Volume Title: Tax Policy and the Economy, Volume 6

Volume Author/Editor: James M. Poterba, editor

Volume Publisher: The MIT Press

Volume ISBN: 0-262-66077-6

Volume URL: http://www.nber.org/books/brad92-1

Conference Date: November 19, 1991

Publication Date: January 1992

Chapter Title: Carbon Tax Design and U.S. Industry Performance

Chapter Author: Lawrence H. Goulder

Chapter URL: http://www.nber.org/chapters/c10840

Chapter pages in book: (p. 59 - 104)

CARBON TAX DESIGN AND U.S. INDUSTRY PERFORMANCE

Lawrence H. Goulder
Stanford University and NBER

EXECUTIVE SUMMARY

This paper examines the effects of a U.S. carbon tax on U.S. industries. We consider alternative tax designs that differ according to the tax treatment of internationally traded goods and the use of tax revenues. The effects of these policy options are explored with a dynamic general equilibrium model of the United States that incorporates international trade.

In general, the burden of a U.S. carbon tax is fairly highly concentrated among a few industries. For these industries, the magnitude of the burden depends critically on the way the tax is designed. The costs to these industries in terms of profits and output are much lower when the tax is introduced on a destination basis (i.e., based on carbon emissions associated with the consumption or use of fuels) than when it is introduced on an origin basis (i.e., based on emissions associated with the production or supply of fuels). On the other hand, for a given tax rate the economy-wide costs are higher when the tax is destination-

This paper was prepared for the NBER Conference on Tax Policy and the Economy, Washington, D.C., November 19, 1991. I am grateful to Lans Bovenberg, Harry Huizinga, Alan Manne, Ron McKinnon, Jim Poterba, and Robert Staiger for helpful suggestions, to Miguel Cruz for excellent research assistance, and to the National Science Foundation (Grant SES-9011722) and Stanford University Center for Economic Policy Research for financial support.

based, reflecting the fact that the nation's "emissions consumption" exceeds its "emissions production."

There are various degrees to which policy makers could implement the destination principle in a carbon tax. This choice critically influences the extent to which the tax preserves "international competitiveness" as well as the administrative feasibility of the tax. One option is to apply the destination principle selectively, imposing the tax on the limited number of carbon-based products with "significant" carbon content. This gives rise to a partial destination-based tax. Such a tax would avert the most serious potential costs in terms of international competitiveness while avoiding the substantial administrative costs that a full destination-based carbon tax could entail. At the same time, the partial destination-based tax could achieve over 90 percent of the reduction in U.S.-consumption-related emissions that would occur under the full destination-based tax.

Using carbon tax revenues to finance cuts in pre-existing distortionary taxes reduces, but does not eliminate, the adverse consequences of the carbon tax policy for industry profits and investment. Aggregate efficiency results suggest that a carbon tax must inevitably generate losses to at least some industries.

I. INTRODUCTION

The past few years have witnessed a dramatic increase in concerns about the extent to which emissions of carbon dioxide (CO_2) and other greenhouse gases might magnify the greenhouse effect and bring about global climate change. These concerns have prompted law makers to consider public policies that limit or discourage production and consumption activities that contribute to emissions of greenhouse gases. One such policy is a carbon tax, a tax on fossil fuels based on their carbon content. Carbon dioxide emissions generally are proportional to carbon content; hence a carbon tax is effectively a tax proportional to the CO_2 emissions generated from the use of fossil fuels.[1]

The environmental benefits from carbon tax-induced reductions in CO_2 emissions need to be weighed against the economic costs that the tax would introduce. These costs include aggregate economic losses, which can be expressed in terms of such macroeconomic variables as GNP and aggregate consumption.[2] The distribution of these costs is also

[1] For a general discussion of the rationale for and potential effects of carbon taxes, see Goulder (1990), Lave (1991), and Poterba (1991).

[2] Several recent studies have employed simulation models to assess the aggregate costs of achieving reductions in CO_2 emissions through carbon taxes. See, for example, Goulder (1991a), Jorgenson and Wilcoxen (1990), and Manne and Richels (1990a, 1990b).

a critical policy consideration. It is important to know, in particular, the extent to which the economic burdens of the tax are concentrated in particular industries. It is also useful to assess the extent to which industries might shift the burden of the tax on to consumers. And it is important to understand the effects of the taxes on the ability of domestic firms to compete in the international marketplace. This paper examines these distributional effects.

Policy makers have several options in the design of a carbon tax. Important choices must be made regarding the application of the tax to internationally traded goods and the use of the revenues gained from the tax. In this paper we examine the importance of these different aspects of tax design to industry profits and to the potential of various industries to compete internationally.

To evaluate these effects, the paper applies a simulation model of the U.S. economy incorporating international trade. The model is general equilibrium in nature, enabling it to capture interactions across industries and between factor and product markets. The model also has a dynamic focus, with intertemporal decision making by firms and households, permitting an assessment of how the effects of taxes change over time as households and firms alter their supplies and demands.

The model is unique in combining three features critical to evaluating the inter-industry and international effects of carbon taxes. First, it contains a detailed treatment of U.S. taxes. The model addresses effects of taxes on investment incentives, equity values, industry profits, and savings decisions. Second, the model isolates major energy inputs and products, and incorporates important margins for substituting carbon-intensive products for other products when relative prices change. Such substitutions occur at both the industry and household level. Third, the model provides for international trade in both industry imputs and consumer goods. It considers how U.S. exports and imports of these goods change in response to changes in the relative prices of U.S. and foreign goods. This combination of features is especially useful for examining the implications of different types of carbon taxes for the distribution of the tax burden and "international competitiveness."

The rest of the paper is organized as follows. Section II discusses important issues related to the design of carbon taxes, indicating the potential significance to industries of the tax treatment of internationally traded goods and the use of tax revenues. Section III describes the simulation model used to evaluate the tax options, and Section IV presents and interprets results from the simulation experiments. Finally, Section V offers conclusions.

II. ISSUES IN TAX DESIGN

A. Basic Issues

It is generally recognized that, of the "greenhouse gases," carbon dioxide makes the largest contribution to the greenhouse effect. The U.S. Environmental Protection Agency (1989) estimates that increases in the atmospheric stock of CO_2 account for about half of the increase in radiative warming attributable to human activities. The CO_2 contribution (both relative and absolute) to such warming is expected to rise over the next century as CO_2 emissions grow. About 23 percent of global emissions of CO_2 stem from U.S. sources, and about 95 percent of U.S.-sourced emissions are generated by the combustion of fossil fuels—coal, oil, and natural gas.[3] The link between fossil fuel burning and CO_2 emissions is a rigid one: CO_2 emissions are an inevitable consequence of fossil fuel combustion. These considerations imply that any policy aimed at reducing the U.S. contribution to the greenhouse effect must confront the use of fossil fuels.

A carbon tax is one policy instrument for discouraging fossil fuel consumption. Such a tax can be justified on efficiency grounds. The environmental costs associated with fossil fuel use are largely external to the agent using the fuels.[4] Thus, in markets for fossil fuels, private costs may fail to capture all social costs.[5] Under these circumstances, the social value of reducing fossil fuel use may exceed the social costs of abatement. The carbon tax can be introduced as a corrective tax which, by internalizing costs that otherwise would be external to market decisions, promotes reduced fossil fuel use.

The externality here is associated with the quantity of CO_2 emissions.[6] The ratio of CO_2 emissions to carbon content of the fossil fuel is virtually the same for all uses of fossil fuels. Thus a tax whose value is based on the carbon content of a given fossil fuel is effectively a tax proportional to

[3] See World Resources Institute (1990, Table 24.2). Fossil fuel burning is the principal contributor to CO_2 emissions in most industrialized countries. The other important contributor is the burning of vegetation. This factor is significant in countries such as Brazil in which deforestation activities constitute a large portion of overall economic activity.

[4] The external costs from fossil fuel combustion include not only the environmental effects in terms of global climate change but also local air pollution. The former externalities are most relevant to CO_2 emissions and a carbon tax. The other externalities could provide an efficiency rationale for other taxes on fossil fuels.

[5] Whether private costs fall short of social costs depends on the extent of other pre-existing fuel taxes as well as the extent of other distortions in the economy.

[6] The external costs associated with a given emission of CO_2 need not be assumed to be constant through time. How the costs change depends on complex relationships between CO_2 emissions, CO_2 stocks, and the radiative warming. Peck and Teisberg (1991) discuss and evaluate these relationships.

CO_2 emissions.[7] Since the environmental damages depend on the quantity and not the value of carbon that is burned, efficiency considerations call for designing the carbon tax as a specific (or unit) tax, not as an *ad valorem* tax.

