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Unilateral CO_2 Reductions and Carbon Leakage: The Consequences of International Trade in Oil and Basic Materials*

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A recursively dynamic general equilibrium model featuring six world regions with trade in energy and non-energy goods is used to simulate the period from 1990 through 2100 in 10-year intervals. The simulations explore the effect of unilateral action by the OECD to curb global CO_2 emissions. Unilateral cuts create incentives for free-riding by non-participating regions, so that global emissions are reduced by less than the amount that the OECD cuts back its regional emissions. Carbon "leakage" occurs through two channels. First, basic materials production increases in unconstrained regions, resulting in increased carbon intensity of GDP. Second, reductions in OECD oil imports cause the world oil price to fall, leading to an increased energy intensity in the non-participant regions. In this paper, we use a general equilibrium model to assess the extent to which these two mechanisms reduce the effectiveness of OECD reductions in curbing global CO_2 concentrations.

1. INTRODUCTION

Two international conferences (Toronto (1988) and Cairo (1990)) have called for significant reductions in worldwide carbon dioxide emissions associated with the combustion of fossil fuels. Europe, Japan, and Australia have already made commitments to lower their CO_2 emission levels. At the last UN conference on global warming held in Rio (June 1992), the European Community proposed a carbon tax for the developed world to curb global CO_2 emissions.

The purpose of this paper is to explore the economic consequences of unilateral cutbacks of CO_2 emissions. 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. Emission limits produce price effects

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which spill over into other markets on both domestic and international levels. The effects are likely to be significant for goods with a high energy content. On the international level, our model incorporates trade in oil, an aggregate non-energy good, and basic intermediate materials (BMAT). BMAT is a category which includes relatively energy-intensive goods such as chemicals, steel, plastic, and glass. The model distinguishes six regions (USA, other OECD countries, USSR, China, MOPEC (Mexico and OPEC), and ROW (rest of the world)). The regional submodel features two macro sectors (BMAT and aggregate output) and a disaggregated energy sector in which final products are electric and non-electric energy.

The model is a "general economic equilibrium" in that all economic activities are summarized in a consistent, albeit highly aggregate, fashion. In this model, prices adjust so that all domestic and international markets clear while producers and consumers make optimal decisions taking market prices as given. When there are region-specific restrictions on carbon emissions associated with energy consumption, we presume that crude oil imports count against the importing region's emission quota. At the same time, we assume that there can be no effective tax on carbon embodied in other imported goods. For this reason, trade in energy-intensive goods such as basic materials can offset the effects of CO_2 cutbacks, particularly if one or more regions take unilateral measures. "Leakage" can also occur when carbon taxes depress the world-market price for oil and thereby change the energy consumption in non-signatory countries.

In the simulations reported in this paper, we "benchmark" our model to quantities and prices for 1990. The projections cover 11 10-year intervals extending from 1990 through 2100. In the baseline scenario "business as usual," an equilibrium trajectory is simulated when no carbon emission limits apply in any region. The counterfactual experiments reduce CO_2 emissions in the OECD between 1 and 4% per annum. We are concerned with the order of magnitude of economic variables; hence, for simplicity, we focus on cuts of specified percentage per annum from the business as usual case rather than on a particular path of emissions reductions.[1]

In a second set of counterfactual cases, we assess the effects of policies which could be adopted to restrict leakage through trade in basic materials. The OECD regions are presently net exporters of basic materials, and the model suggests that these exports will continue into the next century. As a consequence, trade policies to reduce leakage through BMAT trade will involve subsidies for OECD exports rater than taxes on BMAT imports. A policy measure which combines carbon taxes and export subsidies parallels the energy tax proposal by the European Community's commissioner for the environment, Carlo Ripa di Meana. The commissioner's tax design includes exemptions intended to moderate the impact on the competitive position of domestic industry. Notably, the list of sectors which the EEC wants to exempt from the carbon tax are those which are included in our BMAT category.[2]

[1] This approach was recommended by the OECD Public Economics Division in their model comparison project (see [7]).

[2] We do not provide an explicit calculation of the economic effects of the EC proposal in this paper, but we feel that our analysis captures some of the effects. The current EC proposal actually exempts a number of energy-intensive industries from carbon taxes. A precise calculation of the effects of this policy would require a substantial revision of our model structure in view of the possibility that exemptions would induce fuel switching in the affected industries.

We conduct a calculation in which OECD regions subsidize exports of basic materials so that exports remain at business as usual levels through the model horizon. This experiment is also motivated by recent developments in the area of trade and environment. Demands by ecological groups to restrict international trade in environmentally sensitive commodities are being reflected by new trade legislation in the United States and other countries.[3] Our scenario in which BMAT exports by the OECD are subsidized in the presence of carbon taxes exemplifies the idea of this legislation.

Our numerical experiments provide insight into the consequences of unilateral OECD emission restrictions and the extent to which increased emissions by non-OECD countries offset OECD reductions. Our model suggests that the welfare cost of a 2% per annum (compounded) unilateral reduction in carbon emissions by the OECD would have a cost of roughly 2% of GDP. We find that *at the margin* this reduction would be offset by 25% through increased emissions in non-signatory countries. Trade policies to offset leakage through subsidization of energy-intensive industries have at best limited effectiveness. We conclude that for reducing carbon emissions, trade restrictions are a poor substitute for a comprehensive global agreement.

