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THE WELFARE EFFECTS OF FOSSIL CARBON RESTRICTIONS: RESULTS FROM A RECURSIVELY DYNAMIC TRADE MODEL

by
Thomas Rutherford
University of Western Ontario

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THE WELFARE EFFECTS OF FOSSIL CARBON RESTRICTIONS: RESULTS FROM A RECURSIVELY DYNAMIC TRADE MODEL

This paper forms part of an OECD project which addresses the issue of the cost of reducing CO_2 emissions by comparing the results from six global models of a set of standardised reduction scenarios. The project 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.

* * * * *

Ce document fait partie d'un projet de l'OCDE qui s'interroge sur les coûts de réduction des émissions de CO_2 en comparant les résultats de six modèles globaux formés d'un ensemble de scénarios standardisés de réduction. Ce projet met en évidence : i) les émissions projetées de dioxyde de carbone d'ici à la fin du siècle et ii) les taxes sur le carbone et les coûts de production que suppose la réduction de ces émissions.

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Prepared for the Policy Studies Branch, Economics Department, OECD. The views presented here are solely those of the author and do not necessarily represent the views of OECD or its members. Comments from Andrew Dean and Alan Manne are acknowledged without incrimination.

The economic and environmental effects of global warming are of concern to many organizations and individuals. Although the order of magnitude and regional distribution of the effects of global change are uncertain, there exists evidence which suggests that the costs may be high. For this reason, various groups have called for international action to reduce emissions of greenhouse gases, and particularly carbon-dioxide (CO_2) emissions associated with use of fossil fuels (natural gas, oil and coal). CO_2 is thought to account for over half of the change in "global radiative forcing" (see CBO (1990), or Nordhaus (1991)). Proposals at international conferences in Toronto (1988) and Cairo (1990) have called for cuts ranging from 20% to 50% of current emissions rates by some time early in the 21st century. The primary mechanism for achieving these reductions is usually thought to be some form of limitation on the use of carbon-based fuels. (See, for example, Grubb (1991).)

This paper reports on computations conducted as part of the OECD model comparisons project. This paper focuses on simulation experiments which assess the economic costs and consequences of restrictions on carbon dioxide emissions with special attention paid to the effects of unilateral reductions in CO_2 emissions by OECD countries. The framework for this analysis is a recursively-dynamic general equilibrium model which is designed to identify the economic channels through which restrictions on CO_2 emissions affect international trade and the pattern of comparative advantage. The model, nicknamed CRTM (Carbon Rights Trade Model), features 5 regions, 2 non-energy goods, 2 traded energy goods (oil and carbon rights), and 2 non-traded end-use energy goods (secondary electric and non-electric energy). A detailed process submodel distinguishes 15 alternative technologies for producing electric and non-electric energy. Non-energy goods include "basic intermediate materials"

(BMAT) and other non-energy. BMAT represents goods such as steel, plastics, chemicals and glass, most of which are relatively energy-intensive.[1]

When region-specific restrictions are applied to carbon emissions associated with energy consumption, crude oil imports would be counted in the importing region's emission quota. The application of emission restrictions on imports of other commodities is problematic. First of all, it would be administratively costly to assess and tax the carbon imports embodied in all commodities. Second, such taxes would also be incompatible with GATT obligations (see Whalley (1991) for a discussion of these issues). If, however, the OECD countries adopt restrictions on carbon emissions without associated taxes on other commodities, a likely result will be that the production of energy-intensive commodities will relocate to unrestricted countries. The extent to which changes in the pattern of production reduce the effectiveness of unilateral OECD abatement will be explored using the model.

The CRTM is a "general economic equilibrium model" in the sense that in this model, all economic activities are summarized in a consistent (although highly aggregate) fashion. In this model, prices adjust so that all domestic and international markets clear while producers and consumers make optimizing decisions taking market prices as given. From an environmental and welfare perspective, however, the model is incomplete because it only accounts for the direct costs of CO_2 abatement, and it does not include the *benefits* of reduced greenhouse gas concentrations for current and future generations. The benefit side of the issue is difficult to assess, in part due to the wide degree of

[1] Specifically, BMAT includes the following SITC codes: 266-67, 35, 52-53, 55-59 (excluding 5595), 62-64, 66-68.

uncertainty surrounding the relationships between carbon emissions, global warming, economic activity and social welfare. (See Nordhaus (1991).)

The time frame of this analysis covers 1990 through 2100 in 10-year intervals. This is a period which will witness the transition from fossil-based energy supplies to non-conventional ("backstop") sources of electric and non-electric energy. The timing of energy extraction and the resulting changing composition of energy supplies in different regions have important consequences for the analysis.

The current paper focuses on the time profile of three variables: (1) regional welfare measured as percentage changes in final demand (investment plus consumption), (2) carbon tax rates (the equilibrium price for carbon emission permits, expressed in $/ton), and (3) carbon "leakage" rates (representing the percentage by which a unilateral cut in emissions by one or more regions is offset by increased emissions in other regions).

Several insights arise from this analysis. First, in the model as it is currently specified, a 2% *per annum* (*p.a.*) cut in carbon emissions requires carbon taxes in the OECD regions of $200 per ton in the year 2000 rising to over $500 in 2050, and thereafter declining as oil and gas supplies are exhausted. These tax rates represent the *marginal* welfare costs of abatement. Second, the model suggests that the *average* welfare costs of abatement are significant. A 2% *p.a.* reduction produces a long-run GDP loss of more than 2.5% in the USA, 1.5% in other OECD countries, and on the order of 4% in other regions. Third, the simulations indicate that unilateral actions by the OECD produce only moderate reductions in global emissions. As a result of increased emissions by non-participating countries, a severe (4% *p.a.*) OECD reduction produces roughly the same global emission profile through 2050 as a small (1% *p.a.*) global cutback. In the period after 2050, given assumed growth rates for China and ROW, unilateral OECD reductions have an even smaller effect on the global profile.

Focusing on the period through 2050, we find that roughly half of the carbon leakage arises from trade in carbon-intensive goods. The remainder is due to increased energy intensity which arises from a lower world-market price for oil. Marginal leakage rates approach 100% with an OECD cutback of 4% *p.a.* Increasing the OECD reduction from 4% to 5% *p.a.* significantly increases the GDP loss but has a negligible effect on aggregate global emissions.

This paper is organized as follows. Section 1 describes the model structure and parameterization in a complete but non-technical fashion. Section 2 presents an overview of the central "business as usual" scenario. Section 3 presents the results of scenarios in which global emission restrictions are imposed. Section 4 considers the effects of unilateral OECD reductions. Sections 2-4 employ a series of graphs to describe the results. Section 5 summarizes the conclusions and suggests directions in which this research might be extended.[2]

1 Model Structure

CRTM is based on two earlier models. First, it extends an earlier static general equilibrium model of the same name developed jointly with Carlo Perroni (Perroni and Rutherford [1991]). In that model, the focus of the

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[2] Three technical appendices to this paper are available from the author. Appendix A provides an algebraic description of the model, and Appendix B presents the key input data tables. Tables with specific numerical values from some of these experiments are presented in Appendix C.

analysis was the year 2020 and the dynamic evolution of energy supplies was finessed through the calibration of smooth upward sloping marginal cost curves. Both CRTM models are based on the Global 2100 model and dataset developed by Manne and Richels [1990, 1992].