The value of the climate-change-related marginal damages associated with fossil fuel combustion is not known. The uncertainties here are vast.[8] Because the marginal damages are not known, no one can justifiably claim to know the magnitude of the "optimal" carbon tax.[9] One of the few "certainties" related to carbon taxes is that policy makers would need to make adjustments over time: If a carbon tax were to be introduced, it would be reasonable to alter the value of the tax rate in the future as more information became available.[10]

B. Multilateral versus Unilateral Policies and the Treatment of Traded Goods

A carbon tax would raise unit costs to producers of fossil fuels and to users of fossil-fuel-intensive products. If the tax were implemented worldwide at a uniform rate, for given industries the global distribution

[7] A complication arises from the fact that not all of the carbon in fossil fuels is burned. In the U.S., however, the share of carbon that is not combusted is quite small, less than 5% (see OECD/IEA, 1991). Carbon combustion can occur either through the burning of the fossil fuel or through the combustion of a derivative refined fuel. Carbon that is not combusted resides in "feedstocks" or nonfuel products made from fossil fuels. Because the carbon in feedstocks does not contribute to CO_2 (except, perhaps, when these products are incinerated after their useful economic life), there is little rationale for applying a carbon tax here. Thus if a carbon tax is introduced as a tax on fossil fuels, it would seem reasonable to accompany this tax with a rebate to users of feedstock carbon, with the rebate proportional to the carbon content in the feedstock.

[8] Pioneering work to assess the economic value of these benefits has been performed by Nordhaus (1990). The U.S. Environmental Protection Agency recently has begun to devote considerable resources to the study of this issue.

[9] Calculation of the optimal carbon tax rate generally will require other information in addition to the marginal external damages from fossil fuel burning. The literature on optimal taxation in the presence of externalities (see, for example, Sandmo, 1975) indicates that the optimal tax structure must consider not only the externality associated with a good's consumption but also the compensated elasticities of demand for the taxed good and other goods with respect to the price of the taxed good. If the social welfare function assigns different weights to the utilities of different individuals, then the optimal tax also depends on the distribution of the taxed good's consumption across different individuals. These considerations indicate that the optimal carbon tax generally will not involve the same tax per unit of carbon content for different fossil fuels.

[10] This suggests that carbon tax policies that preserve flexibility will often have an advantage over policies that remove future options. It also means that deciding on the appropriate carbon taxes today is fundamentally a problem of decision making under uncertainty, in which upside and downside risks of alternative options need to be considered. For one analysis of this issue, see Manne and Richels (1992).

of the changes in unit costs would be relatively uniform as well. The effects of the tax on the international competitive position of firms in given industries would be relatively small.[11] This is one attraction of multilateral carbon tax policies relative to unilateral initiatives. A multilateral approach also has the virtue of efficiency.[12] Global efficiency is served to the extent that marginal costs (including external costs) and benefits approach equality in all uses of fossil fuels in all regions of the globe. Uncoordinated, unilateral policies involving different tax rates would probably be less efficient.

Multilateral agreements are likely to be hard to achieve, however, for at least two reasons. First, the net benefits from multilateral carbon tax policies would be distributed very unevenly across countries. Large international transfers of funds would be necessary to make the distribution more even. Countries whose net transfers would be negative might be reluctant to support such schemes. Second, even if international transfers could be guaranteed, individual countries would often have incentives to spurn international agreements and act as free riders. Even though all countries could benefit from multilateral action in which all countries impose a carbon tax, a given country might do even better by free riding on an agreement reached by a number of other countries. The incentives to free ride are particularly strong for small countries who would enjoy only a small share of the environmental benefits related to their own emissions reductions.[13]

[11] There would still be some international competitiveness effects to the extent that firms in given industries differ across countries in their reliance on fossil fuels as inputs.

[12] It is important to recognize the sense in which "efficiency" is used here. If a multilateral carbon tax policy causes the marginal costs of emissions reductions to be equated throughout the globe, it will achieve efficiency in the sense that the global emissions reductions will have been attained at minimum cost. A broader notion of efficiency must confront the issue of whether the global reductions were too extensive or inadequate, that is, whether the global carbon tax policy was too severe or too weak. The fact that action has been taken multilaterally does not guarantee efficiency in this broader sense. A general equilibrium efficiency assessment would also consider production complementarities between taxed and untaxed goods, as indicated in Footnote 9.

This discussion of efficiency issues is not meant to suggest that global efficiency should be the only consideration in evaluating carbon tax policies. Distributional issues, for example, the distribution of costs of emissions reductions between richer and poorer countries, are critical as well.

[13] Recent experience suggests that this account of the incentives to small countries may be somewhat narrow. The countries that have already introduced policies resembling carbon taxes include Finland, Sweden, the Netherlands, and Germany. Except for Germany, these are small countries that, according to the present analysis, would have little to gain from such actions. Casual observation suggests that these actions have been taken in part to set an example for other nations to follow. Strong unilateral policies by small countries are rational to the extent that they increase the likelihood that other nations will follow suit.

As emphasized by Poterba (1991), the difficulties in reaching agreements for multilateral action make it reasonable for U.S. policy makers to contemplate unilateral policies even while considering potential multilateral initiatives. A given nation can improve its well being through a unilateral carbon tax, despite the fact that some (and perhaps most) of the environmental benefits from the policy will spill over to other countries.

C. Is A Carbon Tax That Safeguards International Competitiveness Administratively Feasible?

Unilateral policies present special challenges related to the impacts on industries significantly affected by international trade. Consider first an origin-based carbon tax, one that is levied only on domestic producers of fossil fuels. This tax could be imposed at the wellhead for oil and gas and at the mine mouth in the case of coal. By raising their costs, such a tax would put domestic producers at a significant disadvantage relative to their foreign competitors. An alternative is a destination-based tax. This tax applies to carbon that is consumed domestically. The destination (location of consumption) of the carbon, rather than the origin of its production, is the basis of this tax.

A destination-based tax can avoid cost disadvantages that the origin-based tax would impose on domestic producers in home and international markets. There are two potential ways to introduce a destination-based carbon tax. One way is by combining a tax on domestically produced fossil fuels with import levies and export subsidies for traded goods. Import levies and export subsidies would apply to traded fossil fuels according to their carbon content. The import levies would assure that imported fuels faced the same tax as domestically produced fuels consumed at home; the export subsidies would assure that domestically produced fuels devoted to the export market did not face the tax. To eliminate adverse effects on domestic producers of fossil-fuel-intensive products (for example, refined petroleum), the destination-based tax policy would need to include import levies and export subsidies for these products as well as for traded fossil fuels. Imported carbon-based products would need to be taxed according to their carbon content; this would avoid the potential cost disadvantage to domestic producers of carbon-based products. Similarly, exports of carbon-based products would receive a subsidy to offset the cost increase that the increase in fuel costs would otherwise bring about; this would help prevent a competitive disadvantage in the export market.

The second way to implement a destination-based tax appears more straightforward. Here the tax is implemented as one on all final goods purchased domestically, with the tax rate based on carbon content of the final goods. With the same tax rate per unit of carbon, this destination-based tax is equivalent to the first approach involving a fossil fuel tax plus import levies and export subsidies.

In designing a destination-based carbon tax, it helps to distinguish original and absorbed carbon. Original carbon is the carbon naturally contained in fossil fuels. The absorbed carbon of a unit of a given good is the amount of carbon contained in the fossil fuels used directly and indirectly in the manufacture of a unit of the good in question. The actual combustion of absorbed carbon may take place in the manufacturing process (as in the burning of coal to produce steel) or in the final use of a fossil-based product (as in the burning of home heating oil or other refined petroleum products).[14] If a tax were imposed on fossil fuels according to their (original) carbon content, the effect on production costs in a given industry will depend on the total carbon—original plus absorbed—in the goods manufactured by the industry. Appendix A describes in detail the method for evaluating the original and absorbed carbon content of produced goods and the relationship between carbon content and the costs of a carbon tax.

An attraction of the destination-based carbon tax is that it can avoid the direct adverse effects on international competitiveness that can result under the origin-based tax. At the same time, serious questions arise as to the administrative practicality of a full-fledged destination-based tax. Establishing carbon content can be especially difficult if production technologies differ across producers or change significantly with advances in knowledge or new economic conditions. If a destination-based tax were introduced as a domestic fossil fuel tax combined with import levies and export subsidies, the policy would require information on the carbon content of all traded goods. If introduced as a tax on carbon content of final goods consumed, the policy would require information on the carbon content of all final goods. Under either approach, the large numbers of goods involved and the difficulties of establishing carbon content call into question the feasibility of the policy.

The administrative problems are especially daunting under the approach that combines a fossil fuel tax with tariffs and subsidies for traded goods. The difficulties of ascertaining the carbon content of imported goods create scope for exploiting the uncertainties in imposing unjustifiably high tariff rates; this would abuse the environmental basis of the

[14] The amount of absorbed carbon in a given good includes the carbon content of fossil fuels used directly in production as well as the fossil fuels used indirectly in production, that is, the fossil fuels used to create other inputs in the production process. Thus, for example, the absorbed carbon in a unit of steel includes not only the carbon in the coal inputs to steel but also the carbon in the (fossil fuel) inputs to the inputs to steel.

policy and constitute protectionism under another name.[15] Moreover, under current arrangements under the General Agreements on Tariffs and Trade (GATT), the United States does not have the flexibility to levy additional, carbon-based tariffs on many products, since for many important products existing rates are already at the limits negotiated under the GATT.[16]

Do these problems make a destination-based policy impractical? The answer may depend on how fully one wishes to apply the destination principle. A full destination-based carbon tax may be prohibitively costly to administer, but a partial destination-based tax may still be practical. The practicality depends critically on the extensiveness of the set of goods with "significant" carbon content. If relatively few goods have significant carbon content, then it might make sense to design a destination-based tax that applies only to these goods (either through a fossil fuel tax plus import levies and subsidies or through a tax on consumption). A carbon tax that applies the destination principle to this limited set of goods might maintain the advantage of destination-based taxes in terms of preserving international competitiveness while remaining administratively feasible.

