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Costs of Reducing CO2 Emissions: Evidence from Six Global Models

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This paper summarises and analyses results of the OECD's Model Comparisons Project. The aim of the project is to better understand differences across six global models in the cost of reducing carbon dioxide emissions. In order to facilitate comparisons, key assumptions and reduction targets have been standardised. The paper provides evidence on; i) projected carbon dioxide emissions through the next century, and ii) the carbon taxes and output costs entailed in reducing these emissions.

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Ce document résume et analyse les résultats du projet de l'OCDE de comparaison de modèles. Le but de ce projet est de mieux comprendre les différences de coûts de réduction des émissions de dioxide de carbone que font apparaître six modèles globaux. Pour faciliter ces comparaisons les hypothèses clés et les objectifs de réduction ont été standardisés. Cette étude met en évidence ; i) les émissions projetées de dioxyde de carbone d'ici à la fin du siècle prochain et ii) les taxes sur le carbone et les coûts de production que suppose la réduction de ces émissions.

Table of Contents

Costs of Reducing CO_2 Emissions; Evidence from Six Global Models

Andrew Dean and Peter Hoeller [1]

I. Introduction and Summary

As evidence about the potential seriousness of the effects of climate change has mounted, attention has focused on the likely costs of different policies to slow or halt the change. Numerous studies have investigated the possibilities of reducing the emissions of greenhouse gases, the cause of global warming, with most attention being focused on CO_2, the most important greenhouse gas. And various economic models have been developed to examine the likely costs of reducing such emissions. These models have mostly concentrated on man-made emissions of CO_2, which arise almost entirely from the burning of fossil fuels, so that energy-sector detail has been important. There have already been several surveys of these model results (Hoeller *et al.*, 1991; Boero *et al.*, 1991; and Cline, 1992). But each of these surveys has been confronted with the problem of trying to compare like with like, the model results generally being for a variety of different time periods, key baseline assumptions, reduction scenarios and so on. It has thus been difficult to identify the reasons lying behind the broad range of cost estimates presented in these studies.

The OECD's model comparisons project is an attempt to standardise key inputs and reduction targets across different models, so as to better understand the ways in which the various models work and hence the differences in key results -- on baseline CO_2 emission paths, carbon taxes and economic costs [2]. Key economic assumptions and the specification of reduction scenarios are described in the Box overleaf.

In any exercise of this sort, however, there are important limitations to the extent to which standardisation is possible. In the case of comparisons of macroeconomic models, there is at least a national-accounts framework to which all modellers basically adhere. In the case of the modelling of CO_2 emissions and the energy-economy interface, model structures vary considerably and make comparisons more difficult. Furthermore, individual researchers have focused on very different aspects of the problem -- trade, taxation, energy impacts, short-term as against long-term effects and so on -- and have constructed their models accordingly. No one model can deal with all these different aspects at the same time. The brief review of the six global models participating in this project (see Section II below) highlights some of the key model differences and clarifies why there are limits to any comparisons exercise in this area.

The Specification of the OECD Model Comparisons Project

Standardisation across models has been carried out in two key ways; i) specifying a few key economic assumptions for the baseline or "Business-as-Usual" (BaU) scenario of unconstrained CO_2 emissions growth, and ii) specifying a set of common simulations for reducing CO_2 emissions.

Business-as-usual (BaU) emissions; key assumptions

Modellers were asked to assume the growth paths for real GDP and population agreed for the parallel project of the Energy Modelling Forum at Stanford University as well as a common resource base and oil price assumption. The key assumptions are;

i) population rises from 5.3 billion in 1990 to 9.5 billion in 2050 and to 10.4 billion by 2100, by which time it is hardly growing at all (World Bank projections); nearly all of the growth is in China and other developing countries; see Appendix Table A1 for detail;

ii) output growth slows throughout the next century -- from 2 1/2 per cent per annum in the 1990s in OECD countries to only 1 per cent by 2100, and from 4 per cent to less than 3 per cent in developing countries; see Appendix Table A2 for detail;

iii) oil prices are set exogenously at $26 per barrel in 1990 rising by $6 per decade in real terms to reach $50 in 2030, being unchanged thereafter. In the OECD GREEN model, oil prices are determined endogenously but are similar in the BaU scenario to the EMF12 path; they differ in the emission reduction scenarios in response to the imposition of carbon taxes.

Reduction scenarios

Three of the scenarios are specified in terms of reductions (from the BaU emissions path) in the rate of growth of emissions in each region -- by, respectively, 1, 2 and 3 percentage points per annum. In this way, the amount of the reduction, in percentage terms, will be similar across models, although the starting points (the baseline) and destination will vary. Using this method implies that most of the differences between models can be ascribed to model structures rather than being a hybrid, representing both different model structures and different degrees of reduction -- as in target level exercises. The fourth scenario is a stabilisation of emissions at 1990 levels in each region. This would be most stringent for those regions, such as China and RoW, where BaU emissions growth is most rapid, and least stringent for the OECD.

The emission reduction scenarios are applied across all regions, even though the baseline emissions growth varies significantly across regions. These reductions are in no way a recommendation or proposal. Uniform reductions across regions have been suggested for purely expositional reasons and considerations of equity and political feasibility have been ignored. Clearly, the 3 per cent scenario would be regarded as extreme, though it is relatively close to the IPCC scenario for stabilising concentrations by the middle of the next century. The 1 per cent scenario would represent an approximate stabilisation of OECD emissions and perhaps those in the former Soviet Union too -- though this varies across the different baselines -- while still permitting a relatively rapid growth of emissions elsewhere. The 2 per cent scenario, on the other hand, would require absolute cuts in emissions in the OECD and the former Soviet Union and allow some continued, albeit very low growth elsewhere. The three cases probably span the range of targets currently under discussion in international fora. The policy instrument used to achieve these emission curbs is a carbon tax, i.e. a tax levied on the carbon content of primary energy sources.

The models

CRTM:	Carbon Rights Trade Model (see Rutherford, 1992)
ERM:	Edmonds-Reilly Model (see Barns *et al.*, 1992)
GREEN:	OECD Model (see Oliveira Martins *et al.*, 1992)
IEA:	International Energy Agency Model (see Vouyoukas, 1992)
MR:	Manne-Richels Global 2100 Model (see Manne, 1992)
WW:	Whalley-Wigle Model (see Whalley and Wigle, 1992)

The major findings of the project are as follows:

-- There is a wide range of **"business-as-usual" emission paths** with world-wide carbon emissions in 2100 lying between 22 1/2 billion tons and 40 billion tons (with the WW model result of 65 billion tons being an outlier); these numbers are all above the IPCC's 1992 reference case (20 billion tons in 2100), although the IPCC also gives a wide spread for alternative scenarios (Section III).

-- Such a wide range of emissions, even with standardisation of population and output assumptions, points to a considerable unresolved uncertainty about future emissions.

-- A factor identified as being particularly important in determining emissions is the rate of autonomous energy efficiency improvement, which ranges from zero to 1 per cent per annum in the models surveyed; a difference of 0.5 per cent in this parameter, given compounding, can lead to an outcome in 2100 which is as much as 20 billion tons different. Uncertainty about the size of this parameter is likely to remain large as it depends on future technical progress.

-- There are especially large differences in the projections of emissions for China; one particularly important factor here seems to be the prices of fossil fuels used in the different models, with the fastest growth in emissions being projected by the GREEN model which takes account of existing distortions in energy prices, hence building in relatively low prices.

-- **Carbon taxes** vary greatly across regions and across models (see Table 1 summarising simulation results for one of the scenarios). In most models there are rising tax curves, indicating that successive reductions in emissions can only be achieved by ever-larger increases in carbon taxes (Section IV). The early cuts would be relatively cheap but substantial cuts would require very high taxes. For instance, cutting emissions in the United States in 2020 by 45 per cent from baseline (as in the 2 per cent reduction scenario described later) would require carbon taxes ranging from $200 to $350 per ton, compared with current energy taxes in the United States which are the equivalent of about $30 per ton of carbon. But deeper cuts would see taxes in both the United States and other regions rise towards $1 000 or more. An important exception is provided by the MR, GREEN and CRTM models which incorporate carbon-free backstop technologies. As soon as large supplies of newly-developed carbon-free fuels become available, their price puts a ceiling on the required carbon tax. More information on the likely costs and speed of diffusion of such backstop technologies is needed.

-- The **economic costs**, measured here as GDP losses, also vary greatly across models and regions (Section IV). The GDP loss is generally rather high for the Rest of the World region, which includes the major oil-producing developing countries, but for the other regions the losses are less and there are different regional rankings of abatement costs across models. In the case of the 2 per cent

Table 1. **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)

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

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

	CRTM			ERM			GREEN		MR		
Year	2020	2050	2100	2020	2050	2095	2020	2050	2020	2050	2100
United States	1.3	2.5	2.6	2.0	4.9	8.8	1.1	1.3	2.2	2.7	3.1
Other OECD	0.4	1.1	1.5	1.9	3.4	4.8	1.2	1.6	1.1	1.6	1.9
China	2.0	3.1	3.6	2.8	4.3	6.2	0.7	1.5	2.7	3.8	5.0
Former USSR	1.5	5.8	4.1	0.9	2.3	3.7	1.7	3.7	3.1	6.4	5.6
RoW	2.3	2.1	4.5	2.0	3.5	5.1	3.8	4.4	4.9	5.1	5.6
Total	1.5	2.4	3.6	1.9	3.8	5.8	1.9	2.6	2.9	3.7	4.7

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.**

reduction scenario, the GDP loss in 2020 ranges from 1/2 to 2 per cent of GDP in the OECD regions and from roughly 1/2 to 3 per cent of GDP in China and the former Soviet Union. In the case of a stabilisation scenario (keeping emissions at 1990 levels), the GDP loss in the year 2020 ranges between about zero and 2 per cent of GDP for the OECD regions and the former Soviet Union, but is more like 3 to 3 1/2 per cent of GDP for China, where the cuts needed to stabilise emissions would be greatest. As with the tax curves, GDP losses tend to rise more steeply as the degree of reduction increases, except when backstop technologies limit the tax, even though it is assumed that carbon taxes are offset by tax cuts elsewhere and are hence revenue-neutral.

-- The assumed **substitution possibilities**, between different fossil fuels, between fossil and non-fossil fuels and between energy and other production factors, are shown to be important determinants of the differences in taxes and costs across models (Section IV). Low substitution elasticities generally force much of the adjustment of emissions onto reductions in energy intensity and the level of output; to achieve this, taxes must be high and the costs are relatively large. On the other hand, high substitution elasticities enable more switching between fuels, which in general reduces the required taxes and costs.

-- **The composition of primary energy demand and relative energy prices** are also important in determining the amount of substitution that takes place and the taxes necessary to induce fuel switching; a higher share of coal and a lower level of energy prices in China and the former Soviet Union in some models, due to distortions in energy markets, allow both taxes and costs to be lower than models where world market prices for fuels and lower carbon intensity are assumed.

-- **Emissions trading** has the potential to greatly reduce both the global and regional cost of emission reductions because there is a wide dispersion of carbon taxes and abatement costs across regions. The abatement costs are almost halved in the GREEN model, but the gains in two other models (ERM and MR) are less significant (Section V).

A word of caution is necessary about the nature of the model comparisons in this paper. None of the scenarios presented here are in any way a policy prescription. The scenarios have been used as an expositional device to illustrate technical differences in the models. There are important policy messages from this work but none of the scenarios is being actively proposed in the current negotiations. Stabilisation of emissions, however, has been adopted as a goal in the draft framework agreement but only for the developed countries. Furthermore, the costs of reducing energy-related CO_2 emissions are only one part of a complex problem which must take into account other sources and sinks of CO_2, other greenhouse gases and the uncertain estimates of the impact of climate change.

Table 2. **Summary of participating models** (1)

	Model type	Time horizon	Regions	Fuel sources	Comment
Rutherford (CRTM)	recursive dynamic general equilibrium model, calibrated on Global 2100	2100	five	seven including backstop technologies	focus on impact of restrictions on international trade; tradeable permits
Edmonds-Reilly (ERM)	partial equilibrium model with detailed dynamic energy sub-model	2095	nine	six primary and four secondary fuels	energy traded; includes other greenhouse gases; energy-economy links simple
GREEN	recursive dynamic general equilibrium model	2050	twelve	three primary and two secondary fuels plus three backstop technologies	full trade links plus tradeable permits; oil price endogenous
IEA	econometrically-estimated detailed energy model	2005	ten	five with many product breakdowns	much energy detail for OECD regions; no feed-back from the energy sector to the rest of the economy
Manne-Richels (Global 2100) (MR)	dynamic intertemporal optimising model with detailed energy model	2100	five	nine including backstop technologies	forward-looking inter-temporal model; only oil trade is modelled; tradeable permits
Whalley-Wigle (WW)	comparative static general equilibrium model	1990-2100	six	two	trade links; focus on international incidence of carbon taxes

1. The table describes versions of the models as used for this project. A description of the models and their results is provided in the Working Papers written specifically for this project; see Barns *et al*. (1992), Manne (1992), Oliveira Martins *et al*. (1992), Rutherford (1992), Vouyoukas (1992) and Whalley and Wigle (1992).

II. An Overview of the Participating Models

The major features of the six global models participating in the project are given in Table 2. The differences in model type heavily influence the sort of comparisons that can be considered here and, in spite of the standardisation of baseline inputs and scenario design, limit the degree to which results are comparable. The various dimensions in which the comparisons are constrained is explored below by referring to some of the salient features of the models.

Model type. There is one comparative-static general equilibrium model, the Whalley-Wigle model (WW) -- which is used to generate results for the period 1990-2100. It is in the nature of such models that they cannot give dynamic paths so that the results cannot therefore be presented alongside the time-paths of results for the five other models. The IEA model is an econometrically-estimated partial equilibrium model of the energy sector but it takes no account of economic feedbacks from the energy sectors to the aggregate economy; results can therefore only be given for carbon taxes and not for GDP effects. The remaining four models -- Edmonds-Reilly (ERM), Global 2100 of Manne-Richels (MR), the Carbon Rights Trade Model of Rutherford (CRTM) and the OECD model (GREEN) -- are all dynamic models of a partial or general equilibrium type with differing degrees of sectoral and energy detail.

The GREEN and WW models have been built to examine the CO_2 issue from the general macroeconomic and trade perspectives while ERM, MR and IEA were developed as detailed energy models. CRTM is based on the same data and approach as MR. It has, however, a consistent treatment of world trade flows -- a feature lacking in MR -- but, as it currently stands, has achieved this by moving from a forward-looking to a recursive structure. CRTM and MR are optimising models which incorporate numerous alternative technological options, while substitution possibilities are continuous in ERM, GREEN and WW.

Even with similar types of model, parameter values for key relationships can vary significantly. Some of these differences are indicated in Table 3, which provides information on energy efficiency, substitution elasticities and certain other parameters. Some of the differences in baseline emission paths and scenario results investigated below can be explained with reference to the differences shown in this table. There are many other model differences which are not highlighted here. Furthermore, the various differences interact so that decomposing such differences and attributing the differences to particular parameters, model structure or data variations becomes increasingly difficult beyond a certain point. The project has been able to identify reasons for some of the key differences in results but has not been able to track down such differences to the last detail. And some of the reasons ultimately remain obscure.