The model shares a number of structural features in common with Global 2100. These similarities include the following characteristics: the world economy distinguishes five regions - USA, other OECD, USSR, China and ROW (rest of world); 10-year time intervals begin in 2000 and extend to 2100; a process submodel describes the energy sector; carbon constraints are applied on a region-specific or internationally tradeable basis; and there are no inter-regional capital flows (each region operates with balance of payments in every period).

There are important differences between CRTM and Global 2100. First, CRTM distinguishes two non-energy goods: basic materials and other aggregate output. The presence of trade commodities with differing energy intensity provides insights into the extent to which changes in carbon taxes lead to dislocations in energy-intensive sectors. Next, CRTM is based on a recursive rather than a forward-looking dynamic structure. Savings fractions of final consumption are input data which are unaffected by changes in the real interest rate. Also, energy sector decisions respond only to current rather than future prices. One additional difference between the models is that in CRTM, the international oil market clears in every period. When it is able to do so, OPEC restricts oil exports to maintain a target international price.

A CRTM equilibrium path consists of 11 single-period submodels beginning with year 2000 and continuing at 10-year intervals through 2100. Year 1990 is the base year for which reported values are taken as exogenous. The basic flows in a single period model are summarized by Figure 1. Primary factors (capital and labor) are employed together with electric and non-electric energy (E,N) and basic intermediate inputs (B) to produce the domestic region's macro output. This output may then be employed for final demand (consumption and investment, C+I), exports (X), inputs to the production of energy and inputs to the production of basic materials. Macro output, basic intermediate materials and oil are freely traded in the international market.

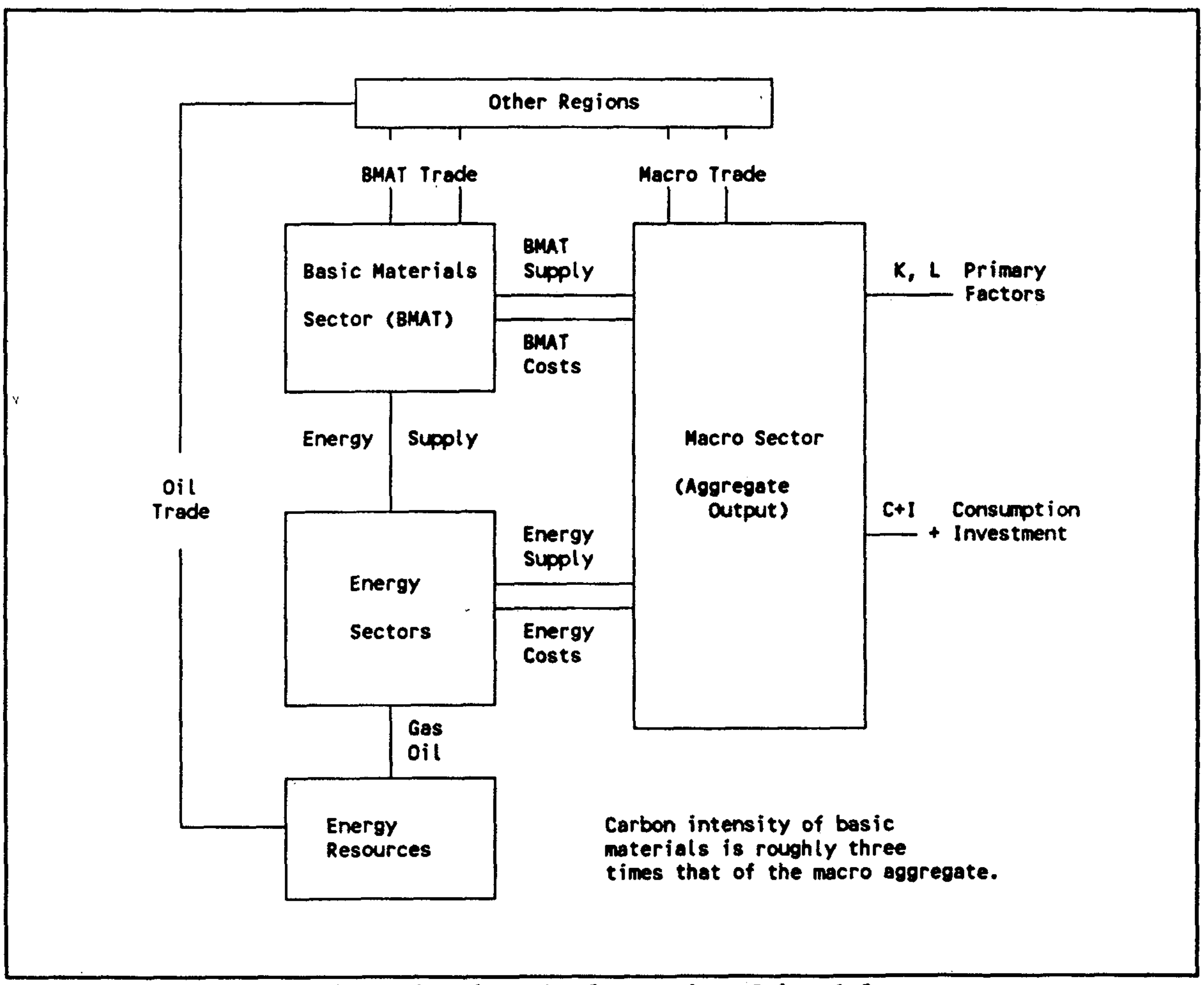

Figure 1 Commodity Flows in the Single Region Submodel

Within each single period model, the following classes of constraints apply:

International markets for goods which may be traded between regions apply to aggregate output, crude oil and basic intermediate materials.

Regional markets apply for primary factors (labor and capital), primary energy supplies (oil and natural gas), and secondary energy supplies (electric and non-electric).

Low and high cost oil and gas supplies arise from a constant ratio depletion model. The extraction profile for low cost supplies is exogenous. The initiation date for tapping high-cost supplies is endogenous, but the subsequent production profile is exogenous.

Energy sector submodels describe current and future sources of energy supplies in different regions. Constant cost coefficients and upper and lower bounds apply to output of all technologies. The rate of introduction of new technologies is limited by marginal costs which rise steeply as production levels exceed the baseline introduction rate.

Nested separable constant elasticity production functions are employed to describe substitution possibilities in the production of basic intermediate materials and new vintage aggregate output. The basic structure of these functions is illustrated in Figure 2.