To begin an exploration of this issue, we present in Table 1 the overall carbon content of the industrial products and consumer goods contained in the model. This content was evaluated using the procedure described in Appendix A. Several findings emerge from the table. First, total embodied carbon content (per dollar of output) is highly concentrated among a few outputs: extracted fossil fuels, refined petroleum products, and electricity. The percentage cost increases from a given carbon tax are similarly concentrated. For consumer goods other than gasoline, a carbon tax would imply a very small cost increase compared with the increase for primary fuels.

The impact on unit costs is not the only relevant consideration in evaluating the impact of a carbon tax on competitiveness. It also is important to take account of the volume of trade. A domestic industry with a significant cost increase suffers no loss of international competitiveness if it is not involved in international trade; a domestic industry with a modest cost increase can suffer a significant loss if it faces stiff competi-

[15] Some might argue that the move from an origin-based to a destination-based carbon tax constitutes protectionism as well. It is difficult to define where protectionism begins.

[16] This is one issue within the broad class of issues concerning the relationship between international trade policies and international environmental concerns. Previous GATT negotiations largely have ignored environmental objectives, but trade negotiators are now beginning to recognize the need for integrating environmental goals with other important international trade objectives.

TABLE 1.
Distribution of Carbon Content and Tax Cost Across Industry and Consumer Good Categories of the Model.

	Carbon Content Per Dollar of Output (10^{-3} metric tons)			Pct. Cost Increase Per Dollar of Carbon Tax	1990 Imports ($ bill.)	Import-Weighted Cost Share	1990 Exports ($ bill.)	Export-Weighted Cost Share
	Original	Absorbed	Total					
A. Industry (and product)								
Agriculture and noncoal mining	0.00	0.06	0.06	0.004	3.7	0.02	21.0	0.32
Coal mining	22.88	5.96	28.84	2.878	0.1	0.69	5.5	64.48
Oil and gas extraction	5.56	0.65	6.21	0.620	71.9	76.34	0.0	0.00
Synthetic fuels	9.82	0.65	10.47	1.045	0.0	0.00	0.0	0.00
Petroleum refining	0.00	3.92	3.92	0.386	23.0	15.19	11.1	17.46
Electric utilities	0.00	2.77	2.77	0.267	0.7	0.32	0.1	0.12
Gas utilities	0.00	2.12	2.12	0.208	3.7	1.31	0.4	0.32
Construction	0.00	0.26	0.26	0.021	0.0	0.00	0.1	0.01
Metals and machinery	0.00	0.11	0.11	0.009	91.3	1.40	62.2	2.27
Motor vehicles (transportation equipment)	0.00	0.17	0.17	0.011	14.5	0.28	0.0	0.00
Miscellaneous manufacturing	0.00	0.22	0.22	0.017	138.7	4.13	131.3	9.32
Services (except electricity and gas)	0.00	0.20	0.20	0.018	10.1	0.31	78.2	5.70
Total					357.7	100.00	309.9	100.00

B. Consumer Good

Food	—	0.21	0.21	0.017	93.2	30.54	42.2	51.18
Alcohol	—	0.21	0.21	0.017	5.6	1.84	2.5	0.19
Tobacco	—	0.21	0.21	0.018	6.7	2.22	3.0	0.26
Utilities	—	1.74	1.74	0.170	0.2	0.52	4.0	0.08
Housing	—	0.03	0.03	0.002	0.0	0.00	0.9	0.00
Furnishing	—	0.23	0.23	0.019	15.4	5.58	7.5	1.67
Appliances	—	0.21	0.21	0.017	15.8	5.22	6.7	1.39
Clothing	—	0.21	0.21	0.018	39.0	12.94	17.2	8.85
Transportation	—	0.20	0.20	0.018	0.0	0.00	2.1	0.00
Motor Vehicles	—	0.19	0.19	0.015	63.5	18.15	37.3	26.91
Services	—	0.20	0.20	0.018	0.2	0.06	10.9	0.03
Financial Services	—	0.20	0.20	0.018	0.0	0.00	7.3	0.00
Recreation	—	0.39	0.39	0.035	23.4	15.63	11.2	6.96
Personal Care	—	0.21	0.21	0.018	15.7	5.17	5.8	1.20
Gasoline	—	2.69	2.69	0.265	0.0	0.00	2.0	0.00
Health	—	0.21	0.21	0.018	6.3	2.12	15.2	1.28
Education	—	0.20	0.20	0.018	0.0	0.00	2.4	0.00
Total					285.0	100.00	178.4	100.00

Notes: Carbon content calculated from 1986 U.S. input-output tables from the February 1991 *Survey of Current Business* and from data on fossil fuel carbon content provided by the Stanford University Energy Modeling Forum (Weyant, 1991). Technique for calculating original and absorbed carbon content and tax cost is described in Appendix A.

tion from imports or devotes a large share of its output to the export market. A rough way to account for the trade dimension is to weight the cost increase by the relative volume of imports or exports. The third-to-last and last columns of Table 1 provide the trade-weighted cost effects. These effects are somewhat more evenly distributed than the unweighted effects. The carbon tax's impact on the metals and machinery industry, in particular, becomes much more significant given the large volumes of imports of such products. Still, for the majority of industries, the carbon tax impact is relatively insignificant. This suggests that a destination-based carbon tax which applies to a fairly limited number of carbon-based products would avert most of the adverse effects on international competitiveness that could arise under an origin-based tax.

Using more disaggregated categories for industries and goods, one can obtain a sharper view of the distribution of carbon content and cost shares. Table 2 provides information similar to that in Table 1, but uses the more detailed industry categories contained in the input-output tables prepared by the Bureau of Economic Analysis of the U.S. Department of Commerce. The input-output tables distinguish eighty-five industries; in Table 2 we list the twenty industries for which a given carbon tax would have the largest cost effect, where the effect here is the product of the percentage cost increase and the volume of imports or exports. The results in Table 2 largely conform to the results under the more aggregated industry categories in Table 1. The percentage cost increases from a given carbon tax are again highly concentrated among a few industries. The trade-weighted cost effects are somewhat more evenly distributed than the unweighted effects, but they are still concentrated in a few industries. Twenty of the eighty-five industries account for over 87 percent of the import-weighted costs, and over 85 percent of the export-weighted costs.

Although the numbers in Tables 1 and 2 are informative, they do not fully convey the likely distribution and overall magnitude of international competitiveness effects from various carbon taxes. One reason is that the tables provide no information on potential behavioral responses to the carbon tax, specifically changes in demand patterns occasioned by changes in the relative prices of domestic and foreign intermediate and consumer goods. A closer assessment of these effects requires attention to policy-induced changes in trade volumes, domestic output levels, and market shares. In Section IV I assess these changes using a simulation model. It should also be kept in mind that aggregation of industries can mask important effects. An even more disaggregated analysis than that provided in Table 2 might reveal some new industries with substantial carbon content.

TABLE 2.
Distribution of Carbon Content and Tax Cost Across BEA Industry Classifications.

A. Industries Ranked by Import-Weighted Cost Share

BEA input-output classification	*Carbon content per dollar of output (*)*	*Pct. cost increase per dollar of carbon tax*	*1986 imports ($ bill.)*	*Import-weighted cost share*
08 Crude petroleum and natural gas	6.14	0.612	21.4	36.11
31 Petroleum refining and related industries	3.60	0.347	14.3	13.68
59 Motor vehicles and equipment	0.51	0.042	73.0	8.51
37 Primary iron and steel manufacturing	1.92	0.179	10.1	5.00
27 Chemicals and selected chemical products	1.34	0.119	10.3	3.37
18 Apparel	0.54	0.045	21.9	2.73
56 Radio, TV, and communication equipment	0.49	0.039	22.7	2.41
57 Electronic components and accessories	0.91	0.074	11.3	2.32
14 Food and kindred products	0.46	0.041	16.5	1.88
24 Paper and allied products, except container	0.94	0.084	8.1	1.86
68 Private electric, gas, water and sanitary	2.39	0.231	2.7	1.74
51 Office, computing and accounting machines	0.51	0.042	14.6	1.68
32 Rubber and miscellaneous plastics products	0.85	0.073	7.6	1.53
38 Primary nonferrous metals manufacturing	0.91	0.077	6.9	1.48
64 Miscellaneous manufacturing	0.42	0.035	14.4	1.40
36 Stone and clay products	0.86	0.079	4.0	0.86
16 Broad and narrow fabrics, yarn and others	1.05	0.089	3.3	0.80
34 Footwear and other leather products	0.43	0.035	7.9	0.75
42 Other fabricated metal products	0.58	0.050	5.5	0.75
63 Optical, opthalmic, and photographic equipment	0.47	0.039	6.2	0.66
Rest of the Sectors	0.50	0.042	222.4	10.49
Total			505.2	100.00