The body of this paper is organized as follows. Section 2 describes the model structure and key parameters underlying technologies and preferences. Section 3 formalizes the connection between costs of unilateral carbon abatement and leakage. Section 4 presents an overview of the central business as usual scenario. Section 5 presents the results of the counterfactual cases with unilateral carbon restrictions in the OECD. Sections 4 and 5 employ a series of graphs to illustrate the results. Section 6 summarizes our findings and makes suggestions for future research. An algebraic description of the model is provided in Appendix A, and a description of the key input data is presented in Appendix B. Both appendices are available from the authors upon request.

2. MODEL STRUCTURE

The present model is based on an earlier model constructed to analyze the welfare effect of carbon taxes in a recursively dynamic five-region framework [10].[4] Both of these models are based on the Global 2100 model and dataset from Manne and Richels [4, 5]. The Global 2100 ROW region is an aggregate of heterogenous countries including OPEC and other oil exporters as well as oil-importing LDC's. For the present study, which is focused on unilateral carbon reductions and leakage, we separated OPEC and Mexico from the Global 2100 ROW region. In the new region (MOPEC), shares of oil and gas production of GNP are significantly higher than in ROW so that one can expect different impacts from OECD carbon taxes on the two regions.

Our model shares a number of structural features with Global 2100. These similarities include a world economy distinguishing five regions, 10-year time intervals beginning in 1990 and extending to 2100, a process submodel describing

[3] For a survey see [11].

[4] In [10], Rutherford extended an earlier static general equilibrium model developed with Perroni and described in [8]. In the static model, the authors focused on the year 2020, in which energy supplies arise from upward-sloping marginal cost curves.

the energy sector, carbon constraints applied on a region-specific basis, and no interregional capital flows (each region operates with balance of payments in every period).

There are, however, important differences between these models. First, our model is based on a recursive rather than a fully intertemporal dynamic structure. Savings fractions of final consumption are input data which are unaffected by changes of the real interest rate. Second, the model distinguishes two non-energy goods: basic materials and an aggregate output. The presence of traded commodities with differing energy intensities provides insights into the extent to which changes in carbon taxes lead to the reallocation of comparative advantage. Third, in the recursive model, the international oil market clears in every period. Finally, Global 2100 incorporates forward-looking resource policies, whereas in our model, the timing of energy extraction and the resulting changing composition of energy supplies are based on static expectations. The treatment of expectations has important consequences for the analysis.

The detailed structure of a single period in each of the periods is shown in Fig. 1. Primary factors (capital and labor) are employed together with electric and non-electric (E, N) and basic intermediate inputs (B) to produce the domestic region's macro output. This output is in turn used for final demand (consumption and investment, $C + I$), as well as for exports (X), and as inputs to the production of energy (EC) and basic materials (BC), respectively. These flows are represented

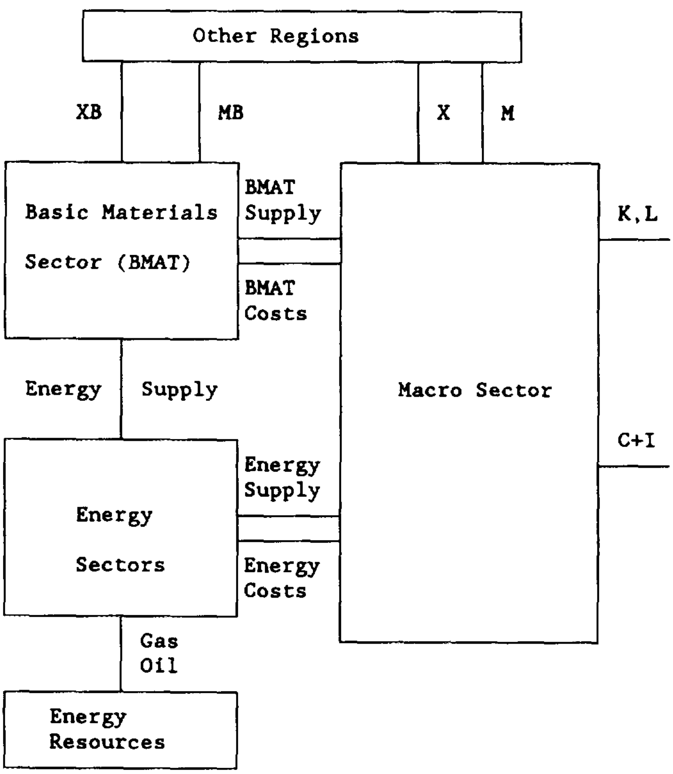

FIG. 1. Commodity flows in the single-region submodel.

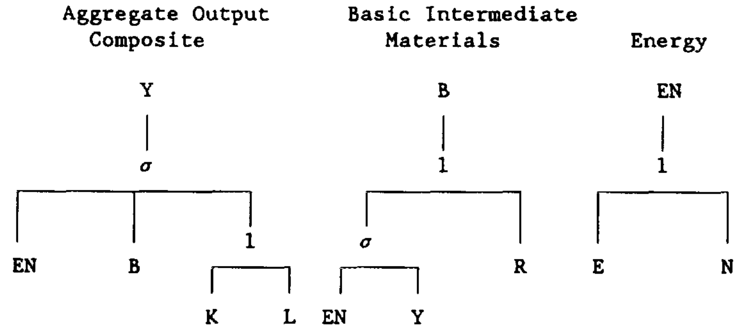

FIG. 2. Nested CES production structures. σ, elasticity of substitution for energy, non-energy, and basic materials inputs to production.

by arrows in the diagram. Aggregate output, basic intermediate materials, and oil are traded in the international market.

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

International markets apply to macro output, crude oil, and basic intermediate materials. There are import and export quotas for oil.