Both *Y* and *B* sectors employ the same secondary energy composite in which there is a constant elasticity of substitution between electric and non-electric energy. In basic materials, the energy composite trades off with inputs of the aggregate good according to a constant elasticity of substitution. In new vintage production functions, the secondary energy composite trades off with inputs of basic intermediate materials, and a Cobb-

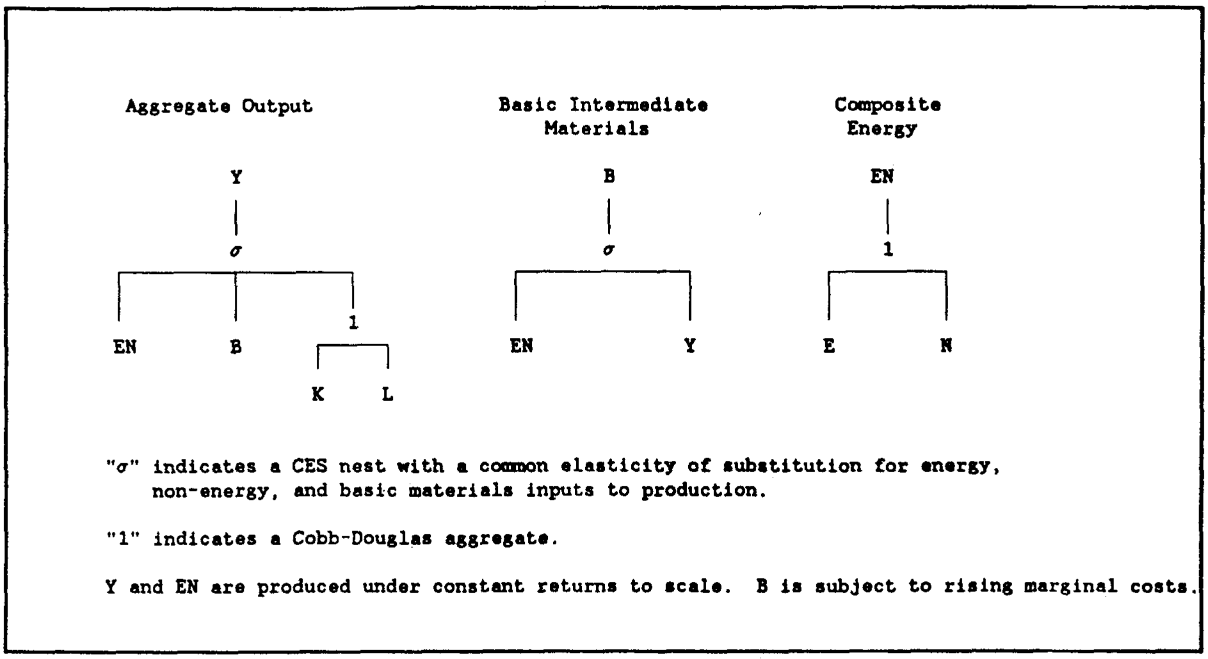

Figure 2 Nested CES Production Structures

Douglas composite of primary factors (labor and capital). Production functions for sectors *Y* and *EN* exhibit constant returns to scale, while sector *B* is subject to decreasing returns to scale.

The basic materials sector is calibrated using rough estimates drawn from input-output tables regarding the share of GDP in these industries (10% in OECD and ROW, 20% in China and USSR), the fraction of energy in production cost (10% in all regions), and the price elasticity of supply (3 in all regions). Further details of model specification are provided in Appendix B.

2 Baseline Scenario - Business as Usual

This section examines the baseline equilibrium from which alternative cutback scenarios are defined. Figure 3 shows model-generated projections for carbon emissions on a regional basis. These emission levels reflect the Stanford Energy Modelling Forum (1991) assumptions regarding potential GDP growth rates. In the first half of the century, the OECD generates a significant fraction of the global emission total, but after 2050 China and ROW become the most significant emitters. These projections underscore the importance of having a comprehensive global agreement.

The slight decline in OECD emissions in 2040 and 2050 (in Figure 3) is due to the oil price paths which are shown in Figure 4. In this model with static expectations, oil prices overshoot the backstop price from 2030 through 2040 in all regions but the USSR. In the Global 2100 dataset, China and USSR are subject to oil export limits which in the Business-as-Usual (BaU) scenario cause the domestic prices in these regions to fall below the prices in the OECD and ROW regions.

The ROW region includes a heterogenous collection of countries, including OPEC and other oil exporters. The input data specifies a "target price" for international oil prices which is used to determine the ROW export profile. In each period in which the ROW domestic price lies below the target price, ROW restricts exports to keep the international price at the target level. In the BaU scenario, the domestic ROW price is below the international price in 2010 and 2020. In the other periods (2000 and from 2030 through 2050), the ROW domestic price rises above the target price profile and the international prices follows as well.

Figures 5 and 6 provide some insight into the nature of the carbon emissions through the next century. Figure 5 shows the carbon intensity of electric energy consumption, and Figure 6 shows the carbon intensity of nonelectric energy consumption. In 1990, the carbon intensity of electric energy production is lower in the other OECD region and the USSR, reflecting

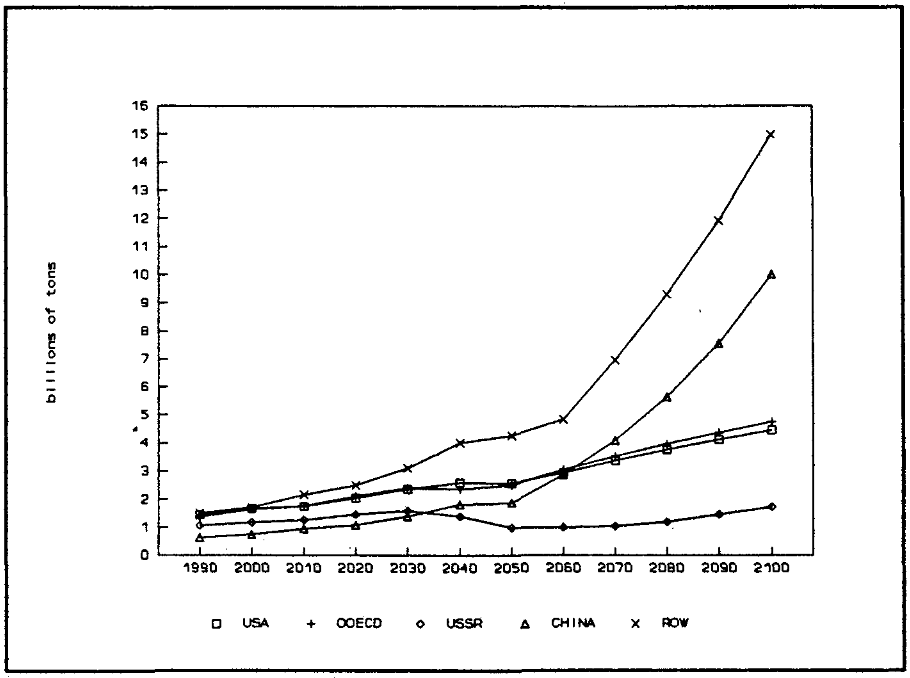

Figure 3 Total Carbon Emissions (Business-as-Usual)