B. Industries Ranked by Export-Weighted Cost Share

BEA input-output classification	*Carbon content per dollar of output (*)*	*Pct. cost increase per dollar of carbon tax*	*1986 exports ($ bill.)*	*Export-weighted cost share*
07 Coal mining	27.54	2.734	3.2	37.68
31 Petroleum refining and related industries	3.60	0.347	6.5	9.64
27 Chemicals and selected chemicals products	1.34	0.119	15.0	7.56
69 Wholesale and retail trade	0.33	0.031	35.0	4.55
08 Crude petroleum and natural gas	6.14	0.612	1.5	3.99
59 Motor vehicles and equipment	0.51	0.042	16.9	3.04
51 Office, computing and accounting equipment	0.51	0.042	15.1	2.66
65 Transportation and warehousing	0.31	0.027	22.5	2.59
60 Aircraft and parts	0.35	0.030	19.3	2.48
28 Plastics and synthetic materials	1.49	0.127	4.5	2.42
57 Electronic components and accessories	0.91	0.074	7.5	2.38
14 Food and kindred products	0.46	0.041	12.1	2.13
24 Paper and allied products, except container	0.94	0.084	4.2	1.49
70 Finance and insurance	0.23	0.021	12.5	1.14
32 Rubber and miscellaneous plastics products	0.85	0.073	3.3	1.02
56 Radio, TV and communication equipment	0.49	0.039	5.3	0.87
37 Primary iron and steel manufacturing	1.92	0.179	1.1	0.86
45 Construction and mining machinery	0.49	0.041	4.8	0.85
38 Primary nonferrous metals manufacturing	0.91	0.077	2.6	0.85
49 General industrial machinery equipment	0.48	0.041	3.6	0.62
Rest of the Sectors	0.76	0.023	208.0	11.20
Total			404.6	100.00

*10^{-3} metric tons

Note: This table employs 1986 data, while Table 1 used 1986 data updated to 1990. The updating procedure generates some differences in carbon content across the two tables.

D. *Revenue Use*

Another important consideration in the design of a carbon tax is how its revenues might be used. One potential use of the revenues would be to finance reductions in other taxes. For example, the revenues could be used to pay for cuts in the corporate income tax. For many industries—particularly those with a relatively modest reliance on fossil fuel inputs—the corporate tax cut could neutralize all of the cost increase implied from the carbon tax.

Using the revenues to finance cuts in other taxes could generate general efficiency benefits as well as reduce the tax burden to particular industries. To the extent that carbon tax revenues are used to reduce other taxes that are highly distortionary, the cut in other taxes avoids tax distortions and leads to efficiency gains over and above the gains from more efficient use of fossil fuels.[17]

Thus, the use of carbon tax revenues, as well as the treatment of imports and exports, are important aspects of the design of a carbon tax. Alternative tax designs could lead to quite different outcomes in terms of the domestic and international distribution of the tax burden. In Section IV we examine numerically the industry effects of these alternative design options. The numerical results stem from the simulation model that I now briefly describe.

III. THE SIMULATION MODEL

I assess the effects of a carbon tax using a general equilibrium model of the United States, which incorporates international trade. Here I sketch out some main features of the model. Some details on the model's structure and parameters are offered in Appendix B. A more complete description is in Goulder (1991a, 1991b).

The model generates paths of equilibrium prices, outputs, and incomes for the U.S. economy under specified policy scenarios. These variables are calculated at yearly intervals beginning in the 1990 benchmark year and usually extending to the year 2065.

[17] Other possibilities are using the revenues to finance increases in federal government spending and using the revenues to reduce the federal debt. The latter alternative is equivalent to reducing future taxes, assuming that the government's debt cannot indefinitely grow faster than the interest rate (see, for example, Barro, 1979). Intuitively, reducing the government debt implies that future interest payments to service the debt will be lower. Hence, lower future taxes will be sufficient to meet the government's spending needs plus interest obligations.

A. The Production Sector

The model divides the U.S. production sector into 13 industries corresponding to the industry goods given in Table 1. The model also distinguishes the 17 consumer goods indicated in Table 1.

Each industry produces a distinct output (X), which is a function of inputs of labor (L), capital (K), an energy composite (E), and a materials composite (M), as well as the current level of investment (I):

$$X = f[g(L,K), h(E,M)] - \phi\,(I/K) \cdot I \tag{1}$$

The energy composite is made up of the outputs of the energy industries, while the materials composite is made up of the outputs of the other industries. Each of the individual inputs ($\bar{x}_1$, $\bar{x}_2$, etc.) making up E and M is, in turn, a composite of a domestic and foreign good from the given industry.[18]

In each industry, managers are assumed to serve stockholders by choosing inputs of labor, energy, and materials, and levels of investment to maximize the value of the firm. The optimal choices of labor and intermediate inputs minimize unit costs. The production system allows for substitutions among inputs at several levels. For example, when the relative price of a given energy input rises, producers generally reduce the relative intensity of use of that input, substituting other, less expensive energy inputs.[19] Similarly, when a domestic input rises in price relative to its foreign counterpart, producers tend to increase the use of the foreign input relative to the domestic input.

A distinguishing feature of the model is its attention to capital adjustment dynamics. In equation (1), $\phi(I/K) \cdot I$ represents capital adjustment (or installation) costs; these are an increasing function of the rate of investment.[20]

[18] The functions f, g, and h, and the aggregation functions for the composites E, M, and $\bar{x}_i$, are CES in form. Consumer goods are produced by combining outputs from the thirteen industries in given proportions.

[19] The model allows for complementarities in production, so that in some cases an increase in the price of a given input will, other things equal, reduce the quantity demanded of some other input.

[20] The cost function, ϕ, represents adjustment costs per unit of investment. This function is convex in I/K (see Appendix B) and expresses the notion that installing new capital necessitates a loss of current output, as existing inputs (K, L, E and M) that otherwise would be used to produce output are diverted to install the new capital. Here adjustment costs are internal to the firm. For a discussion of this and other adjustment cost specifications, see Mussa (1978). In choosing the optimal rate of investment, producers must balance the marginal costs of current investment (both the acquisition costs and installation

B. Special Features of the Oil-Gas and Synfuels Industries

1. Stock Effects in the Oil and Gas Industry. The production structure in the oil and gas industry is somewhat more complex than in other industries to account for the nonrenewable nature of oil and gas stocks. The production specification is:

$$X = \gamma(Z) \cdot f[g(L,K), h(E,M)] - \phi(I/K) \cdot I \tag{2}$$

where γ is a decreasing function of Z, the amount of cumulative extraction (or output) of oil and gas up to the beginning of the current period. The presence of $\gamma(Z)$ in the production function distinguishes the oil and gas industry from other industries. The function γ is decreasing in Z. This captures the fact that as Z rises (or, equivalently, as reserves are depleted), it becomes increasingly difficult to extract oil and gas resources, so that greater quantities of K, L, E, and M are required to achieve any given level of extraction (output). Increasing production costs ultimately induce oil and gas producers to shut down their operations.[21]

2. Emergence of a Backstop Technology. The model incorporates a synthetic fuel, shale oil, as a backstop resource, a perfect substitute for oil and gas. The parameters of the synfuels production function are chosen so that, with real prices of inputs at 1990 levels, it costs $50 to produce the quantity of synfuels with an energy content equivalent to that of a barrel of oil. For comparison, the 1990 price of a barrel of oil was just under $24. As in other industries, in the synfuels industry producers choose input and investment levels to maximize the equity value of the firm. There is, however, one difference. The technology for producing synthetic fuels on a commercial scale is assumed to become known only in the year 2010. Thus, capital formation in the synfuels industry cannot begin until the year 2010. The rate of capital formation and the level of production of synfuels depend directly on the price of oil and gas.

All domestic prices in the model are endogenous, except for the domestic price of oil and gas. The latter is given by the exogenous world price of oil and gas plus whatever oil tariff may apply. This world price is specified as $24 per barrel in 1990 and as rising in real terms by $6.50 per

costs of new capital) with the marginal benefits (the stream of increased dividends made possible by a higher future capital stock).

[21] For a detailed presentation of the economic considerations involved, see Goulder (1991b).

decade.[22] At any given point in time, the supply of imported oil and gas is taken to be perfectly elastic at the given world price. So long as imports are the marginal source of supply to the domestic economy, domestic producers of oil and gas receive the world price (adjusted for tariffs or taxes) for their own output. But rising oil and gas prices stimulate investment in synfuels. Eventually, synfuels production plus domestic oil and gas supply together satisfy all of domestic demand. Synfuels then become the marginal source of supply, and the cost of synfuels production rather than the world oil price dictates the domestic price of fuels.[23]

The gradual replacement of conventional oil and gas fuels by synthetic fuels is significant in a study of the carbon tax because the carbon content of synthetic fuels differs from that of oil and gas. The transition from conventional oil and gas to synfuels tends to make the economy more carbon-intensive and contributes to a gradual increase in the carbon tax base.[24]

C. The Household and Government Sectors

Consumption, labor supply, and saving result from the decisions of an infinitely lived representative household that maximizes intertemporal utility, subject to the constraint that the present value of the consumption stream not exceed the value of the household's overall economic resources. In each period, overall consumption expenditure is allocated across the seventeen types of consumer goods. In most cases, each type includes both domestically produced and foreign-made products. Changes in relative prices cause households to substitute between domestic and foreign goods of a given type.