Time horizon. Four of the models have a long-term horizon which extends to the end of the next century -- CRTM, ERM, MR and WW -- although results for the latter for the period 1990-2100 are given as 1990 discounted present values. The other models have shorter time horizons -- 2050 for GREEN and 2005 for the IEA. In the short time horizon (in climate-change terms) of the IEA model, the capital stock turnover is rather limited. Changes in the capital stock are necessarily more significant for the medium-term models and over the longer term, adjustment costs are a less-important factor since the capital

Table 3. **Key parameters** (1)

	United States	Other OECD	Former Soviet Union	China	RoW
Autonomous energy efficiency improvement (AEEI):					
ERM	1.0	1.0	1.0	1.0	1.0
GREEN	1.0	1.0	1.0	1.0	1.0
IEA (2)	~1.1	~1.1	..	..	..
MR (3)	0.5	0.5	0.25	1.0	0.0
WW	0.0	0.0	0.0	0.0	0.0
Elasticity of substitution between energy and other factors of production:					
ERM	..	..	..	..	..
GREEN (4)	E-K L-KE	E-K L-KE	E-K L-KE	E-K L-KE	E-K L-KE
	0.6 1.0	0.6 1.0	0.6 1.0	0.6 1.0	0.6 1.0
IEA	..	..	..	..	..
MR	0.4	0.4	0.3	0.3	0.3
WW (5)	0.7	0.7	0.7	0.7	0.7
Interfuel substitution elasticities in production:					
ERM	..	..	..	..	..
GREEN	2.0	2.0	2.0	2.0	2.0
IEA (2)	~0.5	~0.5	..	..	..
MR	..	..	..	..	..
WW	5.0	5.0	5.0	5.0	5.0
Interfuel substitution elasticities in final demand:					
ERM	..	..	..	..	..
GREEN	1.2	1.2	1.2	1.2	1.2
IEA	..	..	..	..	..
MR	..	..	..	..	..
WW	5.0	5.0	5.0	5.0	5.0

Energy supply elasticities:		
ERM	Oil	1.0
	Coal	1.0
GREEN	Carbon-free	0.2
	Coal	5.0
	Oil	between 1 and 3
WW	Carbon-based	1.0
	Carbon-free	1.0

1. Regional disaggregation is not the same for all models; see text.
2. Numbers are approximate averages over a variety of parameter values for different fuels and sectors.
3. AEEI is the same across regions from 2050 at 0.5.
4. E-K refers to the energy-capital elasticity of substitution and L-KE refers to the substitution elasticity between labour and the capital-energy bundle. Elasticities shown are long-run values; in the short run, they are about one-tenth of the long-run values.
5. For the production of energy, the elasticity is 1.0.

stock can turn over entirely. Backstop technologies tend to be increasingly important over time.

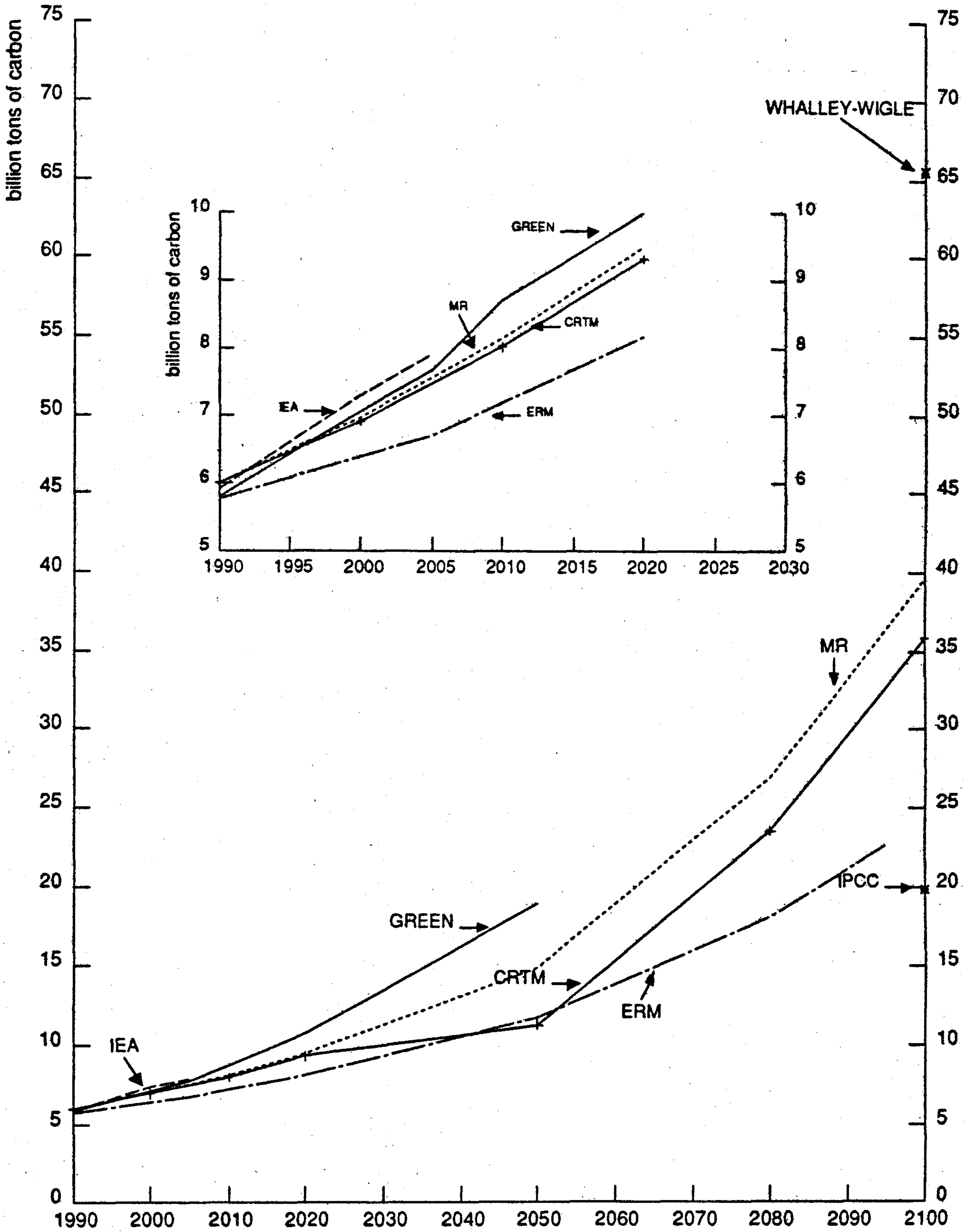
Regions. The regional breakdown of the different models does not always correspond to the breakdown specified for the project. The breakdown requested -- United States, Other OECD, China, the former Soviet Union and the Rest of the World (RoW) -- is based on MR and is thus also available for CRTM. GREEN can also comply with the five-way breakdown, although results are presented in Oliveira Martins *et al.* (1992) for the full twelve-region disaggregation, because of the very different circumstances and behaviour of the various OECD and non-OECD regions. ERM has ten regions which can be aggregated to the five groups apart from the former Soviet Union and China, since eastern European countries and Asian CPEs respectively are included in those two groups, hence reducing also the size of the RoW grouping. The IEA model has a North America group, and hence an "other OECD" group which also excludes Canada, while non-OECD groups are compatible for producing baseline CO_2 emissions but are not modelled for the scenario work. WW also has a North America group, hence also having a slightly reduced other OECD group, and then has oil exporters and the rest of the world. The bottom-line on this is that the regional comparisons are valid for MR, CRTM and GREEN, less valid for ERM and the IEA (which is also incomplete) and most problematic (in the context of this exercise) for WW.

Fuel sources. As noted above, the GREEN and WW models have less energy detail than the other four models. However, WW is the most rudimentary, having only a composite fossil fuel and one non-fossil fuel. This means that inter-fossil fuel substitution -- which is important in most models until well into the next century -- is not feasible in WW, an important factor to bear in mind when considering the costs of reducing CO_2 emissions. For the other models, the substitution between fuels with different carbon intensities is an important part of both baseline emission paths and reduction scenarios.

Backstop technologies. There are no backstop technologies in WW and ERM, an omission which is critical to the results since there is no effective ceiling to the carbon tax. The IEA model also has much technological detail, but backstops are much less important over the short time horizon up to 2005. In contrast, MR, CRTM and GREEN have backstop technologies which limit the carbon tax and hence the cost of emission reductions. Following EMF12 assumptions backstop technologies come on-stream in 2010 and are available at the same constant marginal cost in all regions. Carbon-rich and carbon-free backstops are available for all fossil fuels and electricity, with the carbon-free backstops being considerably more expensive than the new carbon-rich technology.

Data sources. In addition to the above "structural" differences in the six models, there are also significant variations in base-year data. These arise from differences in data requirements for the different models, definitional differences, different starting points (involving different exchange rates, base-year prices and so on) and a significant amount of estimation to get a coherent 1990 starting point. The latter arises both from the non-availability of the right data and also because 1990 data (the starting point for the work in terms of this project) do not exist for many series, often having to be projected by the models from earlier years. These various differences are often unavoidable, but have to be taken very seriously as they clearly influence model results and the comparison of taxes and costs across

Chart 1. **Worldwide BAU CO2 emissions**



IPCC = the new (1992) IPCC reference case.

models. Furthermore, such information is important in attempting to decompose model results.

The Annex provides more information on these data issues. The most important difference, because it influences the BaU emissions and the reduction scenario results, is the difference in baseline energy prices (Annex Tables 2 and 3). Since substitution among fuels is largely price-induced, differences in relative energy prices can lead to considerable differences in fuel composition (Annex Table 4), and hence emissions, in the BaU scenario. In the reduction scenarios, with carbon taxes being based on absolute amounts of dollars per unit of carbon embodied in different fuels, relative energy price differences, both within and across models, are even more important in leading to differences in results. Baseline price differences are especially important for China and the former Soviet Union since the very large energy subsidies in these regions are not taken into account in all of the models.

III. "Business-as-Usual" Emission Paths

Even with a standardisation of assumptions on growth, population and resources, the BaU emission paths vary greatly across the models. This is already a point of concern, since the costs of achieving any target **level** for emissions, such as the stabilisation at 1990 levels, depend critically on the nature of the baseline -- what "distance" does one need to cut. In such "target" cases, it is not only the absolute tons of carbon that will vary across models but also the proportionate cut.

The CO_2 emission paths in the BaU scenario are shown in Chart 1, with the exact numbers and regional details being presented in Tables 4, 5 and 6. There are some differences in the **starting point** for energy-related CO_2 emissions in 1990, ranging from 5.8 billion tons of carbon (GREEN and ERM) to 6.0 billion tons (CRTM and MR). This initial difference of 3 per cent is not trivial, but it is also not surprising given that 1990 data are estimates based on data on energy consumption in earlier years and the application of "carbon emission coefficients" for different categories of fuel [3]. In fact, the differences in the 1990 level of emissions look relatively small when compared with the divergences in CO_2 emissions that open up, even in the **short term**, both for the world and for the different regions.

World emissions grow rather more rapidly over the short to medium-term in GREEN and IEA than in the other models (Chart 1 and Table 4). ERM shows the slowest emissions growth. Up to 2020, emissions in GREEN are growing by up to 1/2 per cent per annum faster than in ERM, despite the assumption of the same autonomous energy efficiency improvement of 1 per cent per annum. Hence a gap of over 1 1/2 billion tons of carbon opens up by 2020 between the top and bottom of the range of models, the 10.8 billion tons of GREEN and the 8.2 billion tons of ERM (Table 4).

Looking beyond 2020, where it is possible to make direct comparisons of time paths for only CRTM, ERM, MR and GREEN (up to 2050), the divergent emission paths for the earlier period open up much farther, so that world emission projections for the year 2100 are almost a magnitude of two different

Table 4. **Worldwide BaU CO_2 emissions**

Billion tons of carbon

	CRTM	ERM(1)	*ERM(2)*	GREEN(1)	*GREEN(2)*	IEA**	MR(1)	*MR(2)*	WW
1990	6.003	5.767	*5.767*	5.815	*5.815*	5.919	6.003	*6.003*	[av.
2000	6.931	..	..	7.071	*7.418*	7.316	6.970	*6.748*	1990
2005	..	6.709	*7.856*	7.704	*8.250*	7.932	..	..	to
2010	8.031	..	..	8.705	*9.452*	..	8.153	*7.581*	2100
2020	9.327	8.180	*10.505*	10.806	*11.938*	..	9.520	*8.681*	is
2050	11.337	11.838	*17.606*	18.998	*21.769*	..	14.992	*11.356*	25.2]
2080	23.519	18.099	*32.185*	..	..	..	26.945	*18.701*	
2100	35.863	22.579*	*41.594**	..	..	..	39.636	*26.039*	65.5

* 2095.

** The IEA model projections in this table have been adjusted to exclude non-fossil solid fuels, bunkers, non-energy use of fossil fuels and petrochemical feedstocks. These categories, included in the standard IEA model output, have not been excluded from the tables in the Appendix or from the results reported in the IEA paper and add around 900 million tons to the 1990 global figure of carbon emissions.

Note: In the three cases (ERM, MR, GREEN) where two emission paths are indicated, the first column denotes the standard model and the italicised second column shows the sensitivity to a different assumption on the autonomous energy efficiency improvement (AEEI). ERM(1), GREEN(1) and MR(2) have an AEEI of 1 per cent per annum while ERM(2), GREEN(2) and MR(1) have an AEEI of 1/2 per cent per annum.

CRTM = Carbon Rights Trade Model (see Rutherford, 1992)
ERM = Edmonds-Reilly Model (see Barns *et al.*, 1992)
GREEN = OECD Model (see Oliveira Martins *et al.*, 1992)
IEA = International Energy Agency Model (see Vouyoukas, 1992)
MR = Manne-Richels Global 2100 Model (see Manne, 1992)
WW = Whalley-Wigle Model (see Whalley and Wigle, 1992)

(Chart 1). Of course what may look to be relatively small differences in annual growth rates of CO_2 emissions compound over a century into significant differences in terms of levels (Table 4). The average growth rate of emissions over the whole of the period 1990-2100 is 1.3 per cent in ERM, 1.6 per cent in CRTM and 1.7 per cent in MR. But the spread between the lowest and highest emissions in 2100 -- 22 1/2 billion tons of carbon in ERM and 39 1/2 billion tons in MR -- is quite startling. WW have a point estimate for 2100 of 65 1/2 billion tons (and an average growth throughout the period of 2.3 per cent), but this seems to reflect both an extremely pessimistic assessment of energy efficiency improvements and the lack of substitution possibilities imposed by the two-fuel structure of the model. All of the model estimates are nevertheless above the new IPCC reference case (in the 1992 IPCC Supplement work), of 19.8 billion tons of carbon in 2100. However, five other scenarios are now given by the IPCC and they range from 4.6 billion tons (a low population, lower growth and low oil and gas availability scenario) to 34.9 billion tons (with more rapid improvement of GNP per capita, a nuclear phase-out and plentiful fossil resources).

The importance of the autonomous energy efficiency parameter (AEEI) in contributing to the large differences in emissions has been revealed by some sensitivity testing (as shown in Table 4 and Chart 1). In an alternative BaU scenario, using ERM but reducing AEEI from 1 per cent per annum to 1/2 per cent in all regions (roughly the MR assumption), world emissions rise from the previous 22 1/2 billion tons to around 42 billion tons by the end of the next century, much in line with the MR results (though there are some offsetting factors that lie behind these rather close results). A similar exercise with MR, this time increasing its AEEI to 1 per cent per annum in all regions, leads to emissions in 2100 of 26 billion tons, much closer to the standard ERM result of 22 1/2 billion tons. On the other hand, imposing a lower AEEI of 1/2 per cent in GREEN takes the 2050 emissions, already the highest among the models, to a higher level still (21.8 billion tons compared with 19 billion tons using the standard model with a 1 per cent AEEI). The high WW result mentioned earlier (65 1/2 billion tons in 2100) is related to the assumption of a zero AEEI.

