 at 5 per cent per year -- trillions of 1990 dollars.

C. Regional coverage of agreements

As compared with a global agreement, unilateral action will affect emissions in the constrained and unconstrained regions mainly via the following mechanisms. First, there will be a switch in comparative advantage in producing energy-intensive goods in favour of the unconstrained region. Second, there will also be an incentive to shift the location of energy-intensive goods to unconstrained regions. Finally, if fossil-fuel prices fall, emissions may be pushed up further in the unconstrained region. On the other hand, lower income in the constrained region will also induce lower income in the unconstrained region, reducing emissions there also. The phenomenon of emissions increasing in unconstrained regions in response to the imposition of carbon constraints in some regions is known as **carbon leakage**.

Model simulations by Rutherford (1992) and Burniaux *et al.* (1992*a* and 1992*b*) shed light on the issue. The two models give widely differing results, with the GREEN model showing virtually the same amount of emissions, whether action is unilateral or global, while the leakage is much larger in Rutherford's model. It seems that different assumptions about fossil-fuel supply are crucial in explaining these results. In Rutherford's model, the rest-of-the-world region which includes OPEC plays the role of price leader in the world oil market. As other regions reduce their oil imports, the rest-of-the-world region restricts its exports in order to sustain the international oil price. With a low supply elasticity in the rest-of-the-world region the additional oil supply leads to a sharp fall in the oil price there and emissions increase sharply. In the GREEN model, the supply curve is more elastic so that oil supply by the energy-exporting LDCs falls, cushioning the fall in oil prices. In addition, the international oil price falls everywhere, leading to substitution out of coal in the coal-rich unconstrained regions. Hence, the amount of carbon leakage is much lower in GREEN, than in Rutherford's model.

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. Simulations with the preliminary version of GREEN (Burniaux *et al.*, 1991) show the stiff penalty imposed by trying to achieve a global target by action in the industrialised countries (OECD countries and the former Soviet Union alone) versus large participation in a global agreement. A 37 per cent global emission reduction by 2020 would imply a fall in emissions in the industrialised countries by two-thirds. This requires carbon taxes in 2020 of $2 200 and $500 per ton of carbon in the OECD region and the former Soviet Union, respectively. In the case of global coverage, the carbon taxes would have been only $308 and $101 for the two regions. Given trade links, energy-exporting LDCs would suffer strong income losses, even if they did not participate in the agreement.

Another regional policy aspect concerns the **point of taxation**. Simulations by Whalley and Wigle (1991) 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. 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 10). If the tax was levied in consuming countries, oil-exporting countries would lose most while the EC and Japan could even gain.

D. Policy instruments other than carbon taxes

a) ***Energy taxes.*** Burniaux *et al.* (1992*b*) present simulations for equi-proportionate cuts in emissions using a pure carbon tax, a pure energy tax and a mixed energy *cum* carbon tax as proposed by the EC Commission. While the carbon tax would lead to a global loss in output of 2 per cent of GDP by 2050 an energy *cum* carbon tax would increase it to 2.4 per cent and an energy tax to 2.8 per cent for the same constraint. The aggregate costs of meeting a given carbon restriction are higher because such taxes are less well focused on the carbon content of the different fuels. Jorgenson and Wilcoxen (1990) also simulate reduction scenarios using taxes other than carbon taxes. For the United States, a tax on the energy content of fuels (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).

b) ***Permit trading.*** While both a carbon tax and emission trading are likely to reach abatement targets at least cost, there are important differences about the way in which each type of instrument operates in practice [13]. In the case of a carbon tax, the price increase per ton of carbon is fixed while the outcome in terms of abatement is uncertain; in the case of emission trading, the emission constraint is fixed while the price is uncertain. There are also important differences in terms of income distribution. In the case of a carbon tax, the revenue accrues to the government in the first instance. With emission permits, the income transfers depend on the initial allocation of permits. The revenue flows associated with the sale of permits between countries could be very large in the case of permit trading. Therefore, welfare consequences for different regions are importantly influenced by the specific type of agreement.