The government collects taxes, issues debt, and purchases goods and services (outputs of the thirteen industries). The wide array of tax instruments in the model includes carbon taxes, output taxes, the corporate income tax, property taxes, sales taxes, and taxes on individual labor and capital income.

In the policy experiments in this paper, we require that government

[22] These price assumptions match reference case assumptions of the Energy Modeling Forum (see Weyant, 1991) at Stanford University.

[23] For details, see Goulder (1991a).

[24] The carbon content per unit of energy from synthetic fuels is about 75 percent greater than that of an equivalent energy unit of oil or gas. Another important factor promoting the trend toward increasing carbon intensity is the substitution of coal for oil and gas. Per unit of energy, coal has 21 percent more carbon than oil and 76 percent more carbon than natural gas. Over time, coal is increasingly substituted for oil and gas because (absent policy changes) coal prices are expected to rise more slowly than prices of oil and gas. This reflects the fact that coal reserves are vastly more abundant than those of oil and gas.

spending and the government deficit follow the same path as in the baseline (status quo) simulation. To meet its cash flow requirements, the government must obtain tax revenues equal to the given overall government spending level minus the given government deficit. Depending on the policy experiment desired, either lump-sum tax adjustments or changes in personal or corporate tax rates are applied to assure that the required total tax revenues are generated.

D. *Equilibrium and Growth*

The solution of the model is a general equilibrium in which supplies and demands balance in all markets at each period of time. Thus the solution requires that supply equal demand for labor inputs and for all produced goods,[25] that firms' demands for loanable funds equal the aggregate supply by households, and that the government's tax revenues equal its spending less the current deficit. These conditions are met through adjustments in output prices, in the market interest rate, and in lump-sum taxes or tax rates.[26]

Economic growth reflects the growth of capital stocks and of potential labor resources. The growth of capital stocks stems from endogenous saving and investment behavior. Potential labor resources are specified as increasing at a constant rate. In each period, potential labor divides between hours worked and leisure time in accordance with utility-maximizing household decisions.

E. *Data and Parameters*

Complete data documentation for model is provided in Cruz and Goulder (1991). In the present subsection I indicate the sources for some important data and parameters. The data stem from several sources. Industry input and output flows (used to establish production function share parameters) were obtained from 1986 input-output tables published in the February 1991 *Survey of Current Business*. These tables were also the source for consumption, investment, government spending, import and export values by industry. The year 1990 is the initial period for the simulations of this paper. To obtain 1990 values, we scaled up the

[25] Because oil and gas and synfuels are perfect substitutes, they generate a single supply-demand condition.

[26] When oil and gas imports are the marginal source of supply for the domestic economy, the quantity of these imports is an equilibrating variable, and the oil and gas price is exogenous. Once synfuels become the marginal source of supply (that is, once synfuels drive oil and gas imports to zero), the synfuels price becomes an equilibrating variable. Since agents are forward-looking, equilibrium in each period depends not only on current prices and taxes but on future magnitudes as well.

1986 data using information for major industry groups in the 1991 *Economic Report of the President*. For the oil and gas, coal, and petroleum refining industries, further adjustments were made to make the relative 1990 values correspond closely to relative values projected for 1988 by the OECD (see OECD/IEA, 1990). The carbon content of different fossil fuels was calculated by multiplying the amount of carbon per unit of heat content times the heat content per unit of fuel. The information used here was taken from the *1989 Annual Energy Outlook* published by the U.S. Department of Energy.

Elasticities of substitution for industry production functions were obtained by transforming translog production function parameters estimated by Dale Jorgenson and Peter Wilcoxen. Elasticities of substitution between domestic and foreign goods were obtained by aggregating estimates from Shiells, Stern, and Deardorff (1986).

In the oil and gas industry, the function $\gamma(Z)$ relates output to cumulative extraction, Z. Although most of the model's parameters derive from econometric estimates, in the case of the γ function existing estimates were not available and it was not possible to obtain information sufficient to generate new estimates. A rough calibration method was employed to generate parameters of the $\gamma(Z)$ function: parameters were chosen so that, given current reserves and projected prices of oil and gas, it would cease to be economic to invest in new domestic oil and gas wells after the year 2030. This is in keeping with the projections of Masters et al. (1987). It should be recognized that because this calibration procedure makes use of projections about future costs and reserves rather than observed magnitudes, the uncertainty bands on the chosen parameters are especially wide.

Appendix B indicates functional forms and lists parameter values for the production and household sectors.

IV. SIMULATION RESULTS

A. The Baseline

The baseline is the projected economic path under the assumption of no change in policy. This is a reference path for evaluating the effects of alternative carbon taxes. Values under the baseline scenario are given in Table 3 and Figure 1.

In the baseline scenario, the exogenously specified increases in world oil and gas prices translate into rising relative prices of commodities that are especially oil and gas intensive, most notably refined petroleum products and natural gas utilities. Consumption of oil and gas increases more slowly than that of coal. The depletion of domestic oil and gas

TABLE 3.
Baseline Values.

Industry	Year	Output price	Domestic output	Net profits	Net investment
Coal mining					
	1990	1.000	37.6	1.0	1.4
	2000	0.998	46.7	1.2	1.8
	2020	0.992	71.3	1.9	2.7
Oil and gas extraction					
	1990	1.000	126.4	33.4	3.9
	2000	1.271	101.5	34.6	3.2
	2020	1.812	62.8	33.4	−3.5
Synthetic fuels					
	1990	1.000	0.0	0.0	0.0
	2000	1.271	0.0	0.0	0.0
	2020	1.812	5.2	−1.0	23.8
Petroleum refining					
	1990	1.000	200.3	15.3	15.8
	2000	1.152	208.1	17.0	18.4
	2020	1.444	247.5	23.4	25.7
Electric utilities					
	1990	1.000	144.5	24.7	45.1
	2000	1.008	175.0	29.3	55.2
	2020	1.022	256.5	42.5	82.5
Gas utilities					
	1990	1.002	135.6	22.0	38.9
	2000	1.074	158.5	26.2	47.7
	2020	1.204	218.5	38.6	71.2
Nonenergy manufacturing					
	1990	1.000	4,919.2	742.5	771.0
	2000	0.993	6,034.4	893.7	948.9
	2020	0.980	9,060.8	1,321.7	1,422.4
Nonenergy services					
	1990	0.999	4,200.6	600.4	700.7
	2000	0.989	5,120.5	706.4	853.9
	2020	0.970	7,597.9	1,010.4	1,266.8
Total					
	1990	1.000	9,764.2	1,439.4	1,576.8
	2000	1.000	11,844.8	1,708.3	1,929.0
	2020	1.000	17,520.5	2,470.8	2,891.5

Output, profits, and investment are in billions of 1990 dollars. Prices are relative to the given year's producer price index.

a.