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

Energy sectors submodels describe current and future sources of energy supplies in different regions. Constant cost and carbon 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.

Low- and high-cost oil and gas supplies arise from a constant ratio depletion model.[5] The extraction profile for low-cost supply is exogenous. The initiation date for tapping high-cost supplies is endogenous but the subsequent production profile is exogenous.

Nested separable constant elasticity production functions are employed to characterize substitution possibilities in the production of basic materials and aggregate output. The basic structure of these functions is illustrated in Fig. 2.

Both Y and B sectors use the same secondary energy composite, in which there is a unitary elasticity of substitution between electric and non-electric energy. In basic materials, the energy composite trades off with inputs of aggregate output according to a constant elasticity of substitution. The macro production function features a constant elasticity of substitution between the secondary energy composite, basic materials, and a Cobb–Douglas composite of primary factors (labor and capital). Finally, a distinction is made between new vintage and extant vintage production. The composition of inputs in both extant macro and basis material production function in 1990 is fixed for successive periods.

[5]The energy submodel corresponds to the ETA model in Global 2100. The electric production technologies include hydro-electricity, remaining coal-fired plants, remaining nuclear plants, new-vintage gas-fired generation, new-vintage coal-fired plants, and "advanced technology electricity." The non-electric supply sectors include coal for direct use, natural gas used for non-electric purposes, synthetic fuels, renewable non-electric power, and low-cost and high-cost oil and gas.

The model has been implemented using GAMS for model generation, updating, and report writing and MPS/GE for model solution.[6] In the single-period submodel, a simultaneous system of 300 non-linear inequalities is solved. One simulation of the 11-period horizon requires roughly 15 minutes with a 25-MHz 80486 microcomputer.

3. LEAKAGE AND THE MARGINAL COST OF ABATEMENT

In this section, we present an analytical framework in which to illustrate how the marginal leakage rate affects the optimal level of emissions for a region undertaking unilateral action. We begin with a static model in which there are two final goods and a single representative agent. Let X represent environmental quality, and let Y represent a composite of other commodities. In this stylized economy, the representative agent chooses a level of carbon emissions C which solves

$$\text{maximize } W(X,Y) \text{ s.t. } X = f(C), \qquad Y = g(C),$$

where function f captures the relationship between carbon emissions and environmental quality—as emissions rise, environmental quality declines ($f'(C) < 0\ \forall C$) —and function g captures the relationship between emissions and consumption possibilities for other goods ($g'(C) > 0\ \forall C$).

The first-order conditions for this single-agent problem are

$$-\frac{\partial W}{\partial X}\frac{df}{dC} = \frac{\partial W}{\partial Y}\frac{dg}{dC}.$$

This equation can be interpreted as equating marginal benefits of carbon emissions with the marginal cost. Marginal benefits, on the left-hand side, are the product of a term representing the marginal utility of environmental quality and a term representing the extent to which carbon emissions affect environmental quality (recall that $f' < 0$). On the right-hand side of this equation we have the product of a term representing the marginal utility of consumption for goods and a term which represents the extent to which increases in carbon emissions make possible additional units of other goods ($g' > 0$). In an intertemporal framework, this model extends into an optimal control setting. The algebraic relations are somewhat more complicated, but the optimality conditions are effectively unchanged. At any point in time, the marginal benefits (present and future) of increased emissions are balanced with the present and future costs.

Now consider a model in which there are two regions, denoted n and s. Suppose that total emissions are given by $C = C_n + C_s(C_n)$. That is, global emissions are the sum of both regions' emissions. We consider the optimal level of emissions for the first region, n, taking the resulting level of emissions by the second region, s, as a function of C_n. Due to international energy market effects, we expect that $dC_s/dC_n < 0$. (As region n's fossil carbon emissions rise, this increases the internation price of oil and, ceteris paribus, causes C_s to decline.)

[6] GAMS (general algebraic modeling system) is described in [1]. MPS/GE stands for mathematical programming system for general equilibrium analysis (see [9]). The interface between these modeling environments is described in [3].

Suppose that region n seeks to maximize its own welfare, taking into account the response of region s. That is, region n solves

$$\text{maximize } W_n(X,Y) \text{ s.t. } X = f[C_n + C_s(C_n)], \qquad Y = g(C_n).$$

For this model, the first-order conditions read

$$-\frac{\partial W}{\partial X}\frac{df}{dC}\left(1 + \frac{dC_s}{dC_n}\right) = \frac{\partial W}{\partial Y}\frac{dg}{dC_n}.$$

In this model we interpret $l = -dC_s/dC_n$ as the *marginal* leakage rate, l. When leakage is zero, we see that the optimality condition for region n acting unilaterally is the same as that for the single-agent model. The optimal level of abatement (when $l = 0$) equates benefits ($b = (\partial W/\partial X)(df/dC)$) with marginal cost ($c = (\partial W/\partial Y)(dg/dC_n)$). If, on the other hand, the leakage rate is positive, then the first-order condition can be interpreted as equating marginal benefits with marginal cost *adjusted for leakage*; i.e.,

$$b = \frac{c}{1 - l}.$$

For example, if the marginal leakage rate is 50%, then a marginal cost calculation based on a single-region model underestimates the true marginal cost of global abatement through unilateral action by a factor of 2.

We conclude by simply pointing out that marginal and average leakage rates are quite distinct. We define the average leakage rate based on a reference level of emissions, $\bar{c}_n$ and $\bar{c}_s$. For a given level of emissions by n, c_n, we have

$$l^{a} = \frac{c_s - \bar{c}_s}{\bar{c}_n - c_n}.$$

In our numerical model, we find that it is common that the average leakage rate may be small while that marginal rate is quite large.