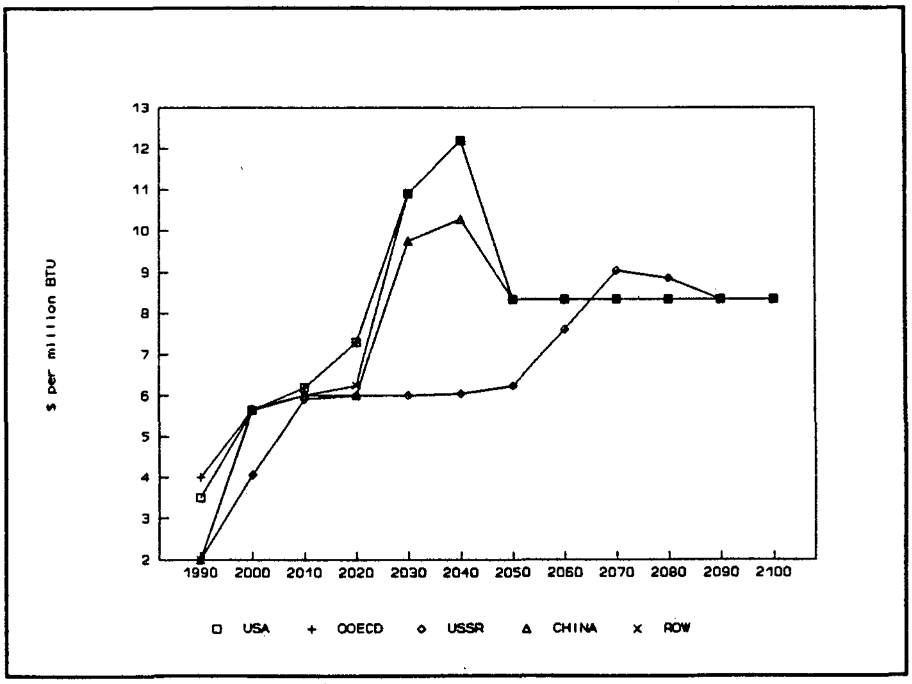

Figure 4 Oil Prices under Business-as-Usual

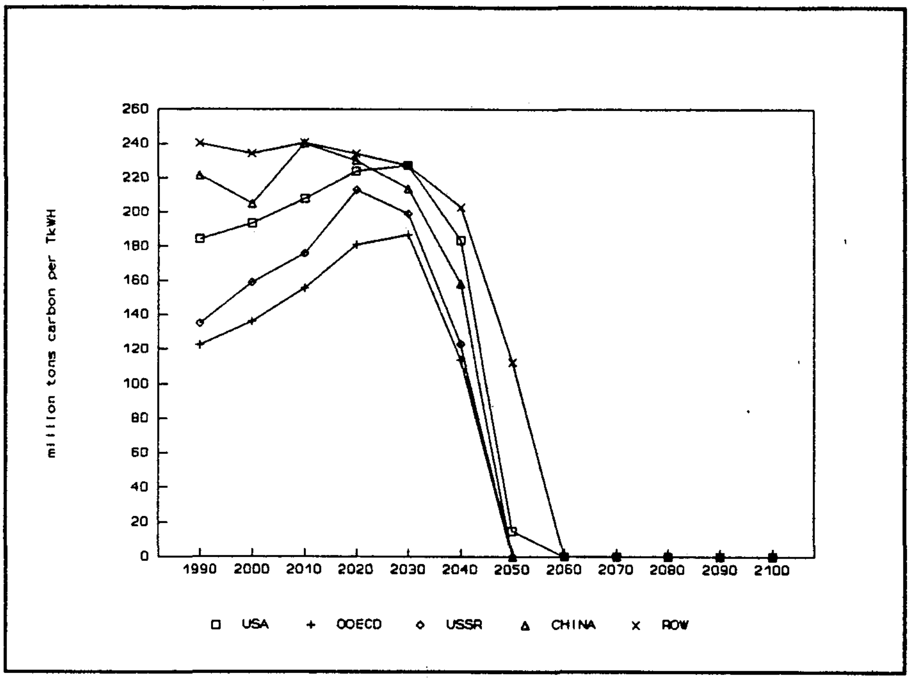

Figure 5 Carbon Intensity of Electric Energy

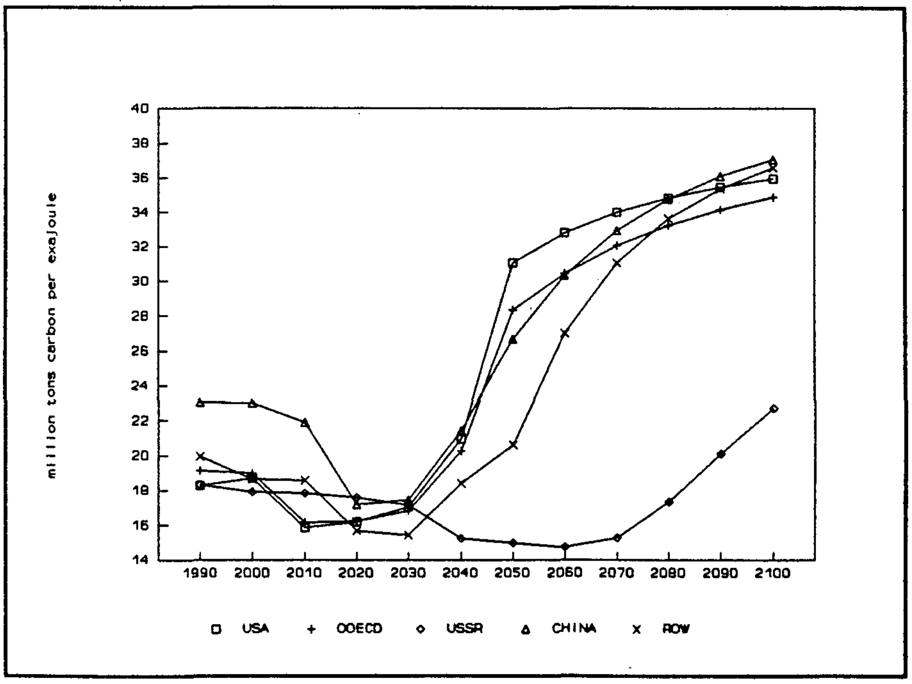

Figure 6 Carbon Intensity of Non-Electric Energy

the relatively larger nuclear share in those regions. The carbon intensity is higher in regions (ROW and China) where coal has a higher share of the electric capacity. The carbon intensity of electric power drops off sharply after 2040 with the emergence of a cost-effective carbon-free electric technology (solar or nuclear power).

The 1990 carbon intensity of nonelectric energy is higher in China due to the larger share of coal direct-use as compared with the other four regions. In all regions except the USSR, the carbon intensity of nonelectric energy rises sharply after 2050 as oil and gas supplies are exhausted and coal-based synthetic nonelectric fuels are introduced. The USSR carbon coefficient remains lower than the other regions due to the persistence of natural gas supplies.