Unfortunately, there is relatively little backing in the econometric literature for specific values of the AEEI parameter, so that modellers have had to use their judgement to select values for this key parameter [4]. MR and CRTM assume different values for different regions, with the growth rate of AEEI lowest in the former Soviet Union (0.25 per cent), intermediate for the OECD (0.5 per cent) and highest in China (1.0 per cent). These values are based on the assumption that those countries with the lowest levels of industrialisation have greater scope for technical progress, but the AEEI parameter then converges to 0.5 in all regions by the middle of the next century. As mentioned above, ERM and GREEN assume a 1 per cent AEEI, which is also roughly the value that comes out of the IEA results, while WW has the lowest value of zero. The inability to tie down this parameter to a much narrower range than this is a severe handicap in trying to get any precision on the future emissions path for CO_2, but the uncertainty on this needs to be recognised.

Given the assumed slowing of both population growth and GNP growth in all regions through the next century, the growth of CO_2 emissions might have been expected to slow, roughly *pari passu*, since the main driving forces behind

Table 5. **OECD and non-OECD BaU CO_2 emissions**
(billion tons of carbon)

OECD

	CRTM	ERM	GREEN	IEA (1)	MR
1990	2.805	2.690	2.758	2.717	2.805
2000	3.317	..	3.120	3.119	3.289
2005	..	3.167	..	3.256	..
2010	3.513	..	3.389	..	3.705
2020	4.180	3.557	3.716	..	4.195
2050	5.074	4.162	4.833	..	6.407
2080	7.739	4.793	..	..	8.193
2100	9.233	5.363*	..	..	9.558

Non-OECD

	CRTM	ERM	GREEN	IEA (1)	MR
1990	3.198	3.077	3.057	3.202	3.198
2000	3.614	..	3.951	4.197	3.681
2005	..	3.542	..	4.676	..
2010	4.377	..	5.317	..	4.449
2020	5.074	4.623	7.090	..	5.325
2050	7.154	7.676	14.165	..	8.584
2080	16.143	13.306	..	..	18.751
2100	26.753	17.216*	..	..	30.079

1. The IEA model projections in this table have been adjusted to exclude non-fossil solid fuels, bunkers, non-energy use of fossil fuels and petrochemical feedstocks. These categories, included in the standard IEA model output, have not been excluded from the tables in the Appendix or from the results reported in the IEA paper and add around 900 million tons to the 1990 global figure of carbon emissions.

* 2095.

Note: The ERM, GREEN and MR numbers used here come from the standard model versions and hence correspond to the column headings ERM(1), GREEN(1) and MR(1) in Table 4.

emissions are consumption and production. There is still much room left, however, for baseline emission paths to vary across models because of differences in the technical specification of the link between emissions and activity in different sectors and the possibilities for substitution. Changes in energy efficiency and in the composition of fuels used (some fuels being much more carbon-intensive than others), both of which have an important influence on emissions, vary considerably. Despite slowing population and growth, world CO_2 emissions growth in CRTM and MR is significantly faster in the second half of the 21st century than earlier and marginally more also in ERM (Table 6).

The strong pick-up in emissions in CRTM and MR is confined to the non-OECD regions; emissions growth slows significantly in the OECD in the second half of the next century while it picks up sharply in China, the former Soviet Union and RoW. In ERM there is an easing of emissions growth in the same period in all regions except for the former Soviet Union. The structure of fuel use is clearly important in explaining the pick-up in emissions, with reserves of natural gas (the "cleanest" fuel in terms of carbon content) eventually running dry. This goes hand-in-hand with a switch to greater use of coal, which is in abundant supply, and the even "dirtier" synfuels, both of which can be expected to be used increasingly in the absence of measures to curb CO_2 emissions or the availability of relatively cheap carbon-free backstop technologies. However, there is also an offsetting switch to non-fossil fuels, with the speeding up or slowing of emissions growth being determined by the exact mix of the different types of fuel switching.

There are important **regional differences in the baseline emission paths** (Tables 5, 6 and Appendix Table A3). In the period up to 2050, the estimated growth rates of emissions in the OECD are relatively close, with all exhibiting a slowing over the period, but there are very different projections for the non-OECD regions. The most important difference is that GREEN shows a significantly higher growth of emissions for China than the other models. The same is true, though to a lesser extent, for the former Soviet Union and the rather heterogeneous RoW region. Faster emission growth in these regions largely reflects the low prices of most energy sources identified in GREEN's data base, which are assumed to prevail. Low energy prices encourage the use of coal and prevent the phase-in of carbon-free backstops. If energy price distortions in these regions were eliminated, world emissions in GREEN in 2050 would come down from 19 billion tons to 15 billion tons of carbon.

Beyond 2050, the range of growth rates across models and regions narrows somewhat. For the OECD, annual emissions growth is reduced to about 1 per cent in CRTM and MR and to just over 1/2 per cent in ERM. For China, these growth rates are, respectively, just under 3 per cent and 2 1/2 per cent and there are similar differences for RoW. The difference in these results is not far from the differences in the assumed AEEIs (1/2 per cent in CRTM and MR and 1 per cent in ERM). However, the former Soviet Union results are roughly the same for the three models which run to 2100.

The contribution to emissions growth of shifts in fuel composition and the energy intensity of output can be calculated by examining the relevant data series in each model. The path of CO_2 emissions (C) per unit of output depends on:

Table 6. **Comparison of average growth rates of CO_2 emissions across models, 1950-2100**

Annual average percentage changes

	Historical data				Baseline projections				
	1950-75	1975-80	1980-85		1985-90	1990-2000	2000-2020	2020-2050	2050-2100
United States	2.3	1.4	-1.0	CRTM	..	1.5	1.1	0.7	1.1
				ERM (1)	1.8	0.8	0.8	0.7	0.6
				GREEN	1.1	1.1	1.1	0.7	..
				IEA (2)	1.3	1.5	0.7	..	..
				MR	..	1.4	1.2	1.5	0.7
Other OECD	2.7	1.8	-1.2	CRTM	..	1.9	1.2	0.6	1.3
				ERM (1)	1.9	1.4	0.8	0.4	0.5
				GREEN	1.7	1.4	0.7	1.0	..
				IEA (2)	2.0	1.3	1.0	..	..
				MR	..	1.8	1.3	1.3	0.9
Former Soviet Union	5.9	2.5	1.9	CRTM	..	1.1	1.1	-1.3	1.1
				ERM (1)	1.3	-0.2	0.6	0.5	1.0
				GREEN	1.6	1.9	1.8	1.0	..
				IEA (2)	2.0	1.9	0.2	..	..
				MR	..	1.2	1.1	-0.3	1.1
China	11.2	5.3	5.4	CRTM	..	1.4	2.0	1.8	3.4
				ERM (1)	2.9	2.3	3.0	2.6	2.3
				GREEN	3.1	3.7	4.6	3.2	..
				IEA (2)	4.4	3.3	3.1	..	..
				MR	..	1.6	2.2	2.6	3.0
RoW	4.7	5.4	2.4	CRTM	..	1.3	2.0	1.8	2.5
				ERM (1)	2.8	1.5	2.0	1.7	1.6
				GREEN	2.6	2.6	2.8	2.3	..
				IEA (2)	2.8	3.0	2.8	..	..
				MR	..	1.5	2.2	1.9	2.5
World	3.6	2.6	0.8	CRTM	..	1.4	1.5	0.7	2.3
				ERM (1)	2.0	1.0	1.3	1.2	1.4
				GREEN	1.8	2.0	2.1	1.9	..
				IEA (2)	2.3	2.1	1.6	..	..
				MR	..	1.5	1.6	1.5	2.0

1. The later periods are 1990-2005, 2005-2020, 2020-2050 and 2050-2095.

2. The periods are 1987-1990, 1990-2000 and 2000-2005.

Sources: Historical data on emissions are from Edmonds and Barns (1990).

i) emission coefficients for coal, oil, gas and carbon-based synfuels,

ii) fuel composition (between carbon-based (FE) and carbon-free fuels), and

iii) energy use (E) per unit of output (GDP).

For any single period, emission intensities (carbon (C) per unit of GDP) can be decomposed into various relevant parts by the following identity:

$$C/GDP = C/FE \, . \, FE/E \, . \, E/GDP \qquad [1]$$

Over time, first differences in the logarithms of the right-hand-side variables show the contributions to changes in emission intensities:

$$\Delta \ln C/GDP = \Delta \ln C/FE + \Delta \ln FE/E + \Delta \ln E/GDP \qquad [2]$$

The first term on the right-hand side shows the effect of changes in the composition of carbon-based fuels on emissions [5]. The second term shows the contribution of any expansion of carbon-free fuels to a reduction in emissions. These two terms therefore capture the contribution of inter-fuel substitution to the change in emission intensities. The final term shows the effect of changes in aggregate energy intensity, i.e. the degree of energy conservation, on emissions.

Changes in GDP are virtually the same (by assumption) across model. Up to 2020, global GDP more than doubles as compared to 1990. Total energy use expands by less. A trend decline in energy intensity thus contributes to the fall in aggregate carbon intensity in all models by about 1/2 to 1 percentage point per year (Table 7). The difference in the trend decline in emission intensities of between 0.6 per cent (GREEN) and 1.4 per cent (ERM) per year is influenced in addition by differences in the contributions of the other two factors, the carbon intensity of carbon-based fuels and the share of carbon-free fuels. In GREEN both are neutral, while in ERM they reinforce it. The decline is also attenuated in MR because of an increase in the carbon intensity of carbon-based fuels, while there is no effect from the two factors in the IEA model.

In GREEN, the trend decline of global energy intensity continues at the same rate between 2020 and 2050, while in ERM and MR the trend decline of global energy intensity is reduced considerably between 2020 and the end of the next century. Indeed, the baseline of Manne even shows a small trend increase. The difference partly reflects different assumptions about energy efficiency improvements. However, the much faster growth of the countries with higher initial (and end-year) energy intensities also plays a role. In addition, relative price changes influence energy intensity, a factor difficult to isolate. Apart from the sharp reduction in the trend decline of energy intensity, increased carbon intensity raises emission intensities in both models and in GREEN up to 2050: coal and carbon-based synfuels gain market shares. On the other hand, emission growth is held back by the rapid expansion of carbon-free energy sources in MR and ERM. In sum, trend declines in global carbon intensity slow considerably after 2020 in MR and ERM, hence offsetting the effect of slowing population and growth rates on the growth of emissions.

Table 7. **Decomposition of baseline scenarios**

Average annual rates of change for global economy

	ERM			GREEN		IEA	MR		
	1990-2020	2020-2050	2050-2100	1990-2020	2020-2050	1990-2005	1990-2020	2020-2050	2050-2100
Aggregate emission intensity	-1.4	-0.8	-0.4	-0.6	-0.2	-1.0	-0.9	-0.4	0.1
Fossil fuel carbon intensity (1)	-0.1	0.2	0.3	0.0	0.5	0.0	0.4	0.2	0.2
Share of carbon-free fuels	-0.1	-0.2	-0.2	0.0	0.0	0.0	-0.2	-0.8	-0.1
Energy intensity	-1.1	-0.8	-0.5	-0.6	-0.6	-1.0	-1.1	0.2	0.0

1. Includes carbon-based synfuels.

Detailed numbers are not available for CRTM. Chart 2, however, provides some insight into the forces shaping carbon emissions in this model during the next century. For electric energy, the carbon intensity is rather stable up to 2030, but drops off sharply due to the emergence of a cost-effective carbon-free electric technology. By 2060, all electric energy is produced by carbon-free technology. The carbon intensity of the non-electric sector, on the other hand, trends down until 2030 but increases sharply in the following decades as high carbon-content synfuels come on-stream. The trend increase appears to become flatter from 2060 onwards. The former Soviet Union follows trends in the other regions with a delay, due to its vast resources of gas. Changes in carbon intensities in the electric and non-electric sectors are largely the same in MR. For both the former Soviet Union and China, CRTM and MR therefore have a strong pick-up in emissions growth as between the two halves of the next century, with the carbon intensity of energy demand increasing as gas and oil become more expensive and a switch is made to dirtier fuels.

The baseline of WW is difficult to compare with the other models because of its static nature. However, the value share for carbon-based energy products in GDP of about 10 per cent for the average of 1990 to 2100 is on the high side, reflecting the absence of any energy efficiency improvement, the absence of carbon-free backstop technologies and limited non-fossil fuel supply. These all contribute to the much higher level of emissions than in the other models.

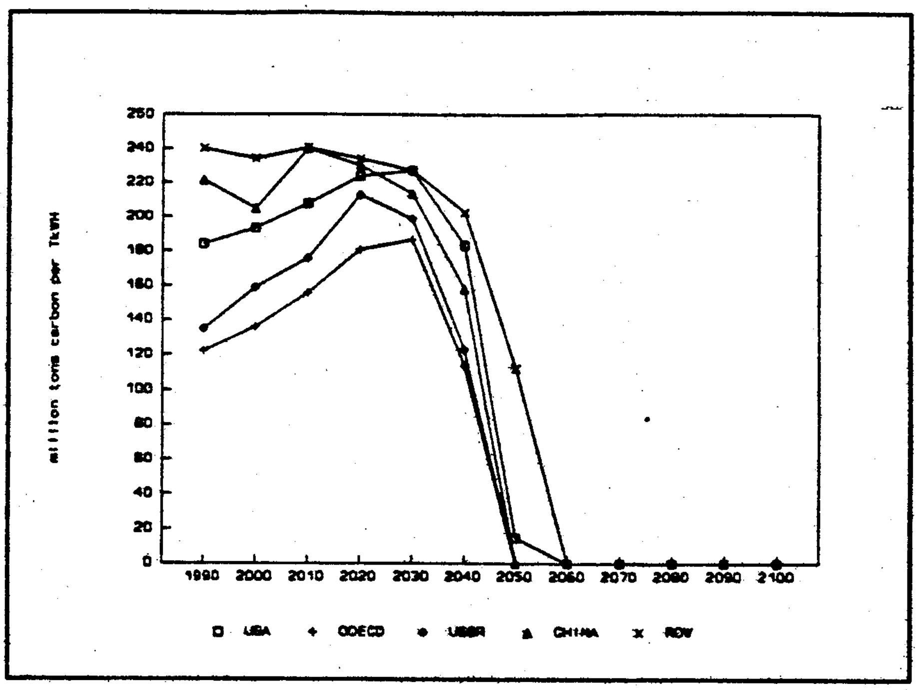
The wide range of estimates for BaU emissions through to the end of the next century contrasts rather starkly with the rather precise numbers set out in the earlier 1990 report by the Intergovernmental Panel on Climate Change (IPCC). The Business-as-Usual scenario gave an estimate of 22 1/2 billion tons in 2100, on the low side of the estimates presented here. This has now been revised down to just under 20 billion tons (Chart 1) but, as noted above, the IPCC now presents a variety of scenarios with a very wide range of 2100 emissions. Clearly, a high degree of uncertainty attaches to all of these numbers and this of course complicates the task of looking at the cost of reaching specific targets set in terms of levels of CO_2 emissions. This is one reason why the current comparisons project has been focused mostly on reductions in the growth rates of emissions rather than on target levels.