4. BUSINESS AS USUAL SCENARIO

The business as usual (BAU) assumptions are based on Energy Modeling Forum (EMF 12) study guidelines [2]. The reference case assumes that world population will double and world GDP will increase by more than ninefold over the next century. In our BAU calculations, the growth factors lead to a rise in carbon emissions from 6 billion tons in 1990 to roughly 36 billion tons in 2100. Figure 3 presents projections for carbon emissions on a regional basis. In all regions but the USSR, which has large natural gas reserves, carbon accumulation accelerates after 2050 when oil and gas are replaced by coal-based synthetic fuels. The rate of emissions growth is lower in the OECD, where labor growth rates projections are smaller. The non-OECD regions increase carbon emissions dramatically as their per capita income levels approach current levels in the OECD. These projections

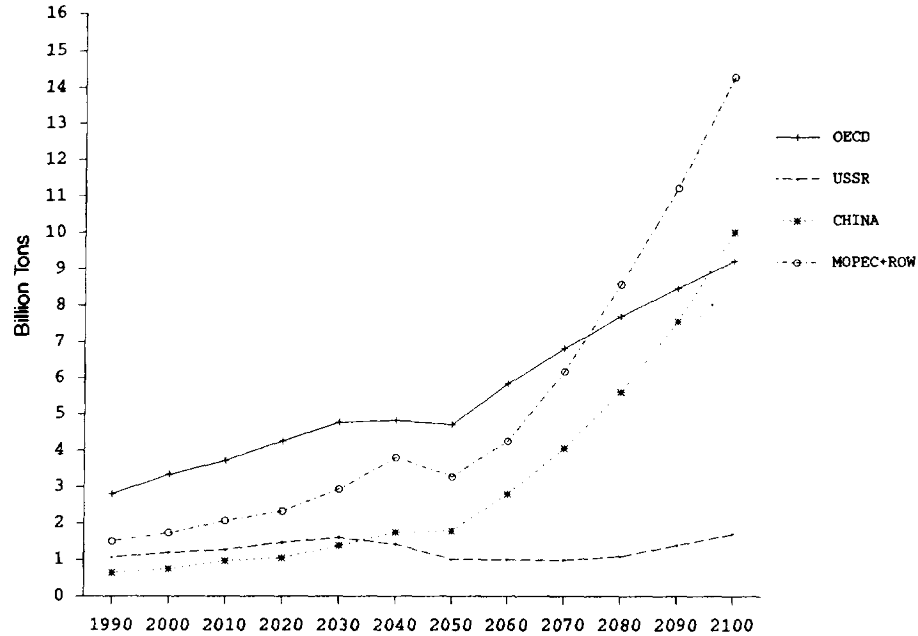

FIG. 3. Total carbon emissions for BAU.

underscore the importance of having a comprehensive global agreement on carbon reduction.

The slight decline in emissions in 2030 and 2040 (in Fig. 3) is explained by the oil price paths which are shown in Fig. 4. Oil prices overshoot their backstop price in 2030 and 2040 in all regions but the USSR. In the Global 2100 dataset, China and the USSR are subject to oil export limits which in the BAU scenario cause the domestic prices in these regions to fall below the prices in the other regions. The oil prices are low in the early decades due to high oil production. Consequently, there is no production of synthetic fuels in this period. Expansion constraints on synfuels production and an early exhaustion of resources cause oil prices to overshoot in 2030 and 2040. In the USSR and MOPEC, the introduction of backstop technologies occurs later, resulting in overshooting oil prices for a second time. Note that the backstop price of oil equals the cost of synthetic fuels, $8.33 per GJ.

Figures 5 and 6 provide some insights into the nature of the carbon emissions through the next century. Figure 5 shows the carbon intensity of electric energy consumption and Fig. 6 the carbon intensity of non-electric energy consumption. In 1990, the carbon intensity of electric energy is lower in the OECD and the USSR, reflecting the relatively larger nuclear share in those regions. The carbon intensity is higher in regions such as ROW and China, where coal has a higher share of the electric capacity. After 2030, the carbon intensity of electric power drops off sharply with the introduction of cost-effective carbon-free electric technologies (solar or nuclear power).

The 1990 carbon intensity of non-electric energy is higher in China due to the larger share of coal direct use as compared with the other four regions. In all

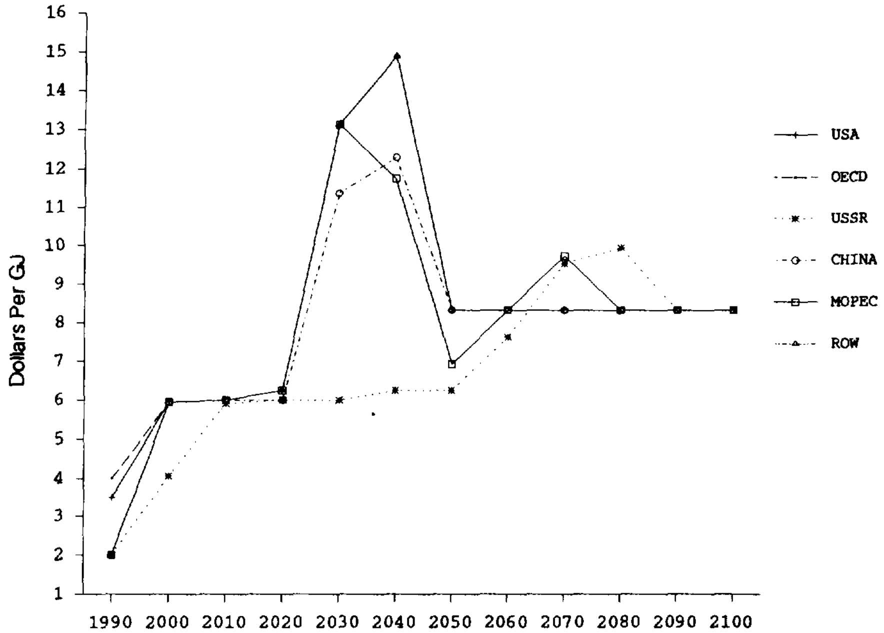

FIG. 4. Oil prices for BAU.