3 Global Reduction Programs

The time profiles of global carbon emission targets for 1%, 2% and 3% *per annum* reductions from the BaU scenario are shown in Figure 7. These are the scenarios which have been adopted by the present OECD in order to facilitate the comparison of results from models based on alternative baseline emission projections. These scenarios represent mild, significant and extreme reduction scenarios, constructed in order to make a meaningful comparison across models. They are not to be interpreted as cutback proposals, *per se*.

Figure 8 shows GDP losses by region for a 2% reduction. The GDP losses are somewhat erratic through 2050, rising from 1% in 2020 to 2.7% after 2050. In the year 2000, oil and gas supplies are relatively inelastic in this model. As a result, the carbon tax which depresses the producer price of oil leads to an improvement in the terms of trade for OECD countries and, consequently, this results in a smaller welfare cost in the short term.[3] The welfare cost for the two OECD regions declines in 2030-2040 relative to the baseline projection. This is due to lower energy costs in those periods. Oil and gas supplies are more plentiful in 2030-2040 as a consequence of carbon taxes applied in 2000-2020.

The burden of a carbon tax allocated on a consumption basis is larger for energy-exporting countries, causing a deterioration in their terms of trade. As has been pointed out by Whalley and Wigle (1990), the relative welfare costs of emission restrictions depends crucially on the distribution of the tax revenues. Here, we assume tax revenues are returned to consuming regions, so the exporting regions are more adversely affected. In this model, the GDP losses for non-OECD regions range from 3.5% for China to over 4% for ROW. Within the OECD, the welfare cost for the US is larger than for the other OECD regions, due primarily to differences in the composition of energy supplies in these countries.

Figure 9 shows the regional carbon taxes which result from a 2% *per annum* reduction. The tax rates are highest in the years when the backstop energy price is overshot, 2040 and 2050. The tax remains high in the USSR after 2050 because of the extended period over which natural gas resources continue to supply that region, so that in the USSR the carbon emission constraint is displacing low-cost, low-carbon natural gas rather than high-cost, high-carbon synthetic fuels as in other regions.

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[3] Welfare cost estimates for 2000 should be regarded cautiously. This model does not incorporate adjustment costs and other disequilibrium phenomena which would dominate the short- to medium-term. An econometric estimate of these costs would probably be more reliable.

Figure 10 shows the USA carbon tax rates for alternative global reductions. A severe (3%) reduction places a premium on natural gas which leads to an earlier introduction date for high-cost supplies. The availability of larger quantities of natural gas in 2050 softens the impact of the carbon constraint. These effects are a direct consequence of our recursive dynamics. A model with consistent expectations would anticipate the carbon tax premium on natural gas and begin extraction of high-cost supplies early enough to avoid bottlenecks such as occur in the 2% case.

Figure 11 indicates that the *relative* (percentage from baseline) welfare costs of carbon restrictions are not particularly sensitive to parameters affecting energy demand growth.[4] The cases labelled AEEI and ESUB illustrate the sensitivity of the welfare cost estimates to assumptions about future energy demand adjustments. Scenario AEEI assumes a 1% per year non-price induced ("autonomous") improvement in energy efficiency, double the standard assumption, whereas case ESUB doubles the elasticity of substitution between energy and non-energy inputs in the production of aggregate output in all regions.

[4] This statement is to be interpreted carefully. It applies when welfare changes are measured relative to the corresponding modified baseline projections. In *absolute* terms, the welfare cost of carbon restrictions does depend crucially on the role for price-induced and autonomous energy conservation.

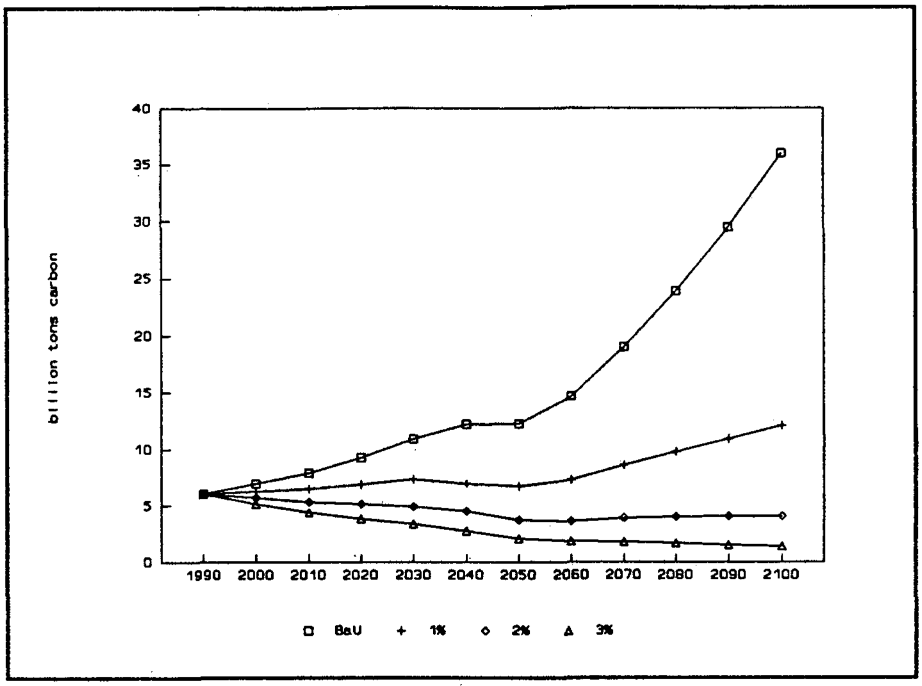

Figure 7 Total Carbon Emissions - Alternative Scenarios

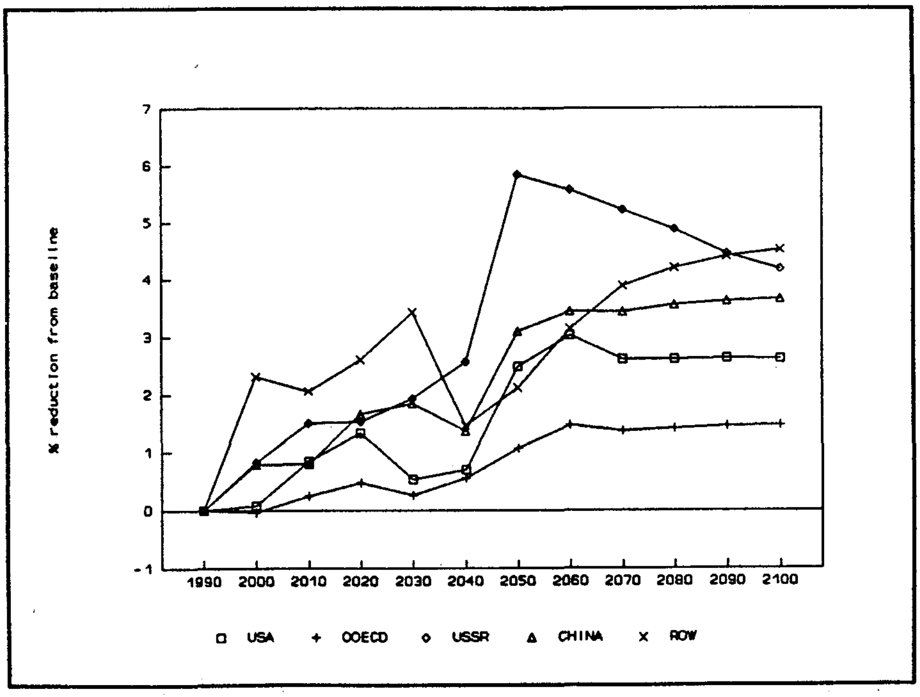

Figure 8 GDP Losses (%) (2% *per annum* Global Reduction)