IV. Analysis of the Reduction Scenarios

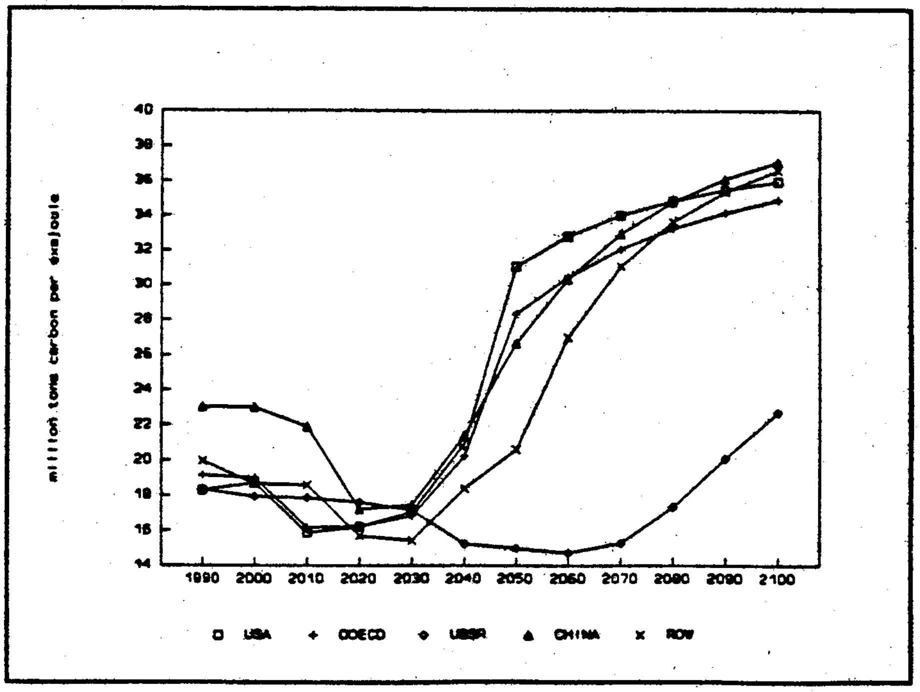
i) Global cost curves

The required carbon taxes to reduce world CO_2 emissions to certain levels in terms of billions of tons of carbon are set out in Chart 3 in a series of marginal tax curves for the years 2000, 2020, 2050 and 2100. Each curve plots out for each model the results of the 1, 2 and 3 per cent scenarios plus the scenario for stabilisation of emissions at 1990 levels (about 6 billion tons). These global tax curves are an emission-weighted average of regional tax curves. (Details are given in Appendix Tables A4 to A12.) Note that the BaU starting points, i.e. the emissions at a zero carbon tax, vary significantly by the later periods, as discussed in the previous section.

Chart 2. Carbon intensity in CRTM



Carbon Intensity of Electric Energy

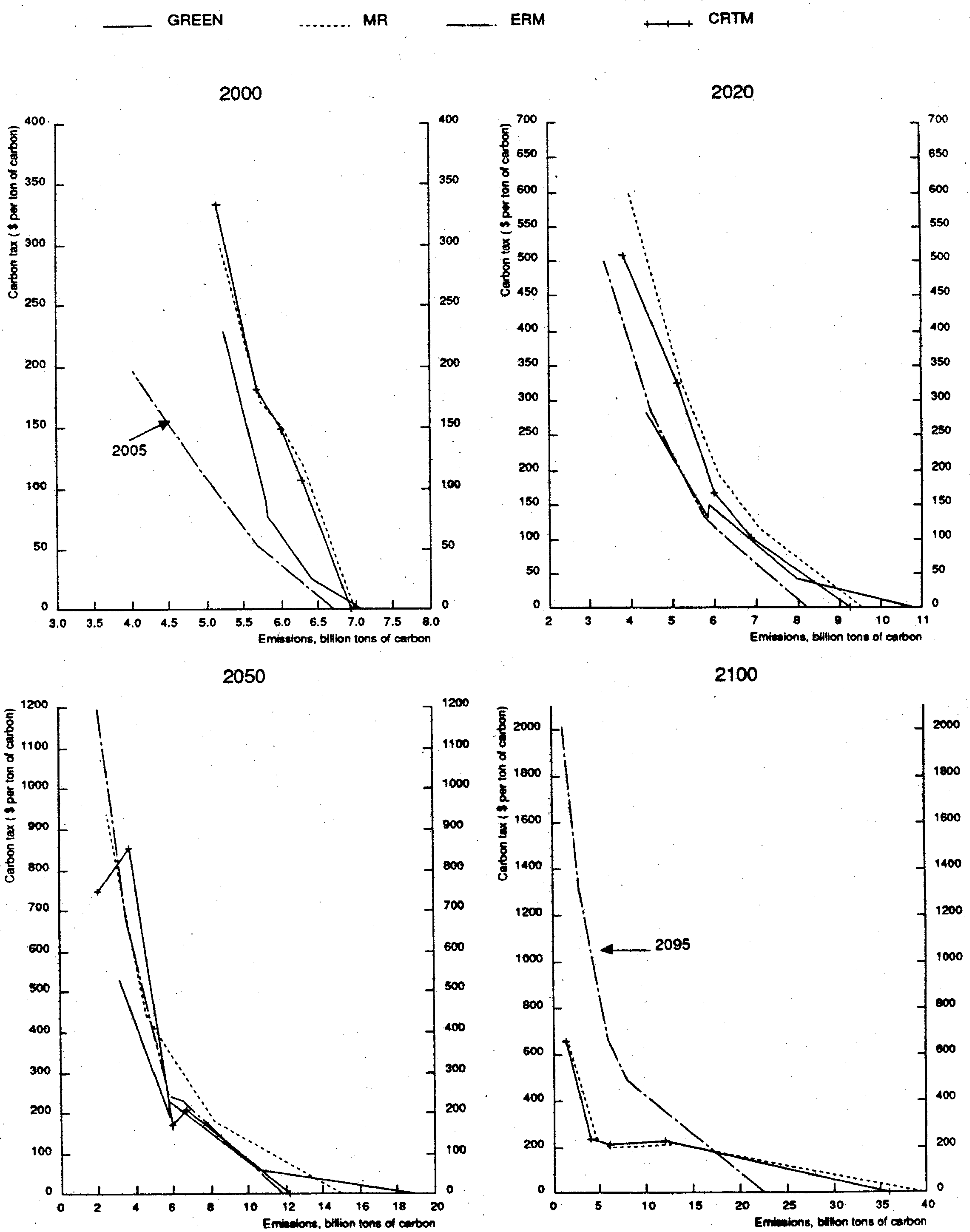


Carbon Intensity of Non-Electric Energy

Source: Rutherford (1992).

Chart 3. **World emissions and carbon taxes**

Note. The scales on the different panels are not standardised.



Furthermore, although these curves have been derived from the reduction scenarios presented in terms of cuts in percentage point growth rates, they can be interpolated to provide the required carbon tax rates for any particular target for the years specified. The main conclusions stemming from the tax curves shown in Chart 3 are the following:

-- The curvature indicates the need for increasing marginal tax increments per unit of reduction in carbon emitted. There are diminishing marginal returns to the tax as cheaper options to reduce emissions are taken first, but it becomes increasingly more difficult to substitute for or economise on fossil fuels. Furthermore, squeezing out the very last units of carbon would entail very high carbon taxes, the world average tax being more than $500 per ton (equivalent to $60 on a barrel of oil) in both 2050 and 2100.

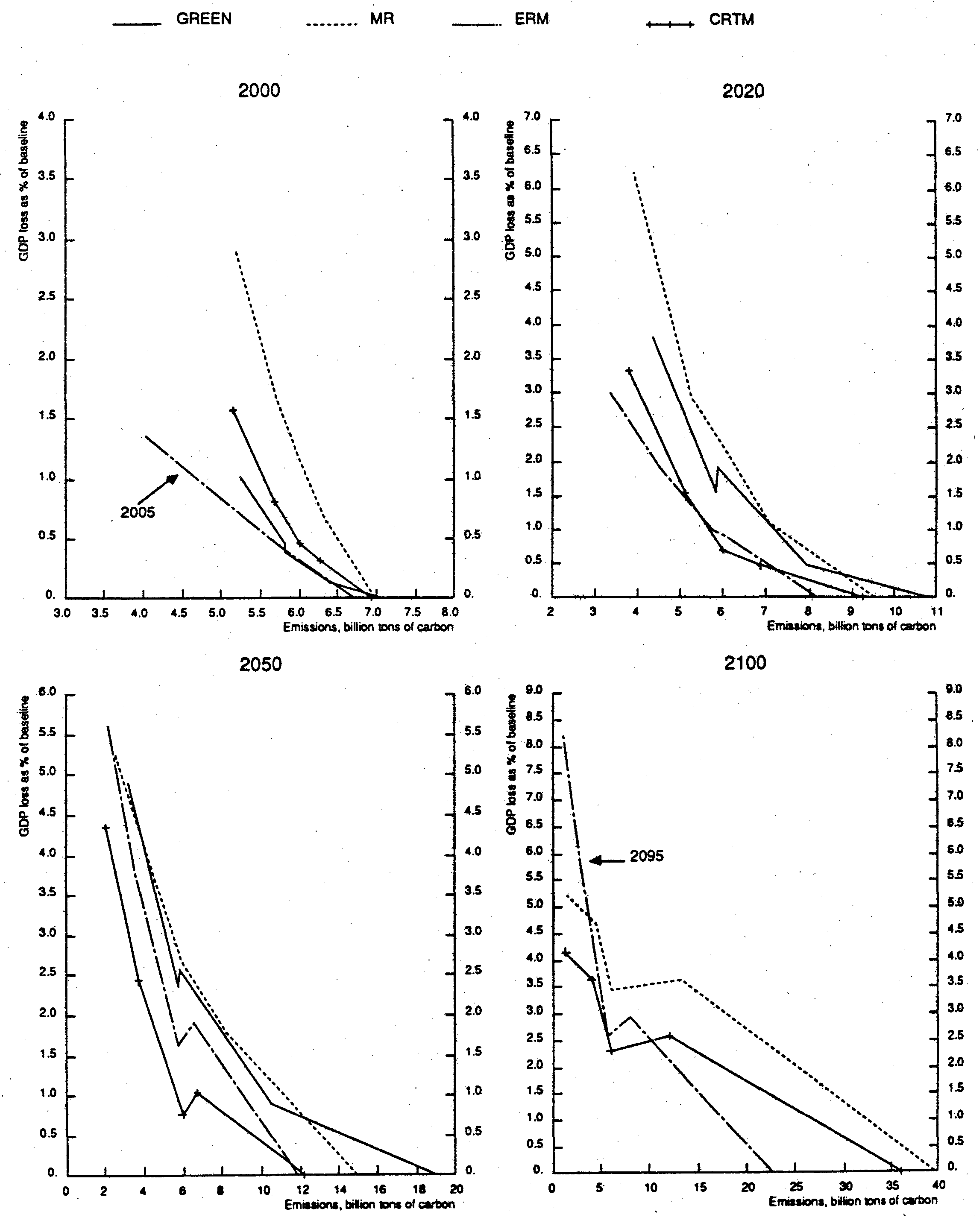
-- In the earlier periods (2000 and 2020) the model results for the world tax curves line up reasonably together, but this is no longer the case (noting also the change in scales in Chart 3) once deep cuts are being made in the later years (2050 and 2100). This is because there are no backstop technologies (unlimited supplies of new, but more expensive, carbon-free fuels) in ERM so that there is no limit to the rise in the tax. Hence, already by 2050, ERM has taxes which rise beyond $1 000 a ton, and these taxes rise inexorably to above $2 000 a ton by 2100. The backstops act to limit the rise in the required tax in CRTM, MR and GREEN because switching to the new technologies is induced by higher carbon taxes [6].

The average economic costs of reducing emissions are closely related to the level of carbon taxes required to ensure the reductions, although there is no simple one-to-one link as many factors come into play. The best cost measure to focus on would be some measure of economic welfare [7], such as the Hicksian equivalent variation [8] that is computed by GREEN and WW. This is not, however, available for any of the other models, which give results only for production-side measures such as GDP. Although GDP is a familiar measure of output, it is only a partial indicator of welfare, failing to take into account, *inter alia,* changes in the terms of trade (which can be especially important for oil-producing countries) and the consumption losses due to the tax. The GDP losses across models are shown in a series of abatement cost curves in Chart 4, with world losses being plotted against reductions in terms of billions of tons of carbon for four snapshot years, in the same way as with the corresponding tax curves in Chart 3.

The initial GDP costs in 2000 lie between 1 and 3 per cent of GDP in the case of the fastest cut in emissions (3 percentage points per annum), while the costs in the 2 per cent case are perhaps half or less. This reflects the upward curvature of the tax curves, indicating again that the speed of adjustment is itself important. By 2020 the range of GDP losses for the largest cuts (3 per cent reduction case) is from 3 to 6 per cent of GDP and by 2100 the range is 4 to 8 per cent. The greatest loss is shown by ERM, reflecting both the highest tax (Chart 3) and also a fairly rigid link between energy prices and GDP that even the authors tend to doubt (Barns *et al.,* 1992).

Chart 4. **World emissions and GDP losses**

Note. The scales on the different panels are not standardised.



ii) Different regional results across models

United States (Charts 5 and 6). There is a reasonable degree of agreement between most of the models for the level of the carbon tax needed for reductions of up to about 45 per cent, which corresponds to about the year 2020 (Chart 5). The IEA model has significantly higher taxes than the other models over the first 15 years, the reason given for this being the concentration of their model on the existing rigidities in the energy system (Vouyoukas, 1992). Beyond 2020, CRTM, ERM and MR begin by showing almost identical taxes of around $350 per ton of carbon for the 45 per cent reduction, but then diverge by an enormous margin. The required tax to achieve a reduction in baseline emissions of close to 90 per cent is just over $200 in CRTM and MR and almost $2 800 in ERM. The former models incorporate backstop technologies which set an upper limit to the carbon tax, after some initial overshooting, but such backstops are absent in ERM. Without backstops the required carbon taxes get driven up to extremely high levels and the typical tax curve exhibits diminishing returns, beginning to curve upwards rather rapidly after the easier fuel substitutions have been made. This is also the case with WW.

It is possible to trace out a tax curve for WW for the period 1990-2100 but it would not show a dynamic time-path but rather relate the required carbon tax to the degree of emission reduction, the cuts being those implied by the 1, 2 and 3 per cent scenarios. Such a chart is not presented here, although the required carbon taxes are shown in Appendix Table A12 and the steady increase in these taxes is discussed in Whalley and Wigle (1992). The WW scenario results indicate that the required carbon taxes are within the range of results of the other models for cuts of about 45 per cent (which for the other models occur in 2020 in the 2 per cent case shown in Chart 5) and then lie between ERM and CRTM/MR, with the absence of backstop technology leading to a rising tax curve as with ERM. The deepest cuts (the 3 per cent scenario) require taxes over the period 1990-2100 of around $1 200 per ton of carbon for WW, which compares with taxes in ERM which are significantly higher than this by the second half of the next century and taxes in the other models which are limited to no more than about $600 per ton as backstop technologies are introduced.

As to cost, the result that stands out is the generally greater cost for WW, not just for the United States but for other regions too. To some extent this would be expected since, as noted above, WW use a welfare measure that goes further than the output losses for the other models. But the absence of backstops, and hence the high taxes required for the deepest cuts, means that the costs are greatest in ERM and WW.