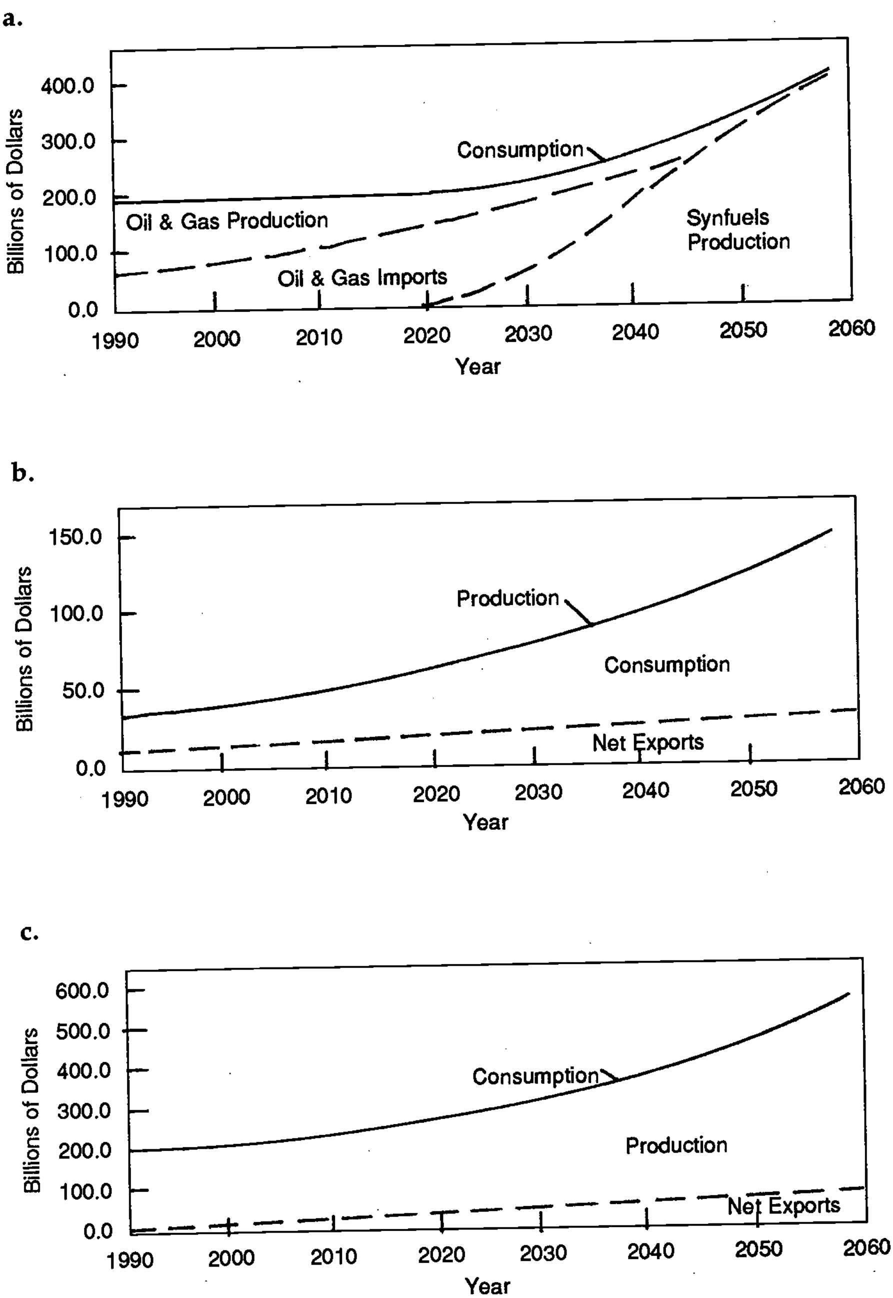


FIGURE 1. *Baseline Fuel Production and Consumption (evaluated at 1990 prices).* a. *oil and gas and synfuel;* b. *coal;* c. *refined petroleum products.*

reserves implies rising unit costs, relatively low gross investment (zero by 2031), and declining output in the domestic oil and gas industry. At the same time, rising oil and gas prices stimulate investment in synthetic fuels. Such fuels entirely eliminate oil and gas imports before the middle of the next century.

B. A Carbon Tax: General Results

Here we examine the consequences of alternative carbon taxes. In all experiments, the carbon tax rate is $25 (in 1990 dollars) per metric ton of carbon at all points in time beginning with the first simulation period (1990). In our first, "central case" experiment, the tax is applied on a partial destination basis: There is a tax on all domestically produced fossil fuels, augmented by a tax on imported fossil fuels and a subsidy for exported fossil fuels. This is not a fully destination-based tax because it does not apply to cover imported fossil-fuel-based products and does not exempt exported fossil-fuel-based products (as discussed in Section II). In this experiment, the path of total revenue from the carbon tax and other pre-existing taxes is kept the same as in the baseline (no-policy-change) case through lump-sum reductions in individual income taxes.

1. Price and Output Effects. Table 4 shows the effects of this tax across industries. To avoid overwhelming the reader with numbers, I have aggregated results for the construction, metals and machinery, motor vehicles, and miscellaneous manufacturing industries into a single "nonenergy manufacturing" category; results for the nonresidential and residential services industries are aggregated into a single "nonenergy services" category.

The coal mining industry feels the greatest impact from the carbon tax. This is in keeping with the fact that coal is the most carbon-intensive of fossil fuels. At unchanged pre-tax prices, the $25 per ton carbon tax would raise the price of coal by 72.0 percent.[27] Table 4 shows that, on impact, the price of coal rises by 64.1 percent, indicating that consumers bear approximately three-fourths of the tax burden. Initially, coal output falls by approximately 37 percent. This substantial reduction allows the coal market to clear at significantly higher coal prices (shifting some of the tax burden on to consumers). Over the

[27] Table 1 shows that at unchanged pretax prices, the cost increase is 2.878 percent per dollar of tax. Multiplying this number times twenty-five yields the figure of 72.0 percent. Note that this increase includes both the direct cost effect from the tax on coal output plus the effect from higher prices of the absorbed carbon used to produce coal.

TABLE 4.
Industry Effects of a $25 per Ton Carbon Tax (percentages changes from baseline path).

Industry	Year	Output price	Domestic output	Net profits	Net investment
Coal mining					
	1990	64.1	−37.1	−41.1	−26.2
	2000	66.3	−39.0	−40.4	−33.3
	2020	68.5	−40.6	−38.2	−38.6
Oil and gas extraction					
	1990	13.9	−1.4	−1.9	1.1
	2000	10.9	−0.9	−2.3	−0.1
	2020	7.7	−0.5	−2.5	−0.6
Synthetic fuels					
	1990	—	—	—	—
	2000	—	—	—	—
	2020	7.7	−41.9	−47.1	−39.1
Petroleum refining					
	1990	7.2	−8.9	−6.0	−3.3
	2000	6.3	−7.2	−4.1	−2.5
	2020	4.8	−5.1	−2.4	−1.7
Electric utilities					
	1990	4.0	−3.3	−1.3	−0.6
	2000	4.3	−3.6	−1.4	−0.8
	2020	4.4	−4.0	−1.5	−1.1
Gas utilities					
	1990	4.6	−2.8	0.6	0.2
	2000	3.5	−2.3	0.1	0.1
	2020	2.4	−1.9	−0.5	−0.0
Nonenergy manufacturing					
	1990	−0.8	−0.3	−1.3	−0.3
	2000	−0.8	−0.4	−1.4	−0.5
	2020	−0.8	−0.6	−1.5	−0.4
Nonenergy services					
	1990	−0.7	−0.4	−1.1	−0.3
	2000	−0.7	−0.5	−1.5	−0.5
	2020	−0.7	−0.6	−1.7	−0.6
Total					
	1990		−0.7	−1.0	−0.3
	2000		−0.9	−1.1	−0.5
	2020		−1.2	−1.2	−0.9

$25 per ton carbon tax on partial destination basis with lump-sum revenue replacement.

longer term, producers adjust further to the policy shock and reduce coal output by a larger percentage (41 percent). The larger reduction in coal output helps bring about the larger percentage increase in coal prices (68.5 percent) in the long run.

Prices also rise substantially in the oil and gas industry. The price rises by 13.9 percent initially (1990) and by 7.7 percent in 2020. The percentage increase is smaller in the long run because the constant real tax is a continuously declining percentage of the rising world oil price. The effects on the synfuels industry are dramatic. These results should be taken as suggestive. They depend upon best guesses about input requirements and adjustment costs for a technology that is still undergoing fundamental changes. The results in Table 4 suggest that a carbon tax would significantly retard the rate of introduction of synfuels: In the year 2020, synfuels output would be 42 percent below the level that it would achieve in that year if there were no carbon tax. In the baseline simulation, synfuels account for about 75 percent of consumption of oil and gas plus synfuels in the year 2040; under the carbon tax, synfuels only account for 57 percent of consumption in that year. The price increase is also significant in the petroleum refining industry, which makes intensive use of oil and gas.

The carbon tax causes some prices to fall in real (or relative) terms. This is the case for the nonenergy manufacturing and services industries, which depend relatively little on fossil fuels for inputs. It should be noted that these are relative price changes. Whether absolute prices would rise in these (and other) industries depends on monetary policy and other factors that are not incorporated in the model.

2. Effects on Profits and Investment. The carbon tax implies a reduction in profits in all industries except in the gas utilities industry, which provides a substitute for electric utilities. (Even the gas utilities industry suffers a loss of profits after 2010.) The percentage reductions in profits differ significantly across industries. Fossil fuel producers generally suffer the largest losses. Interestingly, the effects on profits are minor in the oil and gas industry; we address this issue in subsection C. There are significant reductions in profits in the petroleum refining and electric utilities industries, which make intensive use of fossil fuels. The long-run reductions in profits are small in the gas utilities industry and the nonenergy industries, which depend relatively little on fossil fuels.

In general, changes in investment correspond to anticipated changes in profits. By far the largest reductions in investment occur in the coal mining industry, where investment declines by about 26 percent initially and by 39 percent in 2020.

C. Origin- vs. Destination-Based Taxes

1. Effects on Industry Performance. Table 5 compares results under alternative carbon tax designs. The table considers an origin-based and full destination-based tax as well as the partial destination-based tax just discussed.

Consider first the differences between results for an origin-based tax and for a partial destination-based tax. The differences are dramatic for the domestic oil and gas industry. The former policy does not tax imported oil, while the latter does. The market price that domestic producers receive for oil is the world price gross of any oil tariff. Under the origin-based tax, there is no tariff-induced increase in this market price to offset the tax that must be paid on domestically produced oil. Hence domestic oil production and profits are substantially lower under the origin-based tax. In contrast, under the partial destination-based tax, the tariff on imported oil raises the consumer price of oil by enough to offset the tax on domestically produced oil. The producer price is largely unaffected by the carbon tax. Although the higher consumer price reduces overall demands for oil, domestic producers are largely unaffected because imports, not domestically produced oil, represent the marginal source of supply.

While the oil and gas industry fares much better under the partial destination-based tax, the opposite is true for the petroleum refining industry. This is the case because the partial destination-based tax raises the market price of crude oil, the most important input to this industry.[28] For similar reasons, in the electric utilities, nonenergy manufacturing, and nonenergy services industries profits are lower under the partial destination-based tax than under the origin-based tax.