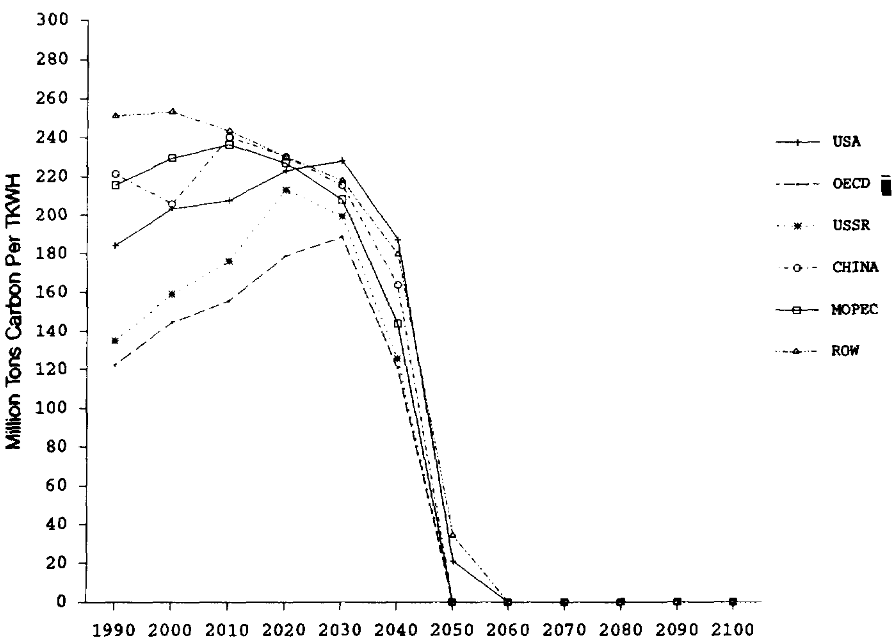

FIG. 5. Carbon intensity of electric energy.

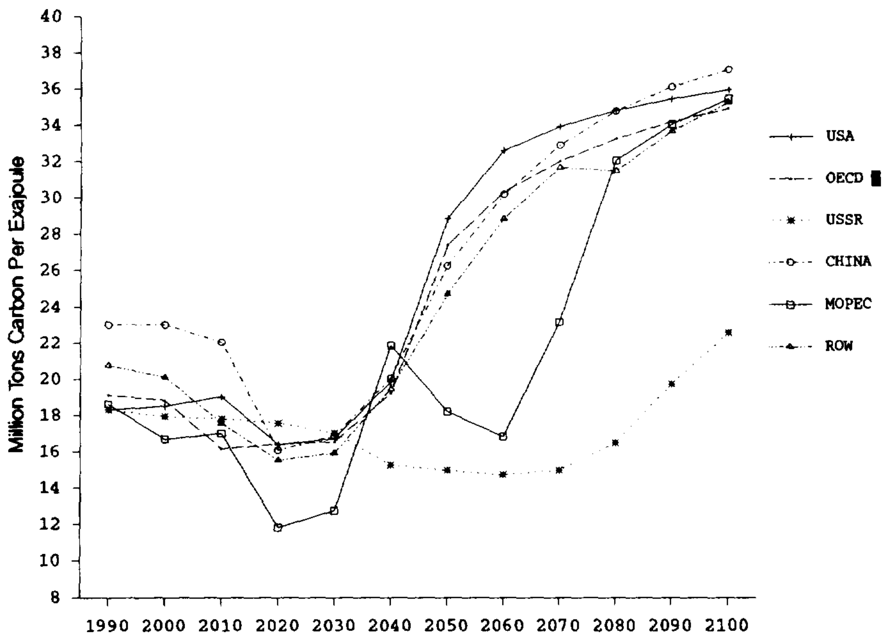

FIG. 6. Carbon intensity of non-electric energy.

regions except the USSR, carbon intensity of non-electric energy rises sharply after 2040 as oil and gas supplies are exhausted and synthetic fuels are introduced. The USSR carbon coefficient remains lower than those of the other regions due to the persistence of natural gas supplies.

4. THE SCOPE OF UNILATERAL ACTION

The counterfactual cases study the impacts of unilateral OECD carbon emission restrictions in two alternative model structures. First we analyze OECD cutbacks ranging from 1 to 4% per annum (pa) from the 1990 level. In an alternative experiment, we fix OECD BMAT trade at the BAU levels throughout the model horizon and study its impact on global carbon emissions. In all counterfactual cases, we assume that emission rights are freely traded among the OECD countries.

Figure 7 displays OECD carbon taxes as a function of unilateral cutbacks. Severe (4%) reductions result in an early introduction date for high-cost supplies. Consequently, tax rates are high and relatively stable. For less restrictive cutbacks, tax rates jump on a higher level when tapping of high-cost natural gas reserves occurs. After that, the availability of larger quantities of natural gas softens the impact of the constraints.