For the other models shown in Chart 6, the GREEN and CRTM GDP losses for the United States are lower in the period to 2050 than those of ERM or MR. The ERM and MR numbers are relatively close up until 2020, indicating costs of about 2 per cent of GDP in achieving the reduction of 45 per cent of baseline emissions, but estimated costs diverge considerably thereafter. MR has the rise in costs tailing off after 2030, as backstop technologies come into play and the tax rate stabilises at its long-run equilibrium level of around $200 per ton of carbon. And CRTM even has the GDP losses being reduced in the period 2020 to 2040. On the other hand, ERM has a continuing sharp rise in costs, though at a decreasing rate beyond 2065 (the slope of the cost curve in Chart 6 begins to ease). *A priori* one might have expected the ERM costs to continue accelerating in parallel with the required tax.

Chart 5. **Carbon taxes in the 2 per cent reduction scenario**

Note. The scales on the different panels are not standardised.

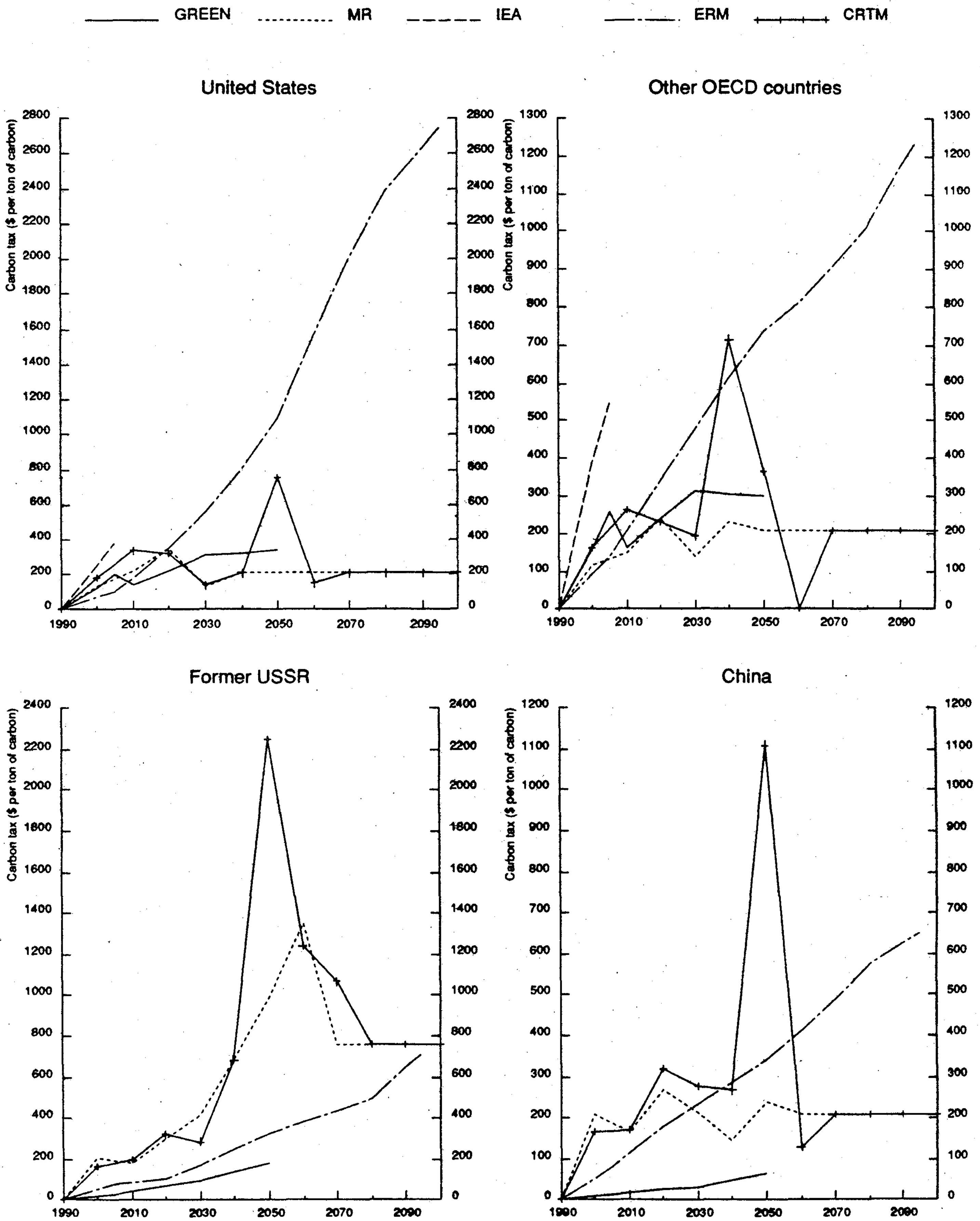
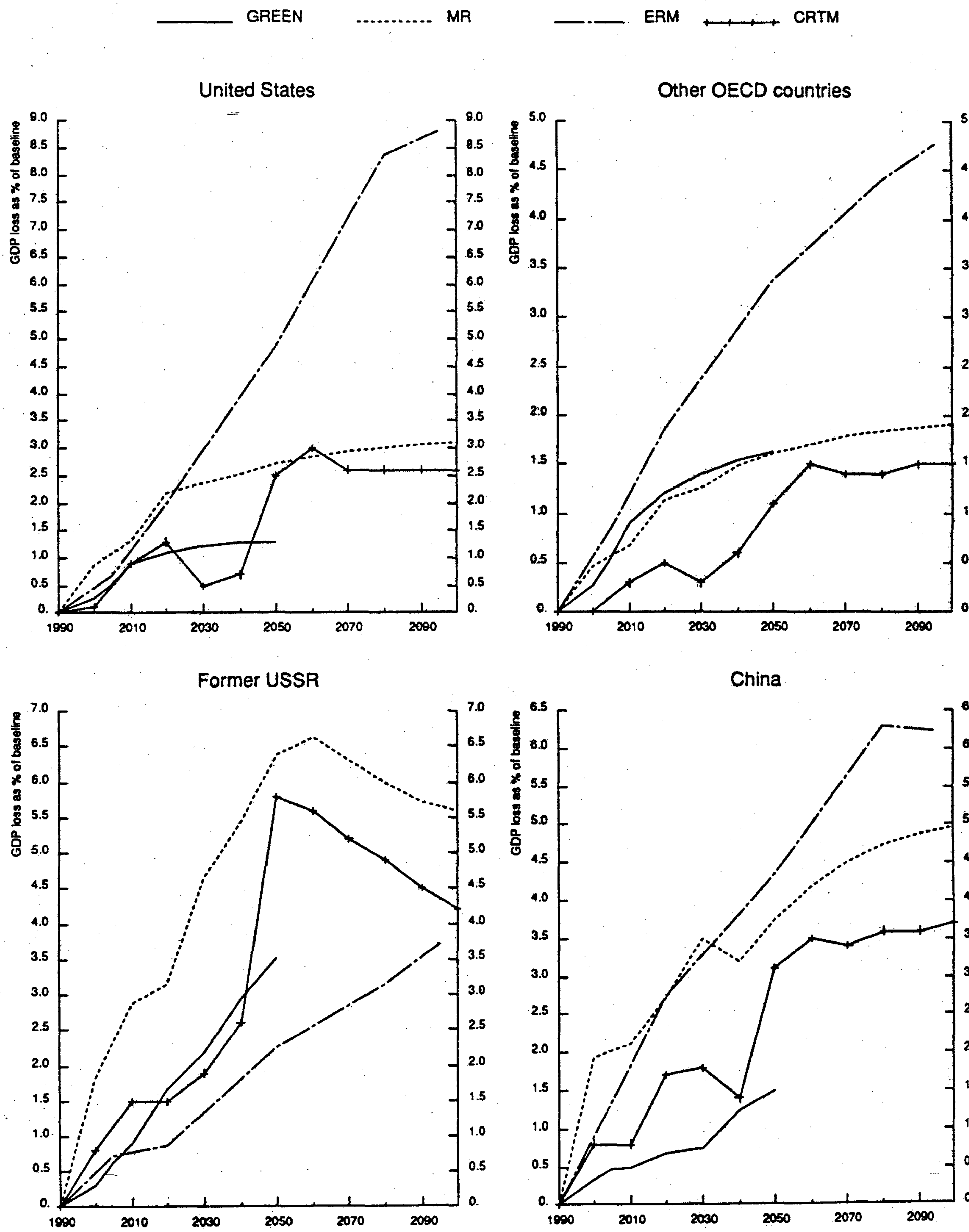


Chart 6. GDP losses in the 2 per cent reduction scenario

Note. The scales on the different panels are not standardised.



Other OECD countries (Charts 5 and 6). The results for the Other OECD countries show little of the clustering over the first 30 years indicated by the U.S. results. It is true that ERM, GREEN and MR show some accord over the period to 2005, and are not so different even up to 2020. But they then diverge markedly, and for the same apparent reason as before -- the impact of backstop technologies in MR and GREEN and their absence in ERM, which drives the tax ever upward in the latter. The CRTM tax is much more volatile but eventually moves to the backstop-determined rate of $208 per ton. The IEA carbon tax is again much higher than for all the other models.

As to the results for costs, the ERM and MR results show a rough "equivalence" between costs and taxes as between the Other OECD and U.S. results -- ERM ends up with roughly the same costs for the same level of required tax, MR has costs for Other OECD countries roughly half those in the U.S. case but for a tax considerably lower than the U.S. case. GREEN results are very similar to MR while GDP losses are lowest for CRTM.

Former Soviet Union (Charts 5 and 6). The ERM and GREEN taxes are similar around 2020 (though diverging more in 2005), with the ERM tax curve indicating diminishing returns through the rest of the century and having much the same profile as for the other regions. But MR has a uniformly higher tax throughout, even with backstop technologies leading to the tax stabilising at about $750 per ton from 2020 on. CRTM, while converging to the same tax rate of $750, overshoots by an enormous amount in the middle of the next century with the tax rising to over $2 000 per ton. In MR the long-run equilibrium tax is determined by the relationship between the relative cost of the synfuels and carbon-free backstops (biomass or hydrogen by electrolysis using a carbon-free electricity) and prices of fossil fuels [9].

The cost curves (Chart 6) tend to track the tax curves (Chart 5) fairly well. However, there is still a relatively large difference between ERM and MR in output costs in 2100 when the required carbon taxes are very close. The MR tax is significantly higher than ERM right through till the end of the next century, in contrast to the situation in other regions, until the effects of backstop technologies lead to the long-run equilibrium price of about $750 a ton in MR. The ERM tax curve gradually catches up to this level by the end of the period (Chart 5) but the GDP loss remains significantly lower.

China (Charts 5 and 6). There are similarities between the results for China and for the former Soviet Union in the four models covered. MR and CRTM are again "out of the blocks" faster with higher tax rates than the others over the short to medium term, but the backstop technology cuts in more rapidly and at the same rate (just over $200) as in the OECD countries. CRTM again has a massive overshoot, a tax of over $1 000 in 2050. The requisite GREEN tax is very much lower than in the other two models. The ERM tax curve has its characteristic shape but the key feature of these different results is the flat profile of the GREEN tax curve. The GREEN paper emphasises the role of very low (by international standards) domestic energy prices in China, particularly for coal, as a major factor accounting for the very flat tax curve. This is one of the factors stressed below in attempting to explain the reasons for the different results.

The cost figures for China, as with the former Soviet Union, mirror the different tax curves rather well, with GREEN giving very low costs as well as taxes and ERM and MR indicating a cross-over in taxes and costs once cuts from baseline levels reach 50 per cent (around 2025). With the costs in ERM and MR being not far apart in 2100, there is again the suspicion that the timing of tax increases has a strong effect on the eventual cost.

Rest of the world (see Appendix Tables). The rest of the world is a rather heterogeneous grouping for most models, so it is probably unwise to read much into any comparisons. For the record, however, the ERM tax curve is characteristic of the model, indicating diminishing returns to the tax rate. The MR tax curve starts off being higher but then oscillates rather curiously before coming down to the backstop price. The costs end up being rather similar by 2100, despite an ERM tax rate which terminates at a level about ten times higher, though the cost in MR is substantially higher throughout the period up till then. The GDP costs, at least in the out years, are rather closer than might be expected from the often very divergent tax curves.

iii) Stabilisation of emissions

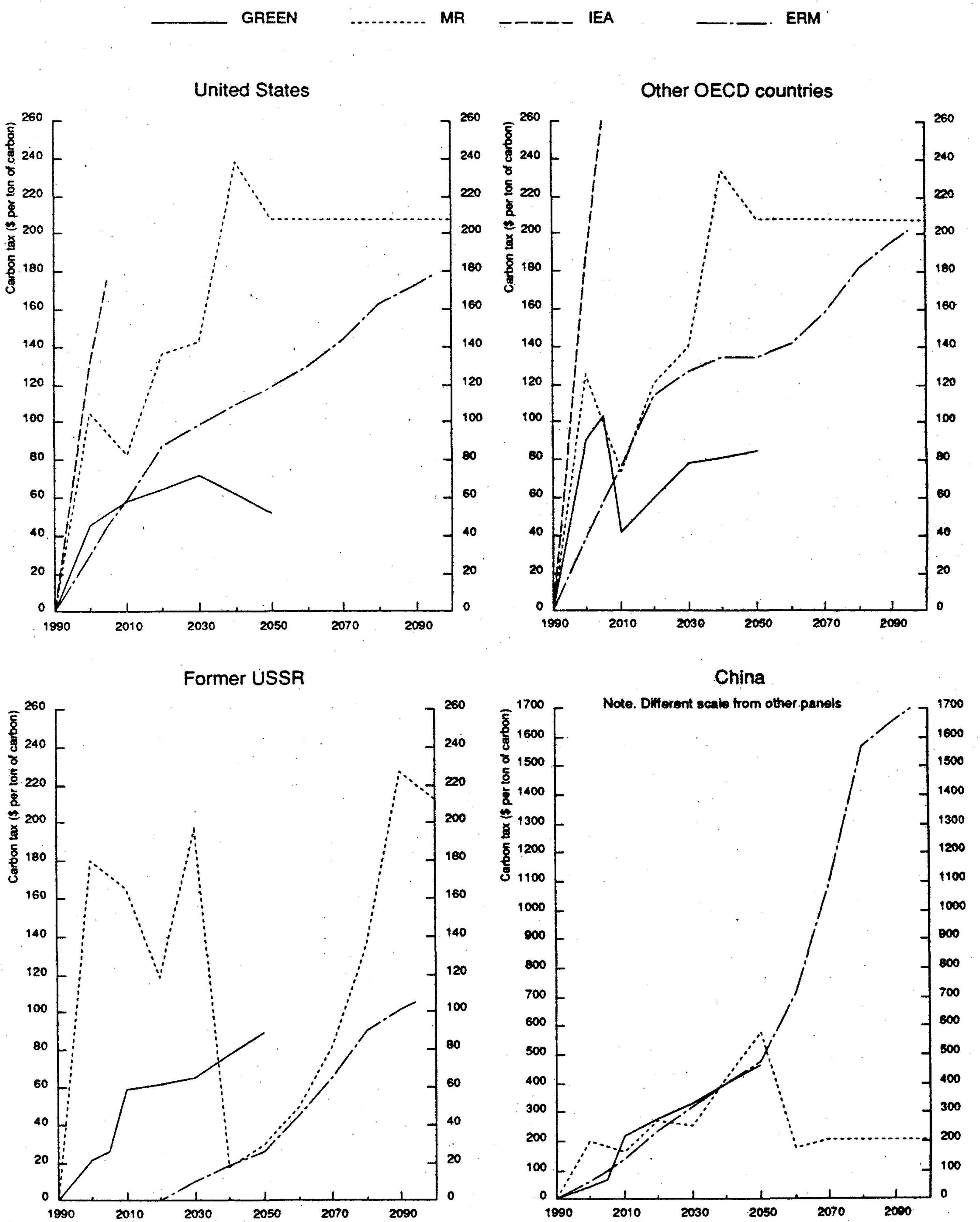
The stabilisation scenario has an entirely different character from the other reduction scenarios. Stabilisation of emissions at 1990 levels is an absolute target and hence the requisite carbon taxes and the associated costs are strongly dependent on the BaU emissions. In principle the results could indeed be inferred from the analysis of the BaU scenarios in Section III and from the reduction scenarios given above, with large reductions (similar to the 2 or 3 per cent case) being required in most models for China and RoW in order to stabilise emissions and smaller reductions (similar to the 1 per cent case) being required for the OECD regions and the former Soviet Union. Across models, we know from the BaU scenarios (Chart 1) that the size of cuts to achieve stabilisation will have to be greatest for WW and then for GREEN and the IEA, while the smallest cuts will be for ERM. Comparisons across models need to take the different BaU paths and hence the size of the cuts into account.