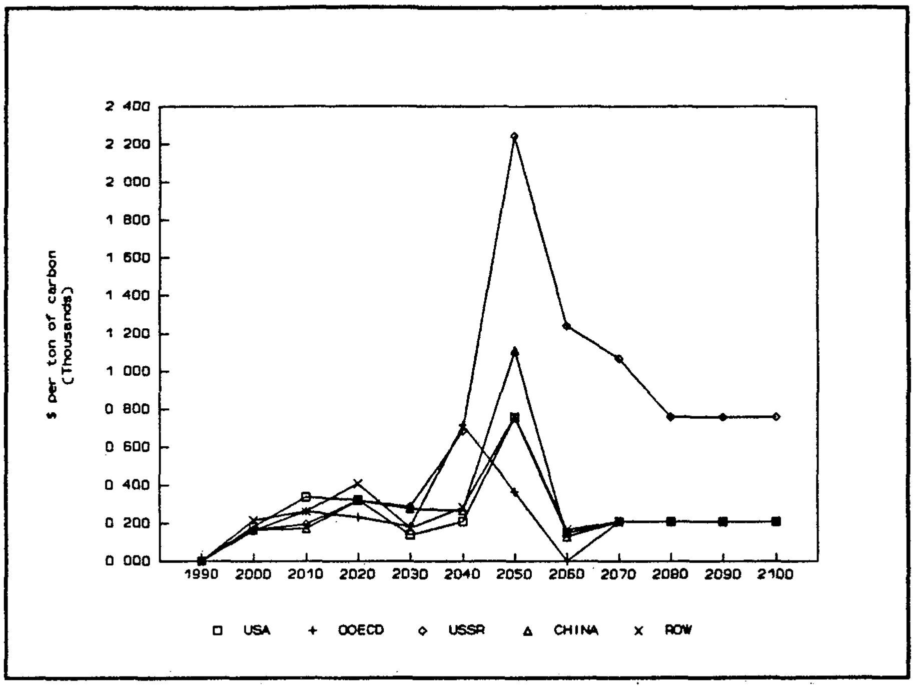

Figure 9 Carbon Tax Rates (2% *p.a.* Global Reduction)

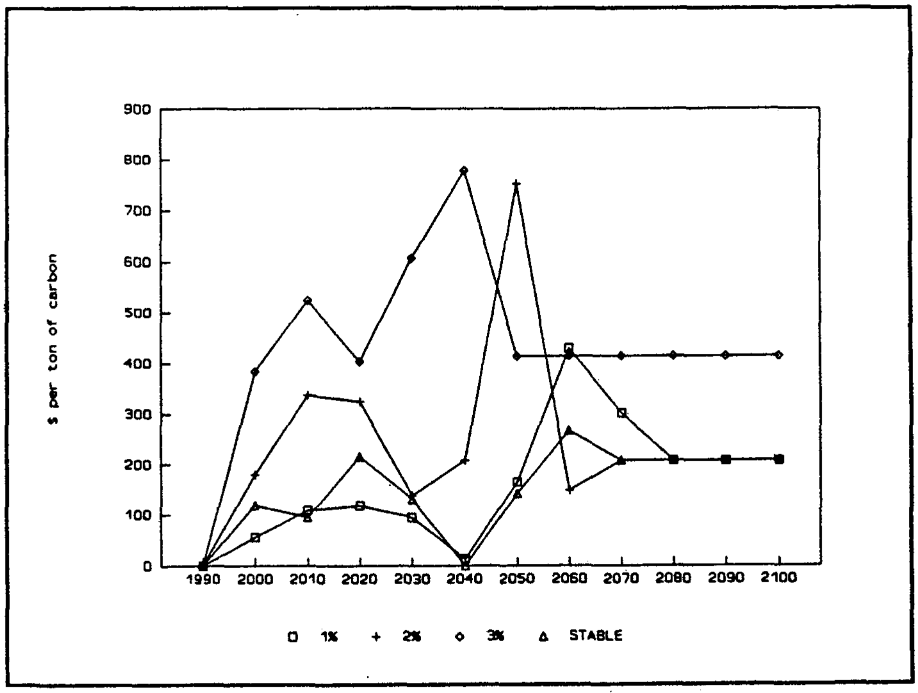

Figure 10 U.S. Carbon Tax Rates for Alternative Cases

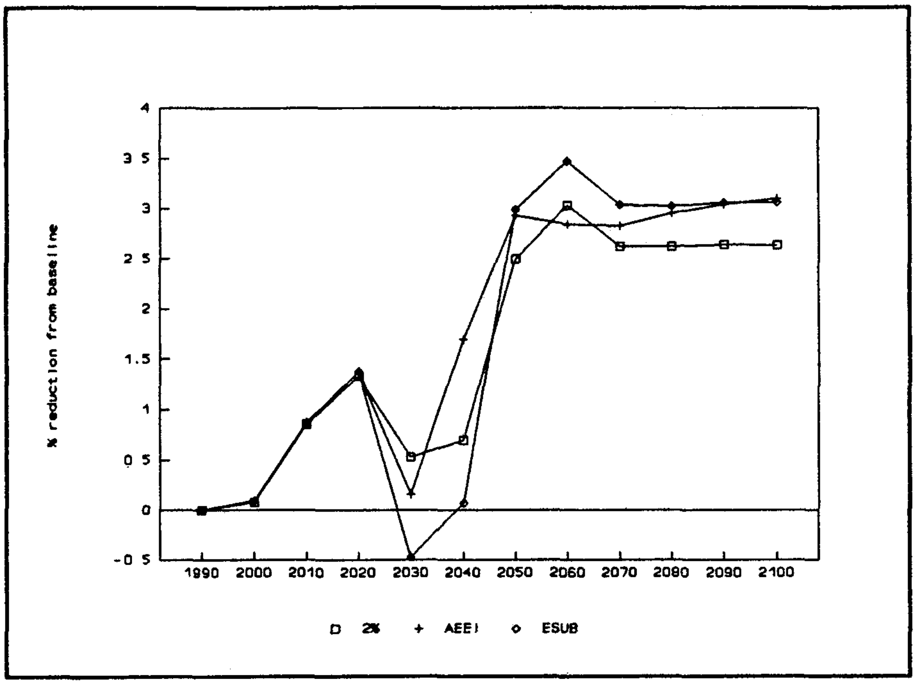

Figure 11 Sensitivity of U.S. GDP Losses to Energy Demand Parameters

4 The Scope of Unilateral OECD Action

We now turn our attention to scenarios in which the OECD undertakes unilateral reductions in carbon emissions. Considering carbon reductions ranging from 2% to 5% *per annum* from the BaU emission levels, Figure 12 indicates that unilateral abatement policies produce increasing welfare costs for the US[5]. Drastic cutbacks (3 to 5% *p.a.*) produce significantly higher costs in the first 30 years with only moderately larger losses later in the period.