Figure 8 presents marginal leakage rates for emission cutbacks between 1 and 4% per annum. One percent carbon reductions produce significantly positive leakage rates from 2020 onward. Marginal leakage peaks in 2030–2040 at roughly 45% and decreases slowly over the rest of the century. Marginal leakage rates equal to 45% translate to a premium of 82% on the direct cost of carbon

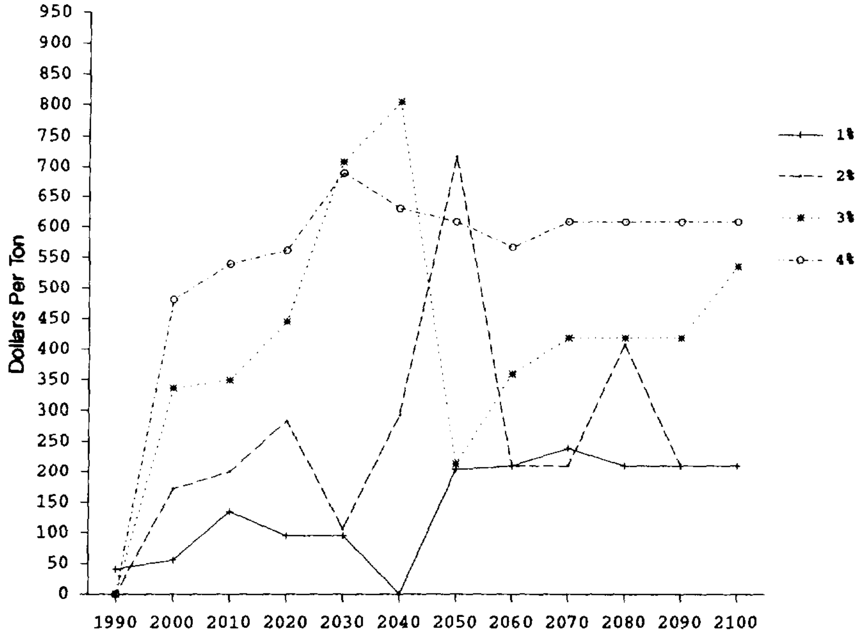

FIG. 7. Carbon taxes in the OECD.

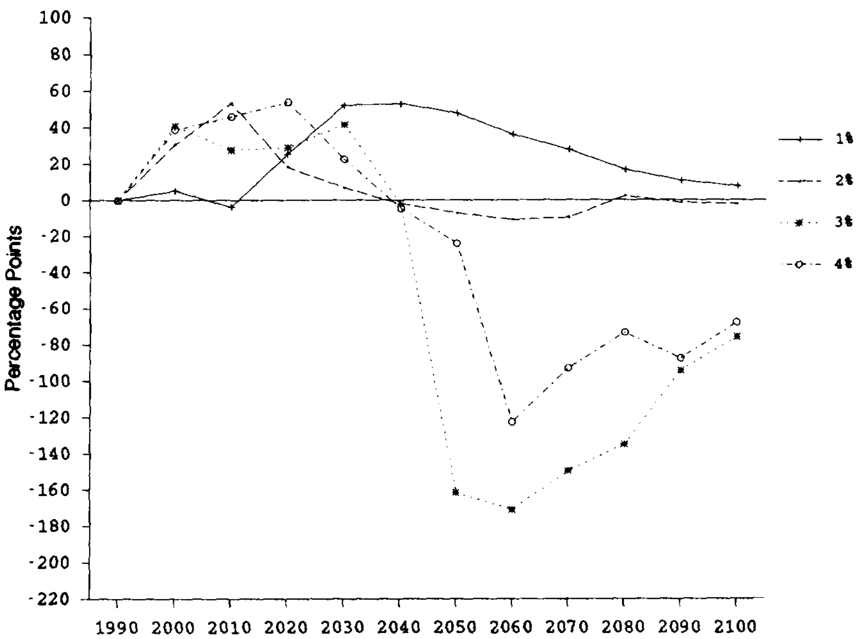

FIG. 8. Marginal leakage rates.

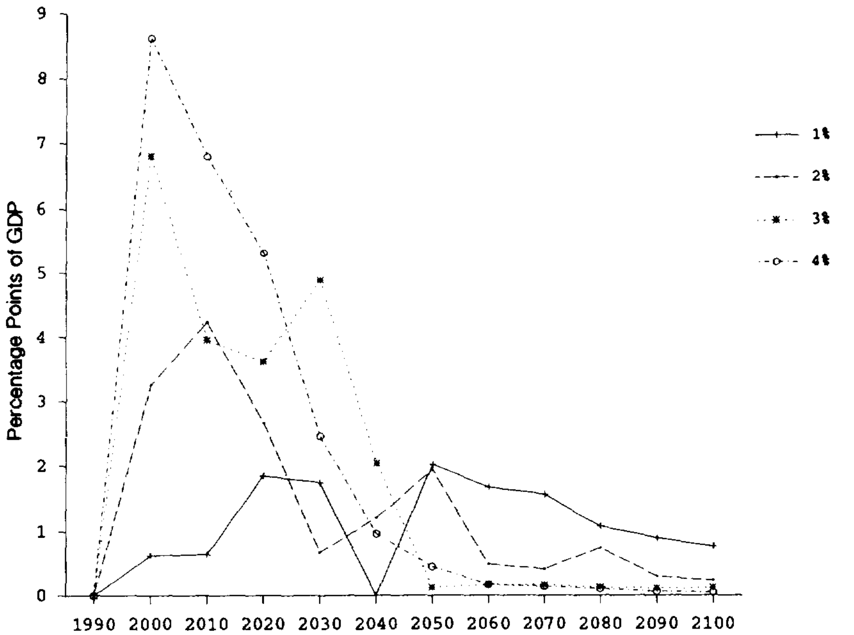

FIG. 9. Welfare costs of unilateral action.