Permits can be auctioned off or allocated among existing sources free of charge according to some distribution rule. Both approaches will result in a cost-effective allocation of abatement, but the initial distribution can be used to pursue distributional goals [14].

c) ***Regulation.*** Most studies show that use of regulations instead of carbon taxes or permit trading could be an expensive route towards achieving a cut in emissions. For example, Nordhaus (1990) suggests that the use of regulatory mechanisms could reduce output growth by an additional 0.2 percentage point over and above an output loss of 0.3 achieved by an economic instrument 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 resulting loss in flexibility leads to a significant increase in economic costs as compared with an economy-wide emissions target. Similarly, Ban (1991)

Table 10. **Producer and consumer taxes**

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) <u>National production taxes</u>		
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) <u>National consumption taxes</u>		
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

1. Hicksian equivalent variation over the period 1990-2030 in 1990 prices as a per cent of GDP in present value terms.

Source: Whalley and Wigle (1991).

simulates a stabilisation of emissions at 1990 levels for Japan, where each energy-using sector has to stay within this upper limit. As compared with the case of a carbon tax, welfare losses would increase by a third under this regulatory approach.

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 lower the growth rate below its baseline level by 0.2 percentage points per annum. If similar action were to be taken in competitor countries (the second scenario), 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, 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. But 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 CO_2 emissions, but only if optimal policies are applied in these areas.

E. Current distortions in factor and goods markets

i) Factor markets

The aggregate cost may depend crucially on the way the **carbon tax revenue is redistributed** within countries. In the absence of careful modelling of fiscal regimes, most models redistribute the carbon tax revenue in a lump-sum fashion. The first study to show the sensitivity of aggregate results to different ways of recycling carbon tax revenue is by Goulder (1991) [15]. In simulations for the United States, Goulder first simulates the effects of a $25 per ton carbon tax with the revenue being recycled in a lump-sum fashion. He then considers the same carbon tax scenario but with the government using the carbon tax revenue to cut other distorting taxes: personal income taxes, corporate taxes and payroll taxes. Welfare losses are considerably lower in these scenarios than in the case of lump-sum repayment: approximately 36 per cent lower with a personal income-tax cut, 34 per cent lower for a profit tax cut and 56 per cent lower when payroll taxes are reduced (Table 11). While the decline is significant, imposing a carbon tax for efficiency reasons alone cannot be justified.

Shackleton *et al.* (1991) have used four U.S. models (Jorgenson/Wilcoxen, Goulder, DRI and LINK) to perform a standardised simulation exercise for EMF12 in order to shed light on the recycling issue. Carbon taxes were imposed at $15 per ton of carbon in 1990 and subsequently increased by 5 per cent annually to reach $40 in 2010 before remaining constant thereafter. In the first scenario, with lump-sum recycling, emissions drop below baseline by 2010 by three times as much (about 35 per cent) using the general equilibrium models of Jorgenson/Wilcoxen and Goulder as in the other two macroeconometric models, reflecting the more optimistic assumptions about substitution possibilities in

Table 11. **Welfare effects of alternative revenue adjustments** (1)

Initial simulation ($25 tax per ton of carbon with lump-sum revenue adjustment)	-0.551
Alternative revenue adjustments	
Cut of personal income taxes	
-- all marginal rates reduced	-0.353
-- labour marginal rates reduced	-0.348
-- capital marginal rates reduced	-0.357
Cut corporate taxes	-0.365
Cut payroll taxes	-0.245

1. The measure of the welfare change is the equivalent variation as a percentage of the present value of household income over the infinite horizon.

Source: Goulder (1991).

the general equilibrium models. In this scenario the GDP level would be reduced by about 1 per cent below baseline in 2010 for all models, except LINK, which shows a much smaller reduction. Recycling in the form of a cut in corporate and personal income taxes, payroll taxes and increases in the investment tax credit produced a rather clear hierarchy of alternative recycling methods: in virtually all the models an increase in the investment tax credit and cut in corporate income tax completely offsets or even more than offsets the GDP loss as these measures spur capital accumulation. A payroll tax cut and personal income tax cut fared better than the lump-sum recycling but would not have offset completely the GDP loss associated with lump-sum recycling in most models. Stronger growth, however, would also increase emissions as against the case of lump-sum recycling, at least for the macroeconometric models.