The interest of the stabilisation scenario is that the climate change convention signed in Rio in June 1992 incorporated the goal for developed countries of stabilising all greenhouse gas emissions at 1990 levels. This was not a firm undertaking, but much of the discussion in the international negotiations preceding the signing revolved around a stabilisation objective. It is not clear, however, that the degree of uncertainty over both the BaU emission paths themselves and the costs involved in reining in CO_2 emissions to 1990 levels has been fully recognised.

The main results for these scenarios are presented in Charts 7 and 8. Several general features stand out;

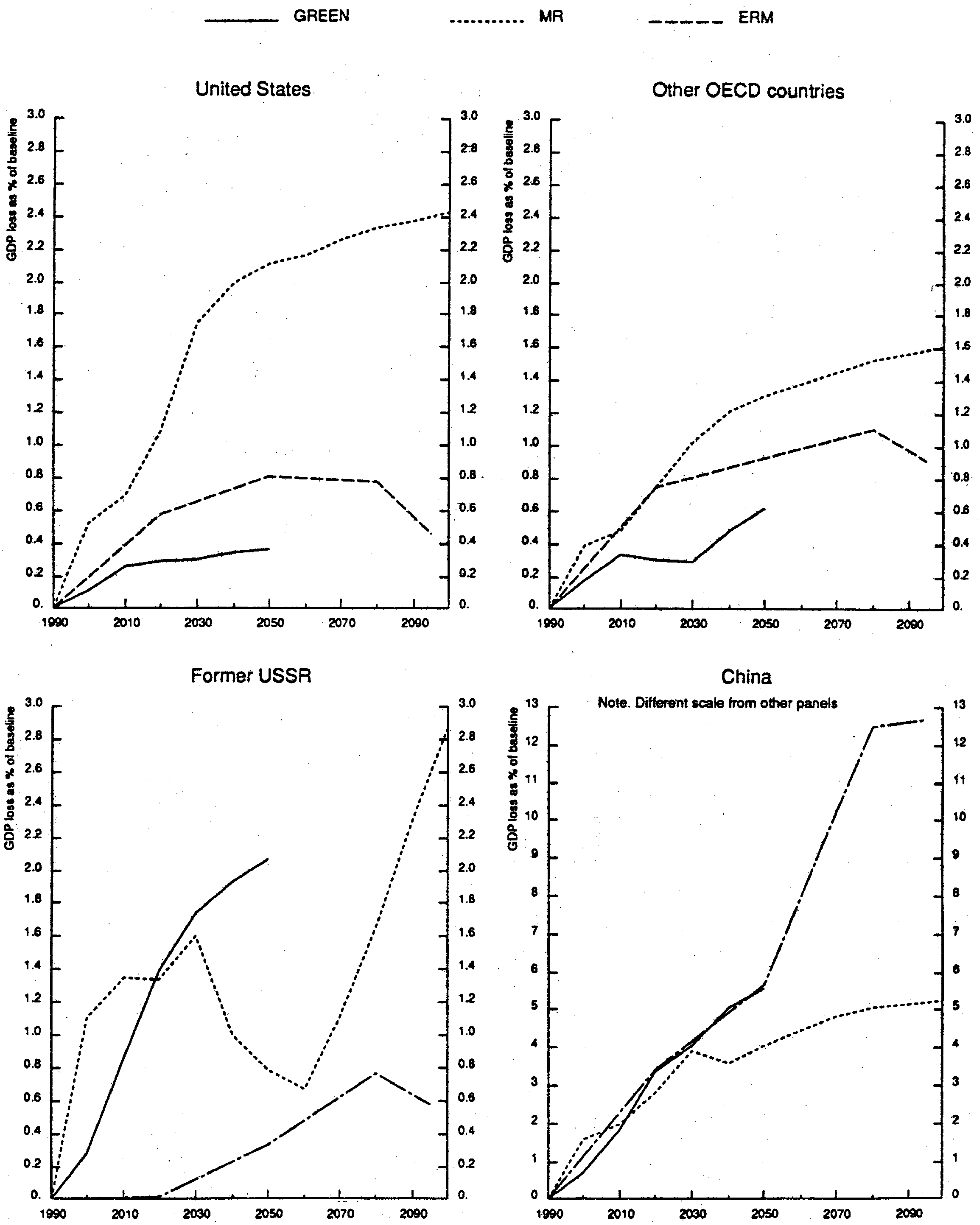
i) The carbon tax for the *OECD regions* is highest in the IEA model and lowest for GREEN from 2010 onwards. The IEA result is as expected; baseline emissions growth is relatively fast and the reduction scenarios indicate higher taxes than elsewhere for any particular reduction. The ERM result, in the middle of the pack, is also not surprising; the required tax was higher in the out years than for others, but baseline emissions growth is much slower. The relatively low tax in GREEN is related to two factors; first, BaU emissions growth for the OECD regions in GREEN is relatively low, even though world emissions are growing much faster than in the other models and, second, backstop

Chart 7. **Carbon taxes in the stabilisation scenario**



Note. CRTM has been omitted because the series is very volatile and hence obscures the other series; it nevertheless has virtually the same terminal level as MR.

Chart 8. **GDP losses in the stabilisation scenario**



Note. CRTM has been omitted because the series is very volatile and hence obscures the other series; it nevertheless has virtually the same terminal level as MR.

technologies start to become important in GREEN as from 2010, given both the assumptions on cost and the differences in base year relative energy prices across OECD countries. The CRTM (data are shown in Appendix Table A7) and MR results lie between the extremes but are rather volatile before settling down at the backstop-related tax ($208 per ton) in the second half of the next century.

ii) For *non-OECD regions*, a major feature is the erratic tax paths, especially for CRTM and MR in the case of the former Soviet Union and, to a lesser extent, for China. For the former Soviet Union, this is related to the slowing and then absolute fall in BaU emissions growth in the first half of the next century; for China it is related to backstop prices and the move to an equilibrium tax of $208 per ton of carbon by 2080. The GREEN and ERM tax curves are rather smoother and indeed rather close in the case of China, though the ERM tax climbs steeply in typical fashion.

iii) The *GDP costs* associated with the stabilisation scenario are relatively small in the case of the OECD regions and the former Soviet Union but very large in the case of China and RoW. These costs in general mirror rather closely the required tax rates. The taxes and costs are so much higher for China and RoW because the BaU emissions growth is so rapid and hence the necessary cut-backs so large. The political reality, of course, is that these regions would not accept a stabilisation target, at least not without massive compensating transfers from other countries.

iv) *Backstop technologies*, in CRTM, GREEN and MR, put a limit on the carbon tax and GDP losses incurred in stabilising emissions, though not for the former Soviet Union where emissions growth is anyway rather modest.

iv) Analysing differences -- the importance of substitution

Substitution elasticities between fuels and between aggregate energy and other inputs play an important role in determining the cost of reducing emissions on average and at the margin. In general, substitution elasticities in each model do not differ across region. Substitution elasticities, however, differ considerably across models. The IEA model, for instance, has rather low fuel substitution elasticities reflecting its short-term focus, while WW do not distinguish between fossil fuels, but assume a high elasticity of substitution between fossil and non-fossil energy sources.

Since baseline scenarios differ considerably with respect to energy prices and fuel composition, the effect of substitution elasticities on simulation results cannot be evaluated in isolation. The existing prices of fuels in the different regions will be important in determining the "leverage" that any particular tax rate will have in inducing fuel switching while the different fuel proportions will determine the scope for switching to cleaner fuels.

The relative importance of energy substitution and conservation effects can be seen by looking at the same sort of decomposition as used above to examine the baseline scenarios. This time the changes in emissions are decomposed into changes in:

1) the carbon intensity of carbon-based fuels arising from substitution between different fossil fuels and carbon-based synfuels;

2) the share of carbon-free fuels in total energy use representing the degree of substitution between carbon-based and carbon-free fuels;

3) the energy intensity of output reflecting switches between energy and other factors (i.e. energy conservation); and

4) output.

The results of this decomposition in terms of the contributions of these variables to the changes in emissions in 2020 in the case of the 2 per cent reduction case are shown in Table 8. For the OECD regions, the IEA model shows the lowest contribution of fuel substitution to cuts in emissions, though the numbers are for the IEA terminal year of 2005 and substitution would be expected to increase with time. Nevertheless, this low degree of substitution to "cleaner" fuels is a major factor in the taxes in the OECD regions being higher in the IEA model than the others. The reduction in emissions comes about through a large fall in energy intensity which contributes close to three-quarters of the fall in emissions, with output being unchanged in the IEA model by assumption. In ERM and MR, changes in energy intensity contribute much less (though over a longer time period). In particular, energy intensity contributes little to the cut in emissions in China and the former Soviet Union in ERM and the contribution is also low in MR. On the other hand, the contribution of energy conservation tends to be relatively high in all models for RoW, reflecting the low share of coal (in a region that includes the major oil-producing developing countries) and hence a rather limited potential for switching to much cleaner fuels.

Fuel substitution is very important in ERM and MR, contributing more than 50 per cent to the fall in emissions, with substitution between carbon-based and carbon-free fuels being more important than switching between carbon-based fuels. Fuel substitution is also significant in GREEN for the OECD regions, contributing from a quarter to a half of the total emission reductions, but is relatively unimportant for the non-OECD regions. The effect of output changes on emissions are minor in all the models covered in the table.

The specific results for the former Soviet Union and China in the GREEN model -- low substitution, very high energy conservation and low taxes -- can be explained by reference to both initial prices in GREEN and the prices of backstop technologies. The low initial prices of fossil fuels in these regions, coal in particular, mean that specific taxes on carbon have more "leverage" than in other regions. Furthermore, prices are not raised to sufficiently high levels to induce switching into either carbon backstops (synfuels) or carbon-free backstops. The position as regards switching to carbon-free fuels in the different regions in GREEN is instructive (see second column of Table 8). While tax-induced price rises lead to switching to carbon-free backstops in the OECD regions (especially the Other OECD where Japan moves quickly to the carbon-free electric option), the price is never high enough to induce such a switch in the former Soviet Union and China. The

Table 8. **Decomposition of emission changes**

Per cent contributions to changes in emissions compared to baseline for the 2 per cent case in 2020

	Change in				Memo item:
	Carbon intensity of fossil fuels (1)	Share of carbon-free fuels	Energy intensity	Output	Carbon tax
ERM					
USA	20	44	33	3	351
Other OECD	19	49	30	3	342
Former Soviet Union	63	16	19	2	104
China	41	32	22	5	182
RoW	-2	60	39	3	430
GREEN					
USA	13	14	71	2	223
Other OECD	19	24	55	2	239
Former Soviet Union	10	4	84	2	69
China	15	1	84	1	26
RoW	8	6	80	6	184
IEA (2)					
North America	12	13	75 (3)	..	376
Other OECD	10	19	72 (3)	..	548
MR					
USA	20	32	45	4	354
Other OECD	18	45	35	2	241
Former Soviet Union	30	37	28	5	301
China	10	54	30	5	271
RoW	29	24	39	8	399

1. Includes carbon-based synfuels.
2. Numbers refer to 2005; emissions are 25 per cent below baseline as compared to 45 per cent for the other model simulations.
3. Contribution of the change in aggregate energy.

interaction of the relatively lower levels of energy prices in the latter two regions (than in either other regions or the other models) as well as the relatively high assumed level of the backstop prices in all the models, means that more of the emission reduction in the GREEN model comes through energy conservation than in ERM or MR, especially for the non-OECD countries. Beyond 2020, as backstops play a more important role in all models, more substitution occurs. In GREEN, for instance, more than half of the emission-reduction in the OECD regions by 2050 is via substitution (in particular switching to carbon-free fuels) although energy conservation remains very high in the non-OECD regions. For MR, the existence of backstop technologies leads to an even stronger switch to carbon-free fuels (with the exception of the former Soviet Union) with over two-thirds of the reduction in emissions in 2050 coming via this route. For ERM this switch is also very important for the OECD but less so for the non-OECD regions. In all the models energy conservation becomes relatively less important over time as fuel substitution comes to dominate, with output reductions making only a limited contribution to the reduction of emissions.

V. Cost-effective Reductions in Emissions

The range of taxes and abatement costs across regions in the different reduction scenarios suggests the potential for savings in the global cost of reducing emissions. If, at the margin, it is more expensive (as reflected in the carbon tax rates) for one region to achieve the reduction objective than another, then it is in principle possible to achieve a mutually-beneficial redistribution of the emission reductions between regions. To get globally cost-effective reductions in emissions, the marginal costs of abatement, as reflected in the regional carbon taxes, should be equated across regions. All the models indicate that equi-proportionate cuts in emissions are incompatible with this condition. 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. Emissions trading, for instance, if feasible, would allow for a more efficient distribution of emission reductions across region by letting countries trade emission rights to the point where carbon taxes were the same in all countries. A global carbon tax would also lead to the marginal cost of reducing emissions being equal for all countries.

Three of the models in the comparisons project (ERM, GREEN and MR) have carried out an emissions-trading scenario. The results for emissions trading are shown for 2020, 2050 and 2100 for the case of the 2 per cent scenario in Table 9. The largest gain is for GREEN; with larger cuts in the regions where abatement is cheapest and smaller reductions elsewhere, the global output loss halves from 2 per cent to 1 per cent of GDP in 2020. All of the models point to gains from this type of emissions trading (Table 9). However, the gains are less in the models with a smaller dispersion in carbon taxes in the no-trade case, for instance ERM and MR. Furthermore, the dispersion of taxes narrows with time as backstop technologies come into play so that the gains from emissions trading diminish correspondingly. This can be seen with the GREEN results for 2050 where the gain from trading is less than in 2020. The sums involved in emissions trading are significant. In 2050 they range from $200 billion in GREEN to over $400 billion in MR, but the revenues fall off thereafter in MR as the backstops reduce the tax dispersion and hence the potential gains from trade. This underlines again the critical importance of the assumptions on backstop technologies for all aspects of the assessment of taxes and costs, including the gains from cost-effective agreements.

Table 9. **Cost differences for emission trading**

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

		ERM (1)		GREEN		MR	
		Tax ($/tC)	GDP loss (%)	Tax ($/tC)	GDP loss (%)	Tax ($/tC)	Welfare loss (2)
2020	No trade	283	1.9	149	1.9	325	..
	Trade	238	1.6	106	1.0	308	..
2050	No trade	680	3.7	230	2.6	448	..
	Trade	498	3.3	182	1.9	374	..
2100	No trade	1 304	5.7	..	..	242	8.0
	Trade	919	5.1	..	..	208	7.5

1. End-year is 2095 for ERM.

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

Notes

1. We are grateful for helpful comments and suggestions to all of the modellers whose work is reviewed in this paper and to the participants in the meetings in Washington and Paris in 1991. We are indebted to Anick Lotrous and Jackie Gardel for their assistance.