restrictions expressed in the revenues of the carbon tax. Two percent and higher cutbacks increase marginal leakage rates substantially in the first three decades but result in negative marginal rates in the second half of the century. This happens because OECD carbon reductions result in lower levels of fossil fuels consumption and delayed extractions of relatively low carbon oil and gas supplies in the region ROW. As a result, there is significantly lower output of carbon-intensive synthetic fuels in the years 2050–2080 when the OECD drastically reduces carbon emissions.

Figure 9 combines the information of the last two figures and presents the welfare costs of unilateral reductions of carbon emission by the OECD. The costs are calculated according to the equation $\partial W/\partial c$ displayed in Section 3. The figure indicates the costs as percentages of OECD GDP. For the first half of the century, we observe that rising OECD emission reductions produce increasing welfare costs. Drastic (4%) cuts produce welfare costs in the range of 3 to 9% of GDP over this period. In the second half of the century, welfare costs are low and decrease with a rise in OECD carbon cutbacks. This happens because of the marginal leakage rates figures which are explained above.

Figure 10 displays a regional decomposition of the global average leakage rate for a 2% pa unilateral emission cut in the OECD. Global leakage rates rise in the early decades, peak in 2030–2040 at 35%, and steadily decline over the remaining period. Carbon taxes in the OECD reduce aggregate world demand for oil and put a downward pressure on world energy prices. As a consequences, ROW increases its oil imports and delays the extraction of high-cost energy resources and the introduction of backstop technologies. This leads to high leakage rates in the transition to the use of new vintage capacities. Interestingly, for MOPEC we do not observe a delayed tapping of high-cost resources in the counterfactual cases.

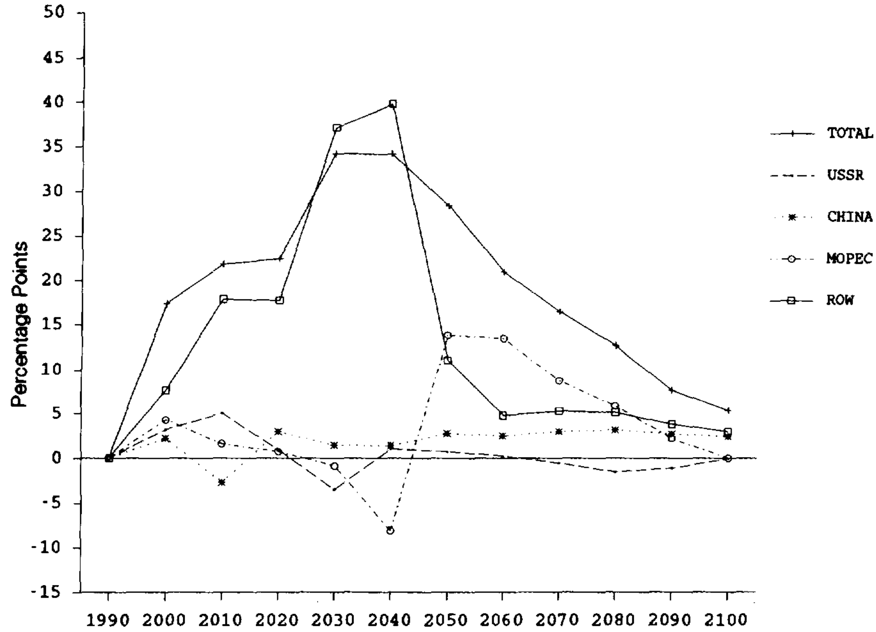

FIG. 10. Global and regional average leakage rates—2% cutbacks.

Instead we see that MOPEC reduces reserve accumulation of high-cost supplies in 2010–2030. Consequently, there is a larger supply of natural gas in the following decades, and hence less demand for synfuel production. This explains the negative leakage rates for MOPEC in 2040 as well as the subsequent jump in the leakage rate. Leakage rates in China and the USSR are very small. This is because their energy markets are virtually decoupled from the world market due to export and import quotas. For more severe unilateral cutbacks by the OECD the pattern of regional contributions to global leakage remains virtually unchanged. It is ROW which determines predominantly the size of global leakage rates.

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 two effects is displayed in Fig. 11. This figure shows the average leakage rates which result from two models. The first is the standard model, with a 2 and 4% emission cut in the OECD. The second model applies an alternative trade structure—one which maintains (by export subsidies) OECD trade in basic materials at exactly the baseline levels throughout the model horizon. In the alternative model structure, carbon leakage arises solely through a price-induced substitution effect. The curves show that both types of leakage are important. This result implies that trade policies designed to prevent migration of basic material production from carbon-constrained to -unconstrained regions do have a negative effect on global carbon emissions. However, the policies must include a higher carbon tax in order to reduce carbon consumption in the sectors which do not produce basic materials.