The move from a partial to full destination-based carbon tax[29] has a profound effect on profits in petroleum refining. The latter tax would eliminate much of the direct cost disadvantage that a carbon tax would otherwise inflict on domestic refiners. While the partial destination-based carbon reduces profits to domestic refiners by about 6 percent in the short run, the full destination-based tax enables these producers to continue to supply the export market, and there is no significant effect on profits.

28 Our analysis assumes that oil and gas production and petroleum refining are carried out by separate enterprises. The analysis for a vertically integrated firm involved in both activities would be considerably more complex.

29 We model the full destination-based tax as a tax on domestic fossil fuels combined with import levies and export subsidies for traded fuels and fossil-fuel-based products. As discussed in Section II, it would be equivalent to implement this policy as a tax on domestic consumption of final goods, with the tax rate based on carbon content.

An important result from Table 5 is that the move from a partial to a full destination-based tax has minimal effect on production and profits by industries other than petroleum refining. This is in keeping with the initial insights that could be gleaned from Table 1. This suggests that a carbon tax that applies the destination principle to a selected set of products (imported fossil fuels, imported refined products, and perhaps a few others) might avoid nearly all of the significant adverse implications for international competitiveness while remaining administratively feasible.

2. ***Implications of Tax Basis for Emissions.*** One argument for a destination-based rather than origin-based carbon tax is that the former is more effective in reducing U.S. demands for fossil fuels and curtailing global carbon emissions. To the extent that an origin-based carbon tax leads producers and consumers to substitute (now cheaper) imports for domestically produced fuels and fossil-fuel-based products, the magnitude of the reduction in domestic consumption of (demands for) carbon-based goods would be smaller and the benefit to the global environment would be reduced. A destination-based tax reduces options for such substitution.

Figure 2 provides information indicating the extent to which this issue may be important. Consider the effects in the year 2000. Under the origin-based tax, U.S. firms reduce production of emissions by 0.60 billion metric tons (Figure 2b), a reduction of about 37 percent from the corresponding year in the baseline. Emissions consumption falls by only 0.26 billion tons, however. This means that the reduction in production is offset by .34 billion in increased "net imports" of emissions.

The destination-based taxes are more effective in reducing emissions demands. As Figure 2a indicates, the reduction in demands is 40 to 45 percent greater under destination-based taxes than under the origin-based tax.[30] At the same time, there is relatively little difference between the partial and full destination-based policies in terms of emissions production and consumption. Although the full destination-based tax expands the range of imports which face the carbon tax, it appears that the volume of trade in these imports and the carbon content of these goods together are not sufficient to have a substantial impact on total emissions consumption. It may be vitally important to some industries (for example, petroleum refining) to expand the carbon tax to cover not only imported fuels but fossil fuel-based products as well; much may be at stake in terms of the international competitiveness of particular indus-

[30] It may be noted that there is a greater cutback in consumption even though U.S. production of emissions is higher under the destination-based policies.

TABLE 5.

Significance of Tax Basis for Profits and International Trade (percentage changes from baseline).

	1 Coal mining		2 Oil and gas extraction		3 Synthetic fuels		4 Petroleum refining		5 Electric utilities		6 Gas utilities		7 Nonenergy manufac-turing		8 Nonenergy services	
	1990	2020	1990	2020	1990	2020	1990	2020	1990	2020	1990	2020	1990	2020	1990	2020
1. Origin-Based Tax																
Output Price	60.8	68.2	0.0	0.1	—	0.1	−0.1	−0.1	2.6	4.1	−0.2	−0.1	−0.1	−0.4	−0.4	−0.3
Domestic Production	−51.4	−53.7	−12.9	−1.3	—	−65.8	0.1	−0.3	−2.4	−3.8	0.0	−0.2	0.0	−0.5	−0.1	−0.5
Domestic Construction	−40.8	−43.0	−1.1	−0.8	—	−65.8	−0.1	−0.3	−2.4	−3.8	0.0	−0.2	−0.2	−0.7	−0.2	−0.5
Exports	−75.5	−78.9	0.0	0.0	—	0.0	1.9	−0.3	−2.4	−4.4	20.0	−2.3	2.5	0.8	2.2	−0.5
Imports	89.1	105.1	21.9	1.9	—	0.0	−0.1	−0.4	−2.4	−3.8	0.0	2.9	−0.6	−0.9	−0.2	−0.5
Profits	−66.2	−59.3	−27.8	−11.0	—	−70.6	0.1	−0.5	−2.2	−2.1	−0.1	−0.6	−0.1	−0.9	−0.4	−1.1

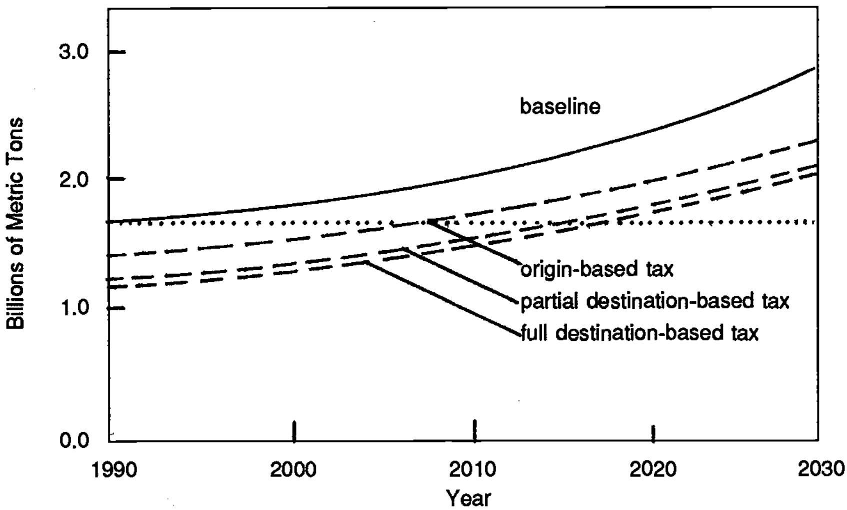
2. Partial Destination-Based Tax

Output Price	64.1	68.6	13.9	7.7	—	7.7	7.2	4.8	4.0	4.4	4.5	2.4	−0.7	−0.8	−0.6	−0.7
Domestic Production	−37.1	−40.6	−1.3	−0.5	—	−41.9	−8.9	−5.1	−3.3	−4.0	−2.8	−1.9	−0.3	−0.6	−0.3	−0.6
Domestic Construction	−41.5	−43.6	−11.7	−5.9	—	−41.9	−3.9	−3.0	−3.2	−4.0	−2.6	−1.8	−0.2	−0.6	−0.2	−0.6
Exports	−26.0	−33.1	0.0	0.0	—	0.0	−31.2	−17.0	−51.6	−52.0	−2.8	−1.9	−1.6	−0.6	−2 .7	−0.6
Imports	−29.8	−32.3	−32.1	−8.4	—	0.0	12.8	8.2	−3.2	−3.8	0.9	4.4	−1.0	−0.8	−0.2	−0.6
Profits	−41.1	−38.2	−1.9	−2.5	—	−47.1	−6.0	−2.4	−1.3	−1.5	0.6	−0.5	−1.3	−1.5	−1.1	−1.7

3. Full Destination-Based Tax

Output Price	64.2	68.6	13.9	7.7	—	7.7	8.3	4.8	4.6	4.6	5.0	2.5	−0.8	−0.8	−0.6	−0.7
Domestic Production	−37.2	−40.8	−1.4	−0.5	—	−41.2	−5.3	−3.6	−3.4	−3.9	−2.6	−1.6	−0.3	−0.7	−0.4	−0.6
Domestic Construction	−41.2	−43.4	−8.9	−4.8	—	−41.2	−5.8	−4.2	−3.4	−3.9	−2.5	−1.7	−0.2	−0.6	−0.3	−0.6
Exports	−27.3	−34.1	0.0	0.0	—	0.0	−1.8	−1.2	−3.4	−3.9	−2.6	−3.0	−2.0	−1.5	−2.7	−0.6
Imports	−29.5	−32.1	−23.7	−6.9	—	0.0	−6.6	−7.1	−3.4	−3.9	−2.5	−1.6	−0.4	−0.6	−0.3	−0.6
Profits	−40.8	−38.1	−1.9	−0.7	—	−46.4	0.1	−0.5	−0.5	−1.0	1.4	−0.1	−1.5	−1.6	−1.0	−1.7

a.



b.