2. The OECD project has been proceeding in parallel and in close co-operation with a similar but more comprehensive exercise being conducted by the Energy Modelling Forum at Stanford University. The latter exercise (known as EMF12) involves more models (especially U.S. national models) and is more focused on detailed energy sector outputs, while the OECD project is limited to **global** models and concentrates on macroeconomic costs. The OECD is grateful to the EMF12 organisers for their help as regards standardisation of inputs, regional breakdowns and other aspects of the project design. The final results of the EMF12 exercise will be published in 1993.

3. Data on CO_2 emissions are calculated in various ways but are essentially based on taking the data for different fuels and applying carbon emission coefficients. The final numbers are estimates which are often based on shaky data, so that some differences in benchmark data are not surprising. Furthermore, 1990 data on world emissions are not available so that modellers are forced to use earlier benchmark years and then make estimates for 1990. The IPCC, in conjunction with OECD/IEA has been working on the development of better data on greenhouse gas emissions and sinks. Their latest estimate of 1990 energy-related carbon emissions is 6.0 billion tons.

4. The technical manual for the GREEN model, which includes a review of parameters in different models, is able to offer rather little information on AEEI; see Burniaux *et al.* (1992).

5. Emission coefficients are the same across models for gas. For oil and oil products, emission coefficients differ by 6 per cent between the models of GREEN and WW, with CRTM, IEA and MR being in between. For coal the differences are even larger though with the same relative positions. In addition, CRTM, GREEN and MR have a backstop technology, synfuels, with an emission coefficient twice as high as that for oil. Also ERM has an additional future energy source, carbonate rock mining, with an emission coefficient somewhat higher than coal. Differences in emission coefficients reflect uncertainties about average emission rates for aggregates including heterogeneous goods. The differences in emission coefficients are, however, not large enough to have a major impact on baseline emissions.

6. In CRTM and MR, backstop technologies restrict the tax to just over \$200 per ton in all the regions except the former Soviet Union, the latter exception meaning that the average world tax in these models is still rising steeply in 2100 for continuing emission cuts. In GREEN, the tax level at which the switch to backstop technologies occurs depends on the initial starting point for the prices of different fuels. This is particularly important for the non-OECD regions because initial energy prices are often far below world prices, so that much higher taxes than in the OECD regions are needed before the backstop technologies become competitive.

7. In the context of this modelling project, which focuses on the costs of policies to slow climate change and ignores the benefits (the damage avoided), the welfare being measured refers only to the cost side; if, in addition, one took into account the benefits, then one would have an overall measure of the welfare effects of the policy change and could then judge the optimal level of abatement.

8. The Hicksian equivalent variation is the increase in income that a consumer would need before the imposition of a carbon tax to allow him to reach the welfare level actually attained after the change in policy.

9. The long-run equilibrium tax (T_C) in the MR model is determined by the relationship between the relative cost of the carbon-free backstop (P_{BS}) and high-cost gas (P_G) and the difference in the carbon content of the fuels (α), or $(P_{BS} - P_G)/\alpha = T_C$, with the prices being measured in \$ per gigajoule of oil equivalent and the carbon content being measured as the tons of carbon per gigajoule of oil equivalent; this works out as (16.667 - 6.25)/(0.01374) = \$758 per ton of carbon. For the former Soviet Union a higher long-run equilibrium carbon tax is required than in the other regions, because much larger gas reserves are assumed to be available.

Annex

Differences in Base-year Data

The base year is 1990 for all the models with the exception of GREEN which has a 1985 base year. Carbon taxes, energy prices and GDPs for GREEN can be converted into corresponding 1990 base-year data using appropriate adjustment factors.

Carbon taxes for all regions are presented in real terms (in 1990 or 1985 prices) in a common currency (U.S. dollars) in all the models. As carbon taxes raise fossil-fuel energy prices by an absolute amount, modellers need to take a view on:

a) relative energy prices in every region; and

b) the appropriate exchange rate in order to convert into a common currency.

The conversion into U.S. dollars is based on market exchange rates (1985 rates for GREEN and 1990 rates for the other models). Real output estimates in U.S. dollars therefore differ significantly. In the former Soviet Union, GDP is estimated to have been $2.7 trillion in 1990 in Manne but only $2.1 in GREEN. A similar difference exists for China. Even among OECD regions, assumptions about differences in price levels are large. ERM and Manne estimate a GDP of somewhat above $10 trillion for the other OECD region, while GREEN estimates only $6.8 trillion in 1990 prices [1]. Output, carbon taxes and energy prices can be converted to a common exchange rate across model, if regional disaggregation does not differ. Such a conversion does not imply that the choice of inter-regional differences in price levels for any model is correct. Table 1 shows regional differences for GDPs for ERM, CRTM/MR and GREEN, recently published OECD data for the OECD regions in 1990 and conversion factors between models [2].

Concerning energy prices, only the world market crude oil price is fixed by assumption in 1990 at $26 per barrel or close to $4000 per terajoule [3]. Deviations of regional crude oil prices from world market prices for any single region and prices of other primary and secondary energy sources are assessed by the modellers. The IEA model relies on published IEA energy price data for the OECD countries, while GREEN uses input-output data and IEA, World Bank and UN energy price data, with regional data being assembled from individual country data. The WW model has a single price for oil, coal and gas across regions based on World Resource Institute data. The energy price data in CRTM, ERM and MR are based on various sources but, at least for the non-OECD countries, data are not based on single-country observations and are often the same across all non-OECD regions.

Base-year prices in U.S. dollars for 1990 are shown in Table 2 for the United States and regional differences relative to the United States in Table 3. There are considerable price differences for primary fossil-fuel energy sources, even for oil, the world market price of which has been standardised (Table 2). Regional variations in prices among models are larger still. While all models have higher or at least as high prices in the other OECD region as in the United States, differences from the United States are large, even if differences in exchange rates are taken into account. For the former Soviet Union, China and RoW, assessment of current energy price levels differs a lot. While GREEN data point to large distortions in energy markets in the non-OECD regions, with energy prices fixed below world market levels or with subsidies, such differences are much less apparent in the MR, CRTM and ERM models and do not exist in WW.

Differences in baseline prices are of considerable importance in shaping baseline projections and simulation results. As substitution among fuels largely depends on relative prices, large differences in baseline prices can lead to considerable differences in projected emission intensities in the baseline scenarios. GREEN's high carbon intensity of fossil fuels in the baseline scenario, for instance, is largely a function of the low coal prices in non-OECD regions. In the reduction scenarios, carbon taxes are levied as an absolute dollar amount on energy prices. If baseline energy prices are low, a given tax will lead to a larger relative price change than in the case of a high baseline price. For the same substitution elasticities, simulation results could differ by significant amounts, largely as a function of baseline price differences across model [4].

Notes

1. CRTM uses the same base-year data as MR, aggregate output plays a limited role for the IEA, and WW give only estimates for the discounted presented value for the entire period. The ERM and MR estimates for GDP are very close, but their regional coverage differs in some instances.

2. Over time, exchange rates are fixed in MR and ERM, while they are endogenous in the baseline and simulations in CRTM, WW and GREEN. This further complicates the work of trying to compare model results.

3. Differences in conversion factors can change the translation of oil prices from $ per barrel to joule by up to 20 per cent.

4. Price differences extend over the projection period. In addition, while coal prices remain at or close to their 1990 price level in all models, gas prices increase in line with oil prices in CRTM, ERM, IEA and MR. In GREEN, on the other hand, ample gas supply is assumed and gas prices change little up to 2050.

Annex Table 1. **Base-year GDP estimates**

$ US billion at 1990 prices

	ERM	CRTM/MR	GREEN	Conversion factor (1)	Published OECD Data: At current exchange rates	At 1985 exchange rates	In PPPs
United States	5 596	5 600	5 330	..	5 392	5 392	5 392
Other OECD	10 203	10 200	6 803 (2)	1.50	10 834	7 373	8 876
OECD total	15 799	15 800	12 133	..	16 226	12 765	14 268
Former Soviet Union	3 411 (3)	2 680	2 097	1.28			
China	1 151	1 100	772	1.43			
Rest of World	2 716	3 340	..	..			
Total	23 077	22 920	..	..			

1. Ratio between Manne/Rutherford and GREEN GDP.

2. Excludes Switzerland and Iceland.

3. Includes eastern Europe.

Annex Table 2. **Base-year energy prices for the United States**

US$ per terajoule at 1990 prices

	ERM	Manne/ Rutherford	GREEN	Whalley and Wigle (1)
Oil	5 437	3 500	4 022	6 084
Gas	2 885	2 800	3 284	4 564
Coal	1 820	2 000	1 226	2 282

1. 1982 prices.

Annex Table 3. **Regional base-year energy prices** (1)
Price in the U.S. = 100

	Canada and Europe	OECD Pacific	USSR/ Eastern Europe	China	Middle East	Africa	Latin America	South and East Asia
ERM								
Primary energy sources								
Oil	148	110	100	100	40	150	102	100
Gas	180	155	100	100	70	100	100	100
Solids	207	100	100	100	100	100	104	104
Solar electricity (2)	162	126	162	139	73	79	139	100
Secondary energy prices								
Liquids	130	106	100	100	62	131	101	100
Gases	163	143	100	100	76	100	100	100
Solids	181	100	100	100	100	100	103	103
Electricity (3)	101	105	100	88	110	93	83	98

	Other OECD	USSR	China	RoW
Manne				
Crude oil	114	57	57	57
Natural gas (4)	100	73	113	100
Coal	150	100	100	100
Electricity price	100	100	100	100

	Japan	EC	Other OECD	USSR	China	India	Energy-exporting LDCs
GREEN							
Crude oil	123	111	93	17	114	79	76
Natural gas	171	152	64	19	118	88	125
Coal	353	191	55	72	60	81	91

Table 3 (continued)

	Japan	Europe
IEA		
Primary energy sources (5)		
Crude oil	107	108
Natural gas	176	142
Coal	146	147
End-use prices		
Gasoline	279	186
Heavy fuel, industry	171	154
Natural gas, industry	368	..
Natural gas, households	402	..
Coal, industry	207	222
Electricity, industry	263	136
Electricity, domestic	233	144

1. While fossil fuel prices differ in Whalley and Wigle, they are the same across regions. Rutherford uses the same database as Manne.

2. Nuclear and hydro price is the same across regions.

3. Electricity prices are based on a detailed electricity generation cost matrix for different fuels and regions.

4. Refers to the year 2000.

5. Index based on border prices.

Annex Table 4. **Global fuel shares in the baseline scenarios**

Per cent of total primary energy demand

		Oil	Gas	Solids	Synfuels	Non-fossil
Manne	1990	41	25	24	0	10
	2020	24	19	41	2	14
	2050	9	11	16	31	33
	2100	1	2	2	57	37
ERM	1990	39	20	28	..	13
	2020	26	26	31	..	16
	2050	13	22	45	..	20
	2095	2	2	69	..	26
GREEN	1990	44	20	32	0	4
	2020	34	18	42	1	5
	2050	16	15	57	6	5

Appendix Table A1. **Population growth assumptions**

Region	1990 level (millions)	Projections (millions)				
		2000	2025	2050	2075	2100
United States	250	267	289	285	283	284
Other OECD	582	617	649	643	640	643
Former Soviet Union	289	306	337	351	361	367
China	1 116	1 285	1 576	1 703	1 750	1 817
Rest of World	3 024	3 701	5 339	6 546	7 143	7 310
World total	5 261	6 176	8 190	9 528	10 177	10 421

Source: EMF12 project specifications, based on World Bank's 1988 population projections.

Appendix Table A2. **Economic growth rate assumptions**

Region	1990 GDP $ trillions	GDP growth rates (per cent)				
		1990-2000	2000-2025	2025-2050	2050-2075	2075-2100
United States	5.60	2.50	2.00	1.50	1.25	1.00
Other OECD	10.20	2.70	2.00	1.50	1.25	1.00
Former Soviet Union	2.68	3.60	3.10	2.35	2.10	1.85
China	1.10	4.50	4.00	3.50	3.25	3.00
Rest of World	3.34	3.75	3.30	2.80	2.55	2.30
World total	22.92	3.01	2.50	2.08	1.96	1.85

Source: EMF12 project specifications.

Appendix Table A3. **BaU CO_2 emissions by region** (1)
Billion tons of carbon

United States

	CRTM	ERM	GREEN	IEA	MR
1990	1.430	1.383	1.339	1.652	1.430
2000	1.665		1.497	1.917	1.649
2005		1.565	1.560	1.987	
2010	1.746		1.684		1.850
2020	2.066	1.764	1.852		2.080
2050	2.567	2.143	2.295		3.278
2080	3.769	2.514			3.972
2100	4.478	2.850*			4.573

Note: IEA data refer to North America.

Other OECD

	CRTM	ERM	GREEN	IEA	MR
1990	1.375	1.307	1.419	1.393	1.375
2000	1.652		1.624	1.579	1.640
2005		1.602	1.698	1.663	
2010	1.767		1.704		1.855
2020	2.114	1.793	1.864		2.115
2050	2.507	2.019	2.539		3.129
2080	3.970	2.279			4.221
2100	4.755	2.513*			4.988

Note: IEA data refer to OECD less North America.

Former USSR

	CRTM	ERM	GREEN	IEA	MR
1990	1.055	1.494	1.010	1.134	1.055
2000	1.173		1.221	1.367	1.184
2005		1.439	1.315	1.382	
2010	1.262		1.536		1.323
2020	1.471	1.583	1.756		1.482
2050	1.004	1.855	2.394		1.372
2080	1.191	2.432			1.792
2100	1.737	2.887*			2.422

Note: ERM data refer to USSR and Eastern Europe.

China

	CRTM	ERM	GREEN	IEA (2)	MR
1990	0.641	0.713	0.608	0.718	0.641
2000	0.739		0.875	0.997	0.754
2005		1.010	1.050	1.160	
2010	0.955		1.363		0.937
2020	1.092	1.571	2.142		1.175
2050	1.880	3.371	5.531		2.508
2080	5.644	6.883			6.359
2100	10.021	9.409*			11.140

Note: ERM data refer to China and Asian CPE's.

Rest of the world

	CRTM	ERM	GREEN	IEA	MR
1990	1.502	0.870	1.438	1.929	1.502
2000	1.702		1.855	2.592	1.743
2005		1.093	2.082	2.981	
2010	2.160		2.418		2.189
2020	2.511	1.465	3.193		2.668
2050	4.270	2.450	6.240		4.704
2080	9.308	3.991			10.600
2100	14.995	4.920*			16.517

1. Global annual average emissions for the period 1990-2100 are 27.1 billion tons of carbon for the WW model. The estimate for 2100 is 72.6 billion tons.

2. IEA numbers by region include non-fossil solid fuels, bunkers, non-energy use of fossil fuels and petrochemical feedstock, hence in general leading to a higher starting point than the other models where such items are usually excluded. See the footnote to Table 4, which gives a global estimate of the difference.

* 2095.