Figure 13 displays the effect of unilateral OECD reductions on global emissions. We find that through 2050, a 3% *p.a.* OECD reduction produces a global effect which is roughly the same as a 1% *p.a.* global cutback. Increasing the OECD cutback from 3% to 4% produces a only small effect on the global total, and an even higher reduction (from 4% to 5%) produces virtually no effect on global emission. It appears that as a result of "leakage", the OECD can produce little more than a 1% *p.a.* reduction in global emissions through 2050. In other words, when the OECD cutback exceeds 3% *p.a.*, the marginal leakage rate is nearly 100%.

When we look at the period after 2050, we see that unilateral OECD cutbacks has significantly less effect than a 1% global reduction. This is due to the growth rates for China and ROW which are assumed to remain high well into the next century, so that OECD emissions represent successively smaller fractions of global emissions in each decade. To the extent that

[5] Welfare costs for the other-OECD region are qualitatively similar although they remain lower than those in the US in all periods at roughly the same proportion as in the 2% global abatement case (see Figure 8).

these growth assumptions are plausible, there is limited scope for significant cutbacks in 2100 without a comprehensive global agreement.

Returning to the consequences of OECD abatement in the period through 2050, we observe that leakage can arise from two channels. The first is leakage through trade which occurs when the production of carbon-intensive goods migrates from carbon-constrained to unconstrained locations. The second source of leakage is price-induced substitution which leads to an increased carbon intensity of production outside the OECD. A decomposition of these effects is displayed in Figure 14. This figure shows the leakage rates which result from two models. The first is the standard model, with a 3% *p.a.* unilateral emission cut in the OECD. The second curve is an alternative model structure - one which assumes that basic materials trade is maintained (by OECD export subsidies) at exactly the baseline levels throughout the model horizon.[6] In the alternative model structure, carbon leakage arises solely through price-induced substitution effect. This shows that both types of leakage are important.

The final figure (Figure 15) indicates the regional allocation of leakage for a 2% *p.a.* OECD cutback. For the reference parameter values, region ROW is the main source of leakage in the first few periods. This happens because in this model, ROW takes the role of OPEC price-leader. As the OECD reduces oil imports, there is downward pressure on the international oil price. To sustain the international price, ROW severely restricts

[6] This case is included in order to better understand the results and should not be interpreted as a policy prescription. It is interesting that using the reference parameters, the model identifies the OECD regions as net *exporters* of basic materials into the next century, so that restriction of leakage through trade requires subsidies on OECD exports rather than tariffs on imports of these goods.

exports. This leads to a sharp fall in the ROW energy and the consequent leakage through both substitution and increased BMAT production.

In both models, leakage rates are highest in years 2000-2030 and they are then negative later in the century. This happens because the OECD carbon restrictions lead to lower levels of fossil-fuel consumption and delayed extraction of relatively low-carbon oil and gas supplies in region ROW. As a result, there is significantly lower output of carbon-intensive synthetic fuels in the ROW in years 2060-2080 when the OECD unilaterally reduces carbon emissions.