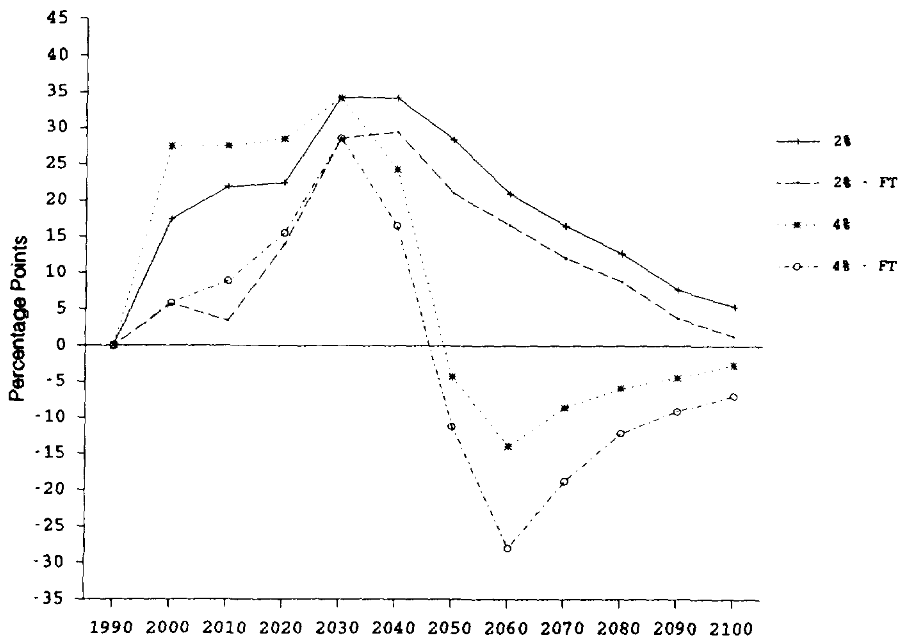

FIG. 11. Leakage rates for alternative model structures.

5. SUMMARY AND CONCLUSION

In this study, we have investigated the implications of international trade linkages in determining the economic effects of unilateral CO_2 emission restrictions. We have analyzed these issues in the context of a recursively dynamic general equilibrium model. The insights which emerge from the simulations are as follows:

(1) The time profiles of carbon emissions from 1990 to 2100 show that electric energy is relatively more carbon intensive than non-electric energy up to the time that a carbon-free electric energy becomes cost effective. The trend in carbon intensity of non-electric 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 synthetics are used to replace oil and natural gas.

(2) Over the period 2000–2050, marginal leakage rates are positive and increase with carbon emission cutbacks in the OECD. Severe (3–4%) cuts produce marginal leakage rates in the range of 40%. Over the period 2060–2100 leakage rates are negative for cuts greater than 1%. This happens because carbon taxes in the OECD delay tapping of high-cost energy supplies and the introduction of carbon-intensive production of synthetic fuels.

(3) The welfare costs of unilateral OECD carbon abatement are substantial for the first half of the century. For this period, welfare costs range between 2 and 8% of CDP for emission cuts between 2 and 4% per annum. Due to negative marginal leakage rates, welfare costs in the second half of the century are below 1% of GDP.

(4) A regional decomposition of leakage reveals that change in carbon emissions in the ROW is the primary factor for leakage. This increase results from an economy-wide increase in energy intensity as well as from a shift toward the production of carbon-intensive goods.

(5) Restrictions on trade in basic materials produce lower leakage rates. In this sense, OECD trade policy can be used to affect emissions in other regions, but this instrument has only limited effectiveness. Trade restrictions to reduce carbon emissions are a poor substitute for a comprehensive global agreement.

These results should be viewed as purely exploratory, given the high degree of uncertainty surrounding the key parameters describing technologies and preferences. Finally, this paper did not consider the benefits of reduced greenhouse gases for current and future generations. The benefits of carbon emission reductions are much more uncertain than the costs. This notwithstanding, it would be interesting to undertake further research along the line of Nordhaus [6], who incorporates estimated damage curves from global warming.

REFERENCES

1. A. Brooke, D. Kendrick, and A. Meeraus, "GAMS: A User's Guide," Scientific Press, San Francisco, CA (1988).
2. Energy Modeling Forum, "Study Design for EMF 12 Global Climate Change: Energy Sector Impacts of Greenhouse Gas Emission Control Strategies," Terman Engineering Center, Stanford University, Stanford, CA (1991).
3. T. F. Rutherford, "Applied General Equilibrium Modeling Using MPS/GE as a GAMS Subsystem," Working Paper 92-15, University of Colorado (1992).
4. A. S. Manne and R. G. Richels, Global CO_2 emission reductions: The impacts of rising energy costs, *Energy J.* **12**, 87–107 (1990).
5. A. S. Manne and R. G. Richels, "Buying Greenhouse Insurance—The Economic Costs of CO_2 Emission Limits," MIT Press, Cambridge, MA (1992).
6. Nordhaus, W. D., To slow or not to slow: The economics of the greenhouse effect, *Econom. J.* **101**, 920–937 (1991).
7. A. Dean and P. Hoeller, "Costs of Reducing CO_2 Emissions: Evidence from Six Global Models," OECD Working Paper 122, OECD Secretariat, Paris (1992).
8. C. Perroni and T. F. Rutherford, International trade in carbon emission rights and basic materials: General equilibrium calculations for 2020, *Scand. J. Econom.*, forthcoming (1993).
9. T. F. Rutherford, General equilibrium modelling with MPS/GE, Mimeo, University of Western Ontario (1989).
10. T. F. Rutherford, "The Welfare Effects of Fossil Carbon Restrictions: Results from a Recursively Dynamic Trade Model," OECD Working Paper 112, OECD Secretariat, Paris (1992).
11. A. Subramanian, Trade measures for environment: A nearly empty box? *World Economy* 135–152 (1992).