Shah and Larsen (1992) provide partial and comparative static analysis of the effects of using carbon tax revenues to reduce taxes on labour and capital in India, Indonesia, Pakistan, the United States and Japan. They conclude that the replacement of corporate taxes by a carbon tax would pay on efficiency considerations alone in countries with low or no pre-existing energy taxes, such as Indonesia or India.

ii) Goods markets

The base-year data for OECD's GREEN model highlight **large differentials in energy prices** across regions (Table 12). A major reason for the price differences are taxes and subsidies, with subsidies being particularly high in some non-OECD regions. A possible alternative to an international agreement imposing carbon taxes would be the elimination of subsidies in these regions. Based on some crude calculations, subsidy rates are estimated to average worldwide between 15 per cent for coal to 33 per cent for gas. In a simulation by Burniaux *et al.* (1992*b*) initial wedges between domestic and "world" prices are removed gradually over the period 1990-2000. World emissions would be 7 per cent lower in 2000 and 20 per cent lower in 2050. The OECD regions experience small welfare gains, while large gains from removing distortions are simulated for the former Soviet Union: its real income is nearly 15 per cent above the baseline level in 2050. Most other regions also record welfare gains.

Shah and Larsen (1992) also point to fiscal and regulatory regimes in energy markets which differ considerably across countries. They estimate world energy subsidies were in excess of $230 billion in 1990 and in revenue terms the equivalent to a negative carbon tax of $40 per ton of carbon. Elimination of such subsidies are estimated to reduce carbon emissions by 21 per cent in subsidising countries and almost 10 per cent globally. Removal of subsidies would improve allocative efficiency and generate a welfare gain in subsidising countries. On the other hand, model simulations may have underestimated the economic cost for high-tax countries. As the economic cost increases roughly with the square of the carbon tax rate, the omission of existing taxes could bias cost calculations downwards, especially in Japan and Europe (Hoeller and Coppel, 1992).

Table 12. **Emission shares and prices in the benchmark data set of GREEN**

A. Share of fossil fuels in total CO_2 emissions (%)

	United States	Japan	EC	Other OECD	Energy-exporting LDCs	China	Former Soviet Union	India	CEECs	DAEs	Brazil	RoW	WORLD
Coal	34.7	30.5	32.9	32.8	20.0	86.2	38.1	74.1	66.9	37.5	21.0	45.3	42.0
Crude oil	46.7	61.4	51.8	51.1	61.6	12.5	33.4	24.4	20.1	60.2	76.1	46.7	42.2
Gas	18.6	8.1	15.3	16.1	18.4	1.4	28.6	1.6	13.0	2.3	2.9	8.0	15.8

B. Relative fossil-fuel prices in 1985 (1)

Average price in U.S. = 100

	United States	Japan	EC	Other OECD	Energy-exporting LDCs	China	Former Soviet Union	India	CEECs	DAEs	Brazil	RoW	WORLD
Coal	35.4	126.4	63.9	27.0	30.8	20.5	24.8	25.6	26.2	68.5	110.6	25.7	35.8
Crude oil	152.2	178.3	166.7	136.8	99.4	155.0	24.1	95.4	100.1	135.2	123.8	142.5	119.9
Gas	92.5	167.1	140.6	81.9	84.4	106.7	17.0	61.3	44.9	166.1	71.9	198.6	76.4
Average	100.0	162.6	131.2	92.4	87.8	46.9	21.8	47.8	48.4	118.5	120.1	106.7	81.6

1. Defined as the unit value of one terajoule relative to the average unit value of fossil fuels in the United States. Fossil fuel demands are converted into a common energy unit (1 terajoule = 10 E 12 joules). This facilitates the conversion into tons of carbon emitted with the help of widely-used conversion factors: 1 terajoule of coal = 23.3 tons carbon, 1 terajoule of oil = 19.2 tons of carbon, 1 terajoule of gas = 13.7 tons of carbon.

Source: Burniaux *et al.* (1992*b*).

F. Distributional and sectoral change

i) Effects on income distribution

The introduction of carbon taxes has direct **distributional implications** as additional tax payments reduce household incomes and also has more indirect consequences through increased prices of energy-intensive goods [16]. An important policy question is whether those effects are likely to be regressive (falling more on poor households) or progressive (falling more on rich households).

Concerning the direct effect, Smith (1992) shows that there is no clear answer for European countries. While a carbon-cum-energy tax of the size proposed by the European Commission (about $10 per barrel of oil) would clearly be regressive for spending on domestic heating, lighting and power, spending shares on motor fuels increase with income levels. Except for the United Kingdom and Ireland (see also Scott, 1992) where the carbon tax is clearly regressive, the tax is likely to have a broadly neutral distributional effect for most European countries. Model-based calculations for Norway also show a fairly homogeneous distribution of welfare losses across households (Alfsen *et al.*, 1992). On the other hand, regressivity is also found for the United States (Poterba, 1991). Mechanical exercises based on household income and spending surveys or model simulations allowing for changes in spending patterns do not produce widely differing results. However, the studies discussed here do not treat the distributional consequences in a global general equilibrium framework. The tax may, for instance, be shifted back to foreign owners of energy resources with little domestic distributional consequence.