Appendix Table A4. **Carbon tax:**
1 percentage point reduction in growth of CO_2 emissions

Dollars per ton of carbon

United States

	CRTM	ERM	GREEN	MR	IEA (1)
1990	0	0	0	0	0
2000	55	37	31	71	88
2005		55	42		123
2010	109	69	39	76	
2020	118	96	48	125	
2050	165	314	65	185	
2080	208	793		208	
2100	208	1 138 (2)		208	

Other OECD

	CRTM	ERM	GREEN	MR	IEA
1990	0	0	0	0	0
2000	56	37	49	60	161
2005		56	70		231
2010	95	80	58	73	
2020	118	127	73	120	
2050	199	241	94	186	
2080	208	378		209	
2100	208	440 (2)		208	

Former USSR

	CRTM	ERM	GREEN	MR
1990	0	0	0	0
2000	147	25	0	164
2005		38	13	
2010	137	51	16	133
2020	7	78	25	84
2050	845	105	49	382
2080	736	150		608
2100	608	160 (2)		194

1. North America, i.e. comprises Canada.
2. Last year covered is 2095 instead of 2100.

China

	CRTM	ERM	GREEN	MR
1990	0	0	0	0
2000	138	25	5	165
2005		38	6	
2010	15	55	8	58
2020	152	90	10	95
2050	306	174	22	152
2080	208	315		208
2100	208	332 (2)		208

Rest of the World

	CRTM	ERM	GREEN	MR
1990	0	0	0	0
2000	166	36	26	166
2005		55	37	
2010	40	93	40	79
2020	108	170	54	127
2050	45	330	90	133
2080	257	508		208
2100	208	624 (2)		208

Appendix Table A5. **Carbon tax:**
2 percentage points reduction in growth of CO_2 emissions

Dollars per ton of carbon

United States

	CRTM	ERM	GREEN	MR	IEA (1)
1990	0	0	0	0	0
2000	181	70	122	132	256
2005		105	200		376
2010	337	187	139	218	
2020	324	351	223	354	
2050	754	1 096	340	208	
2080	208	2 382		208	
2100	208	2 754 (2)		208	

Other OECD

	CRTM	ERM	GREEN	MR	IEA
1990	0	0	0	0	0
2000	163	95	158	117	388
2005		142	259		548
2010	264	209	165	147	
2020	233	342	239	241	
2050	365	734	299	208	
2080	208	1 013		208	
2100	208	1 240 (2)		208	

Former USSR

	CRTM	ERM	GREEN	MR
1990	0	0	0	0
2000	166	55	24	206
2005		82	34	
2010	198	89	44	184
2020	322	104	69	301
2050	2 245	325	180	990
2080	758	496		758
2100	758	719 (2)		758

1. North America, i.e. comprises Canada.
2. Last year covered is 2095 instead of 2100.

China

	CRTM	ERM	GREEN	MR
1990	0	0	0	0
2000	166	54	13	211
2005		81	16	
2010	172	115	20	166
2020	320	182	26	271
2050	1 109	341	67	240
2080	208	574		208
2100	208	651 (2)		208

Rest of the World

	CRTM	ERM	GREEN	MR
1990	0	0	0	0
2000	216	99	82	220
2005		148	132	
2010	262	242	127	266
2020	409	430	184	399
2050	763	1 012	329	727
2080	208	1 799		211
2100	208	2 021 (2)		208

Appendix Table A6. **Carbon tax:**
3 percentage points reduction in growth of CO_2 emissions

Dollars per ton of carbon

United States

	CRTM	ERM	GREEN	MR	IEA (1)
1990	0	0	0	0	0
2000	384	120	353	341	500
2005		180	662		700
2010	525	332	224	387	
2020	404	635	376	622	
2050	415	2 000	629	208	
2080	415	3 200		208	
2100	415	3 800 (2)		208	

Other OECD

	CRTM	ERM	GREEN	MR	IEA
1990	0	0	0	0	0
2000	308	168	396	221	857
2005		252	755		1 222
2010	413	374	305	328	
2020	411	617	414	450	
2050	535	1 322	605	208	
2080	535	1 810		567	
2100	567	2 060 (2)		567	

Former USSR

	CRTM	ERM	GREEN	MR
1990	0	0	0	0
2000	263	93	46	239
2005		140	69	
2010	385	157	94	328
2020	481	190	163	524
2050	1 616	595	507	1 903
2080	1 067	900		8 865
2100	1 067	1 300 (2)		1 013

1. North America, i.e. comprises Canada.
2. Last year covered is 2095 instead of 2100.

China

	CRTM	ERM	GREEN	MR
1990	0	0	0	0
2000	298	93	25	224
2005		140	34	
2010	304	200	44	276
2020	520	320	65	445
2050	608	620	278	608
2080	608	1 000		608
2100	608	1 180 (2)		608

Rest of the World

	CRTM	ERM	GREEN	MR
1990	0	0	0	0
2000	371	176	201	413
2005		264	364	
2010	509	431	239	629
2020	685	768	370	816
2050	926	1 766	702	1 822
2080	736	2 769		996
2100	736	3 031 (2)		792

Appendix Table A7. **Carbon tax: Stabilisation scenario in growth of CO_2 emissions**

Dollars per ton of carbon

United States

	CRTM	ERM	GREEN	MR	IEA (1)
1990	0	0	0	0	0
2000	119	30	45	105	131
2005		45	52		176
2010	95	59	58	83	
2020	215	88	65	136	
2050	142	119	51	208	
2080	208	163		208	
2100	208	178 (2)		208	

Other OECD

	CRTM	ERM	GREEN	MR	IEA
1990	0	0	0	0	0
2000	139	39	90	125	185
2005		58	104		260
2010	95	77	42	74	
2020	180	114	60	121	
2050	216	134	85	208	
2080	208	182		208	
2100	208	202 (2)		208	

Former USSR

	CRTM	ERM	GREEN	MR
1990	0	0	0	0
2000	164	0	22	180
2005		0	26	
2010	104	0	59	166
2020	31	0	62	119
2050	0	26	89	30
2080	103	90		136
2100	208	106 (2)		212

1. North America, i.e. comprises Canada.
2. Last year covered is 2095 instead of 2100.

China

	CRTM	ERM	GREEN	MR
1990	0	0	0	0
2000	166	64	44	200
2005		96	67	
2010	166	143	220	166
2020	234	237	279	270
2050	82	478	466	580
2080	208	1 570		208
2100	208	1 700 (2)		208

Rest of the World

	CRTM	ERM	GREEN	MR
1990	0	0	0	0
2000	166	69	144	179
2005		104	219	
2010	216	189	182	240
2020	178	361	255	329
2050	309	779	404	709
2080	208	1 714		336
2100	208	2 236 (2)		169

Appendix Table A8. **GDP loss:**
1 percentage point reduction in growth of CO_2 emissions

Percentage change relative to baseline

United States

	CRTM	ERM	GREEN	MR
1990	0.00		0.00	0.00
2000	-0.10		0.07	0.36
2005		0.37	0.12	
2010	0.20		0.18	0.53
2020	0.50	0.63	0.24	0.80
2050	1.20	1.89	0.44	1.41
2080	1.70	3.51		2.13
2100	1.80	4.33 (1)		2.34

Other OECD

	CRTM	ERM	GREEN	MR
1990	0.00		0.00	0.00
2000	-0.10		0.07	0.22
2005		0.36	0.12	
2010	0.00		0.24	0.35
2020	0.20	0.79	0.35	0.53
2050	0.60	1.55	0.70	0.91
2080	0.80	1.99		1.35
2100	1.00	1.99 (1)		1.49

Former USSR

	CRTM	ERM	GREEN	MR
1990	0.00		0.00	0.00
2000	0.30		0.10	0.95
2005		0.37	0.20	
2010	0.60		0.27	1.16
2020	0.40	0.70	0.41	1.28
2050	2.20	1.08	0.96	2.30
2080	2.60	1.21		3.32
2100	2.10	1.01 (1)		3.20

1. **Last year covered is 2095 instead of 2100.**

China

	CRTM	ERM	GREEN	MR
1990	0.00		0.00	0.00
2000	0.20		0.12	0.74
2005		0.70	0.16	
2010	0.20		0.18	0.78
2020	0.50	1.51	0.28	1.13
2050	1.40	2.82	0.87	2.22
2080	2.50	3.99		3.54
2100	2.60	3.69 (1)		3.93

Rest of the World

	CRTM	ERM	GREEN	MR
1990	0.00		0.00	0.01
2000	1.20		0.35	1.24
2005		0.32	0.58	
2010	0.50		0.73	1.06
2020	0.70	0.95	0.89	1.71
2050	0.80	1.60	1.42	2.27
2080	3.10	2.12		4.00
2100	3.40	2.26 (1)		4.53

Appendix Table A9. **GDP loss:**
2 percentage points reduction in growth of CO_2 emissions

Percentage change relative to baseline

United States

	CRTM	ERM	GREEN	MR
1990	0.00		0.00	0.00
2000	0.10		0.27	0.88
2005		0.68	0.51	
2010	0.90		0.92	1.32
2020	1.30	1.99	1.11	2.16
2050	2.50	4.86	1.30	2.72
2080	2.60	8.38		3.01
2100	2.60	8.81 (1)		3.08

Other OECD

	CRTM	ERM	GREEN	MR
1990	0.00		0.00	0.00
2000	0.00		0.27	0.47
2005		0.85	0.54	
2010	0.30		0.91	0.68
2020	0.50	1.85	1.20	1.14
2050	1.10	3.37	1.64	1.62
2080	1.40	4.41		1.85
2100	1.50	4.77 (1)		1.92

Former USSR

	CRTM	ERM	GREEN	MR
1990	0.00		0.00	0.00
2000	0.80		0.32	1.81
2005		0.72	0.63	
2010	1.50		0.89	2.87
2020	1.50	0.88	1.66	3.14
2050	5.80	2.26	3.51	6.38
2080	4.90	3.15		5.98
2100	4.20	3.71 (1)		5.59

1. **Last year covered is 2095 instead of 2100.**

China

	CRTM	ERM	GREEN	MR
1990	0.00		0.00	0.00
2000	0.80		0.33	1.94
2005		1.35	0.46	
2010	0.80		0.50	2.13
2020	1.70	2.75	0.67	2.71
2050	3.10	4.34	1.50	3.75
2080	3.60	6.29		4.72
2100	3.70	6.23 (1)		4.97

Rest of the World

	CRTM	ERM	GREEN	MR
1990	0.00		0.00	0.01
2000	2.30		1.04	3.18
2005		0.83	1.82	
2010	2.10		2.46	3.78
2020	2.60	2.04	3.82	4.88
2050	2.10	3.54	4.38	5.10
2080	4.20	4.55		5.07
2100	4.50	5.08 (1)		5.62

Appendix Table A10. **GDP loss:**
3 percentage points reduction in growth of CO_2 emissions

Percentage change relative to baseline

United States

	CRTM	ERM	GREEN	MR
1990	0.00		0.00	0.00
2000	0.50		0.69	1.70
2005		1.09	1.37	
2010	1.90		2.30	2.64
2020	2.50	3.23	2.44	4.19
2050	2.40	7.53	2.11	3.33
2080	2.80	10.11		3.39
2100	2.80	10.94 (1)		3.34

Other OECD

	CRTM	ERM	GREEN	MR
1990	0.00		0.00	0.00
2000	0.10		0.69	0.89
2005		1.39	1.39	
2010	0.60		2.05	1.39
2020	0.90	2.99	2.22	2.07
2050	1.50	5.13	2.29	1.96
2080	1.70	6.47		2.08
2100	1.70	6.88 (1)		2.11

Former USSR

	CRTM	ERM	GREEN	MR
1990	0.00		0.00	0.00
2000	1.40		0.71	2.96
2005		1.14	1.38	
2010	2.70		1.90	4.91
2020	3.30	1.48	3.54	7.29
2050	7.20	3.37	7.14	8.48
2080	6.00	4.51		7.39
2100	5.10	5.73 (1)		6.73

1. **Last year covered is** 2095 **instead of** 2100.

China

	CRTM	ERM	GREEN	MR
1990	0.00		0.00	0.00
2000	1.50		0.65	2.97
2005		2.13	0.93	
2010	2.20		1.00	3.93
2020	3.60	4.31	1.35	5.70
2050	4.60	6.49	2.32	5.49
2080	4.30	8.83		5.44
2100	4.20	9.49 (1)		5.41

Rest of the World

	CRTM	ERM	GREEN	MR
1990	0.00		0.00	0.01
2000	4.20		2.14	5.88
2005		1.37	3.78	
2010	4.80		5.02	8.17
2020	5.90	3.27	7.57	10.80
2050	6.40	5.27	9.31	7.84
2080	5.50	6.38		6.61
2100	5.20	7.04 (1)		6.37

Appendix Table A11. **GDP loss:**
Stabilisation scenario in growth of CO_2 emissions

Percentage change relative to baseline

United States

	CRTM	ERM	GREEN	MR
1990	0.00		0.00	0.00
2000	-0.20		0.11	0.52
2005		0.31	0.16	
2010	0.10		0.26	0.69
2020	0.40	0.58	0.29	1.08
2050	0.90	0.81	0.36	2.11
2080	1.60	0.78		2.33
2100	1.80	0.46 (1)		2.43

Other OECD

	CRTM	ERM	GREEN	MR
1990	0.00		0.00	0.00
2000	-0.20		0.17	0.39
2005		0.40	0.26	
2010	0.10		0.33	0.48
2020	0.10	0.74	0.30	0.75
2050	0.30	0.92	0.62	1.31
2080	0.90	1.11		1.53
2100	1.00	0.91 (1)		1.61

Former USSR

	CRTM	ERM	GREEN	MR
1990	0.00		0.00	0.00
2000	0.40		0.28	1.11
2005		0.02	0.50	
2010	0.10		0.86	1.35
2020	0.00	0.02	1.39	1.34
2050	-0.10	0.33	2.07	0.79
2080	0.00	0.77		1.66
2100	0.60	0.58 (1)		2.87

1. Last year covered is 2095 instead of 2100.

China

	CRTM	ERM	GREEN	MR
1990	0.00		0.00	0.00
2000	0.50		0.70	1.59
2005		1.57	1.07	
2010	0.80		1.84	2.01
2020	1.30	3.42	3.37	2.80
2050	2.20	5.67	5.56	4.05
2080	3.70	12.49		5.06
2100	3.80	12.70 (1)		5.23

Rest of the World

	CRTM	ERM	GREEN	MR
1990	0.00		0.00	0.01
2000	1.70		1.08	2.29
2005		0.64	1.87	
2010	1.00		2.73	3.01
2020	1.90	1.76	3.89	4.67
2050	1.10	2.96	4.45	5.20
2080	4.00	3.79		5.38
2100	4.50	3.69 (1)		5.69

Appendix Table A12. **Simulation results of the Whalley-Wigle model** (1)

	Percentage point reduction of CO_2 emissions by			Stabilisation of emissions
	1 per cent	2 per cent	3 per cent	
	Carbon emissions			
Global reduction (as % of BaU)	55	76	85	78
	Carbon tax ($ per ton)			
North America	379	790	1 247	680
Japan	363	744	1 158	649
European Community	390	841	1 361	717
Other OECD	298	537	761	499
Oil exporting LDCs	380	932	1 692	1 008
Rest of the World	417	958	1 606	1 511
	Welfare loss (2)			
North America	4.5	10.0	14.4	7.5
Japan	-0.1	2.5	4.7	1.2
European Community	1.8	5.8	9.2	3.9
Other OECD	2.2	4.5	6.1	3.5
Oil exporting LDCs	19.6	27.4	33.5	27.5
Rest of the World	9.8	21.4	30.3	29.4
Total	6.2	13.4	19.1	15.2

1. Emission reductions, carbon taxes and welfare losses refer to 1990-2100 average values. Transactions are presented in present value terms in 1990 U.S. dollars.

2. Hicksian equivalent variation expressed as a per cent of baseline GDP.

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