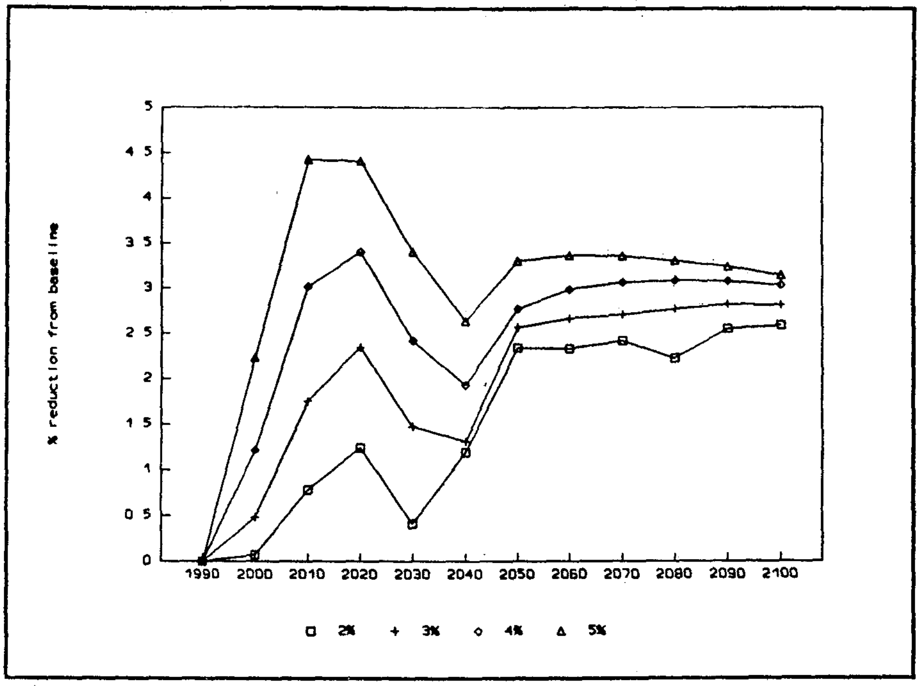

Figure 12 U.S. GDP Losses from Unilateral OECD Cutbacks

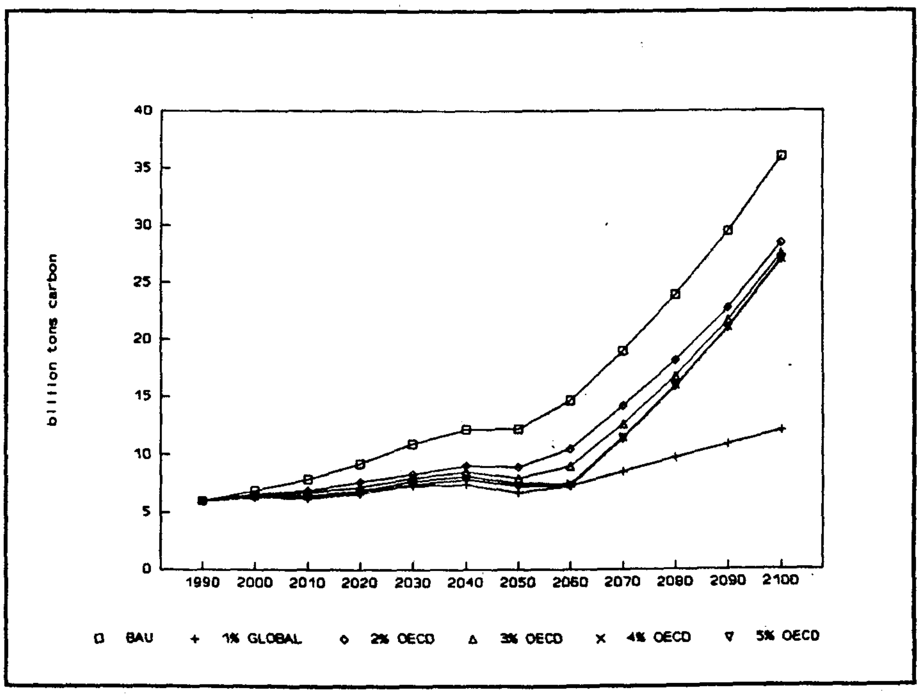

Figure 13 Carbon Emissions Comparison - Global versus Unilateral Abatement Programs

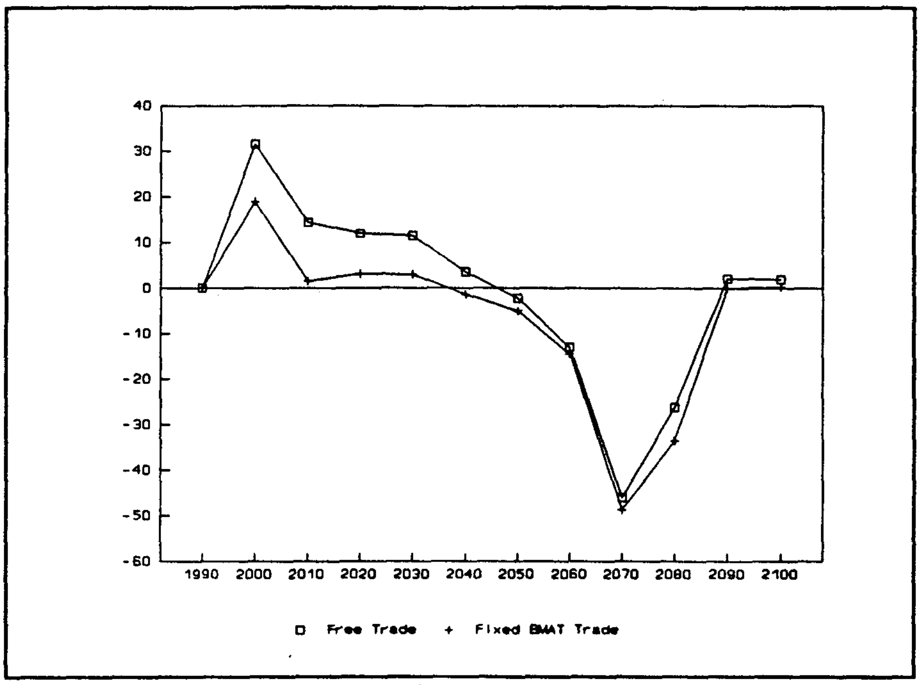

Figure 14 Leakage Rates for a 3% p.a. OECD Reduction

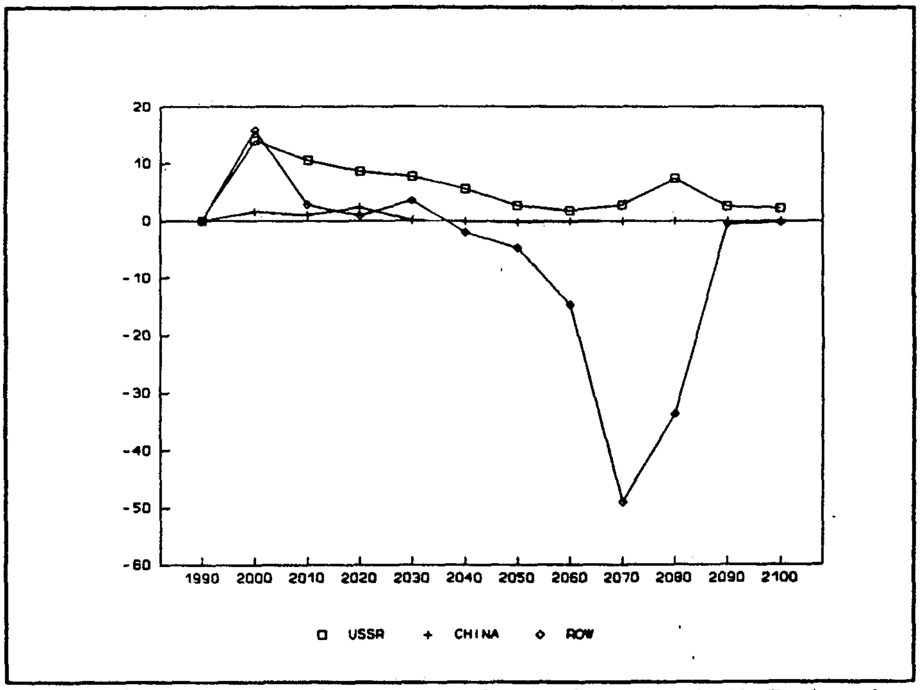

Figure 15 Leakage by Region for a 3% p.a. OECD Reduction

5 Summary and Conclusions

This paper has considered the consequences of carbon emission restrictions in a general equilibrium trade model which takes into account a variety of economic mechanisms. The modelling work has produced several insights:

(i) The time profile of carbon emissions from 1990 to 2100 show that electric energy is relatively carbon intensive through 2050 when carbon-free electric energy becomes cost effective. The trend in carbon intensity of nonelectric energy is the reverse. Through the period when traditional fossil fuels are dominant the carbon coefficient for non-electric energy is relatively low. There is a sharp increase in carbon content of primary energy when coal-based synthetic are used to replace oil and natural gas.

(ii) Global reductions in carbon emissions produce relatively larger welfare costs for energy-exporting regions due to changes in the terms of trade. Within the OECD, the composition of energy resource supplies and electric generating capacity leads to a somewhat higher costs for the US as compared with other OECD regions.

(iii) Welfare cost estimates from a consistent baseline case are not particularly sensitive to the prospects for price-induced and autonomous energy substitution.

(iv) Due to international trade linkages, the scope for unilateral OECD action to reduce global concentrations are severely limited. The costs of OECD cutbacks increase with the level of cutback, but the impact on global emissions drop off sharply. The *marginal* leakage rate in 2000-2010 is nearly 100% for cutbacks above 3% *p.a.* A decomposition of the leakage shows that both trade and substitution are responsible for a 30% average leakage rate in 2000.

(v) The response of oil supplies to softening international oil prices plays a crucial role in determining the leakage rate for a particular OECD curtailment. In this model, OPEC restricts exports to maintain a constant international price; and the domestic energy price in ROW then adjusts sharply downward.

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