The recycling of the tax receipts also has distributional implications. As argued above, the money could be used to reduce the most distortionary taxes on labour and capital use. If those were cuts in corporate taxes or increases in saving incentives, there could be an additional regressive effect, even though such tax changes may be preferred on efficiency considerations. On the other hand, using the tax receipts to reduce any regressivity of the carbon tax may leave less money to reduce the aggregate cost of the carbon tax. If carbon taxes are thought to be regressive, there is a clear trade-off between efficiency and equity in the use of the revenues.

ii) Industrial structure

Sizeable carbon taxes would lead to large **sectoral shifts** in the long run. Most studies include sufficient industry detail to trace major changes. The need for adjustment would clearly be large for fossil-fuel producers. All studies concur that there would be a massive shift out of coal, while the effect on oil and especially gas production is less clear, at least over the next decades. Energy-intensive industries are also likely to suffer relatively larger output losses. The size of the losses would depend on the regional scope of any agreement and the market power of producers. But substitution possibilities also matter. If a switch to clean fuels is possible at low cost, the output of energy-intensive industries may change little.

G. Other benefits from reducing CO_2 emissions

Nearly all of the studies covered above focus only on the costs, and in some the benefits, of reducing CO_2 emissions and take no account of the favourable reductions in the emissions of airborne pollutants. Glomsrød *et al.* (1990) and Alfsen *et al.* (1992) also provide estimates of the benefits from reduced fossil-fuel use stemming from reductions in airborne 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 CO_2 in Norway would have virtually no benefit in terms of reduced warming globally, reductions in airborne 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.

Notes

1. The authors are members of the Public Economics Division of the Economics Department. They would like to thank Tom Jones, John Martin and Jan Corfee-Morlot for helpful comments and Jackie Gardel and Anick Lotrous for technical assistance.

2. In the meantime, Barrett (1991), Boero *et al.* (1991), Cline (1991) and Nordhaus (1991) have provided surveys of the cost of reducing emissions. All these surveys are excellent overview papers, which try to cover different topics: the paper by Cline (1991) explains five global models and results in detail; Boero *et al.* (1991) focus on differences in model outcomes and their causes; Barrett (1991) discusses the issues surrounding the potential use of economic instruments to respond to global warming; and Nordhaus (1991) reviews cost estimates for reducing CO_2 and CFC emissions as well as the cost of reforestation.

3. Only four models cover GHG emissions other than fossil-fuel CO_2 emissions (Mintzer, 1987; Nordhaus, 1991*a*; Edmonds and Barns, 1990; and Peck and Teisberg, 1990).

4. A "backstop technology" is a new or unproven technology which is expected to become 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.

5. For partial equilibrium analyses see, for instance, Chandler (1990), who surveys energy policy responses for eight countries; a similar study by Capros *et al.* (1990); a Report for the European Commission (1990) or Ingham and Ulph (1990), who concentrate on the U.K. manufacturing sector.

6. 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 available and the studies by Reilly *et al.* (1987) and Nordhaus and Yohe (1983) which focus on the probability distribution of emission scenarios.

7. As they are assumed to be available at infinitely elastic supply at given prices in all regions, there is no incentive to trade backstops.

8. 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.

9. Boero *et al.* (1991) also summarise elasticity assumptions for many of the single-country models.

10. An important aspect of high capital turnover is that high investment will lead to lower adjustment costs.

11. Manne and Rutherford are developing a new five-region intertemporal equilibrium version of Global 2100 with more extensive trade links.

12. The model of Peck and Teisberg is calibrated on the model of Manne and Richels.

13. For the same constraint, the price per ton of emission and a carbon tax will coincide if permits are freely transferable, transactions cost are low and all market participants are price takers.

14. The same can be achieved with a carbon tax if tax revenues are collected by an international body and redistributed by some distribution rule.

15. This issue is also addressed in the Norwegian SIMEN study (Bye *et al.*, 1989). 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.

16. There are many dimensions to any discussion of distributional issues. Distribution of cost across regions and countries for emission reduction scenarios has been discussed above. The regional distribution of benefits from avoiding climate change is highly uncertain. There are no studies comparing differences in the distributional effects of different policies to reduce emissions.

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