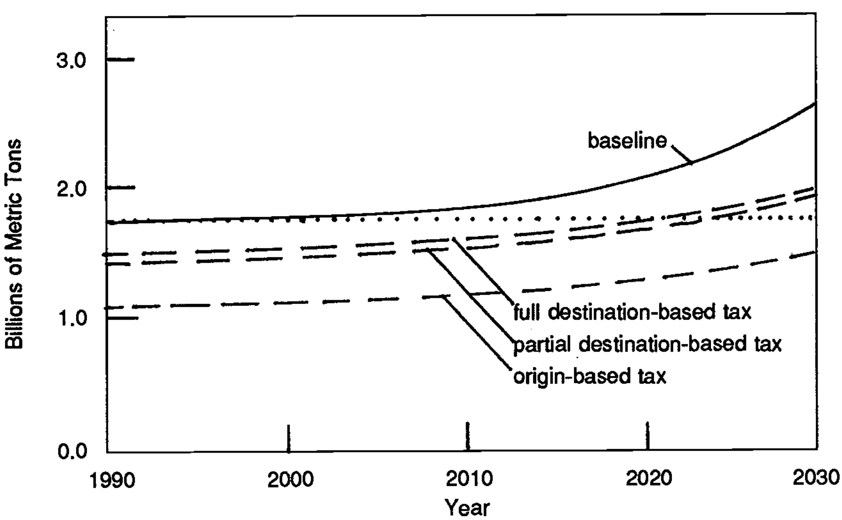


FIGURE 2. *Carbon Emissions under Alternative Carbon Taxes.* **a.** *consumption (emissions demanded);* **b.** *production (emissions supplied).*

tries. But in terms of U.S. emissions consumption, it would appear that much less hangs in the balance.

D. Implications of Alternative Revenue Uses

Table 6 compares results under different specifications for the use of the tax revenues. All policy experiments involve the partial destination-based tax. The first experiment is the same one as considered in subsection A, and involves lump-sum replacement of the tax revenues. In the second experiment, additional revenues from the tax are returned through reductions in the statutory corporate income tax rate. In the last experiment, the additional revenues are returned through reductions in the marginal tax rates applied to individual labor and capital income.[31]

The profits performance of all industries is better, but only slightly better, under the latter two policies than under lump-sum revenue replacement. Lowering corporate or individual tax rates has the attraction of reducing the efficiency losses that these distortionary taxes generate. In contrast, returning revenues in lump-sum fashion yields no direct efficiency benefit. The more favorable profits performance under the corporate and personal tax reduction cases is consistent with the improvement in economic efficiency.

Although the picture improves when revenues finance reductions in distortionary taxes, none of these policies succeeds in eliminating the burden (in terms of lost profits) to all industries. Fossil fuel producers, in particular, still experience lost profits, although the losses are smaller. These results suggest that sagacious use of tax revenues would not prevent at least some industries from adverse effects from a carbon tax. This conclusion is reinforced by the aggregate efficiency results reported in the next subsection.

E. Some Aggregate Results

Table 7 displays GNP and welfare effects of the various tax options we have considered. Numbers in parentheses are percentage changes in GNP relative to the baseline simulation.

In all the cases considered, the carbon tax causes GNP to fall. The GNP falls by considerably more under the destination-based carbon taxes than under the origin-based tax. This is in keeping with the fact that the United States is a net importer of emissions: There are more emissions associated with its consumption than with its production. The destination-based tax

[31] This experiment involves proportionate reductions in the marginal rates on labor income, dividend and interest income, and capital gains income for the representative household. The benchmark marginal rates are weighted averages of rates faced by U.S. households, with weights based on income levels.

TABLE 6.

Effects of a Carbon Tax under Alternative Specifications for Revenue Use.

	1 Coal mining		2 Oil & Gas extraction		3 Synthetic fuels		4 Petroleum refining		5 Electric utilities		6 Gas utilities		7 Nonenergy manufacturing		8 Nonenergy services	
	1990	2020	1990	2020	1990	2020	1990	2020	1990	2020	1990	2020	1990	2020	1990	2020
1. Lump-Sum Tax Replacement																
Domestic Production	−37.1	−40.6	−1.4	−0.5	.	−41.9	−8.9	−5.1	−3.3	−4.0	−2.8	−1.9	−0.3	−0.6	−0.4	−0.6
Net Investment	−26.2	−38.6	1.1	−0.6	.	−39.1	−3.3	−1.7	−0.6	−1.1	0.2	−0.1	−0.3	−0.4	−0.3	−0.6
Net Profits	−41.1	−38.2	−1.9	−0.8	.	−47.1	−6.1	−2.4	−1.3	−1.5	0.6	−0.5	−1.3	−1.5	−1.1	−1.7
2. Corporate Income Tax Replacement																
Domestic Production	−37.1	−40.5	−1.4	−0.6	.	−41.9	−8.7	−5.0	−3.3	−3.9	−2.8	−1.8	−0.3	−0.4	−0.4	−0.5
Net Investment	−26.0	−38.4	1.0	−0.6	.	−38.8	−3.2	−1.3	−0.6	−1.0	0.2	0.1	−0.1	0.1	−0.3	−0.4
Net Profits	−41.0	−37.9	−1.5	−0.2	.	−28.0	−5.7	−2.0	−1.1	−1.2	0.7	−0.1	−0.9	−1.0	−0.7	−1.3
3. Personal Income Tax Replacement																
Domestic Production	−37.1	−40.5	−1.4	−0.5	.	−41.9	−8.7	−5.0	−3.3	−3.9	−2.8	−1.8	−0.3	−0.5	−0.4	−0.5
Net Investment	−26.1	−38.5	1.1	−0.5	.	−39.1	−3.2	−1.5	−0.5	−1.1	0.3	0.0	−0.2	−0.2	−0.2	−0.5
Net Profits	−41.0	−38.0	−1.6	−0.6	.	−37.8	−6.0	−2.1	−1.2	−1.3	0.6	−0.4	−1.0	−1.1	−0.9	−1.5

TABLE 7.
Effects on GNP and Welfare.

	Real GNP 1990	2000	2020	Welfare Change
Baseline:	5603.9	6773.1	9876.0	
Carbon Tax:				
Origin Basis	5581.6	6739.6	9800.5	−0.633
	(−0.40)	(−0.49)	(−0.76)	
Partial Destination Basis	5566.5	6715.9	9769.1	−0.712
(Lump-Sum Replacement)	(−0.67)	(−0.84)	(−1.08)	
Full Destination Basis	5563.5	6712.3	9763.6	−0.726
	(−0.72)	(−0.90)	(−1.14)	
Partial Destination Basis,	5567.5	6725.7	9800.9	−0.482
Corporate Tax Replacement	(−0.65)	(−0.70)	(−0.76)	
Partial Destination Basis,	5568.0	6723.7	9793.0	−0.536
Personal Tax Replacement	(−0.64)	(−0.73)	(−0.84)	

Note: The upper number in each pair of GNP figures is GNP in billions of 1990 dollars. The lower number is the percentage change from the baseline. The welfare change is the equivalent variation as a percentage of baseline financial wealth.

applies to emissions consumption, the origin-based tax to production. The destination-based tax therefore has a larger base, which contributes to the larger GNP impact.[32]

When carbon tax revenues are used to reduce other distortionary taxes, the GNP effects are still negative, but smaller in absolute value than under the lump-sum tax case.

In all simulations, the percentage losses of GNP are greater in the long run than in the short run. This is in keeping with the gradual shift of the economy away from oil and gas and toward coal and synfuels, which are more carbon-intensive and yield a larger tax base.[33]

Welfare changes are similar to the changes in GNP. The measure of welfare change is the equivalent variation as a percentage of baseline wealth.[34] Even when carbon tax revenues finance cuts in distortionary

[32] The model is somewhat biased toward pessimism in its assessment of GNP losses from the destination-based taxes. The model assumes the United States has no monopsony power to influence world prices of the goods it imports. If reduced imports caused world (pre-tariff) import prices to fall, the magnitude of the adverse effects on U.S. GNP would be smaller.

[33] On impact, the carbon tax induces substitutions of oil and gas for coal, which is more carbon-intensive and more highly taxed. Following this initial effect, coal use rises more quickly than oil and gas use. This reflects rising real world prices of oil and gas and relatively steady real prices of coal.

[34] Wealth is the present value of after-tax labor and capital income over an infinite time horizon.

taxes, the welfare changes are negative. The consistently negative effects on GNP and welfare are in keeping with the effects on industry profits noted earlier.

The negative welfare numbers for the last two policies given in the table suggest that carbon taxes cannot be justified on narrow efficiency grounds; they indicate that these taxes tend to cause greater distortions than the distortionary taxes they might partly replace.[35] It should be kept in mind that these welfare figures disregard the environmental benefits from reduced carbon emissions. These results indicate that one needs to invoke these environmental benefits to justify carbon tax policies.

F. *Sensitivity Analysis*

Here I explore the extent to which the distribution of industry burdens under a carbon tax might be sensitive to the values of important parameters. I concentrate on the distribution of industry burdens under the original simulation described under IV.A.: The partial destination-based carbon tax with revenues returned to the economy in lump-sum fashion.

I consider the implications of changes in the values of (1) elasticities of substitution between domestically produced and foreign-made intermediate inputs or consumer goods, (2) other elasticities of substitution in production, and (3) initial domestic oil and gas reserves. Results are summarized in Table 8.

Changing the values of the "Armington" elasticities of substitution between domestic and foreign goods does not dramatically alter the results. One reason for this is that the partial destination-based carbon tax applies equally to domestic and foreign fossil fuels, leaving relative prices of domestic and foreign fossil fuels largely unchanged. This tax puts domestic producers of refined petroleum products at a significant disadvantage relative to their foreign competitors, however, because imported refined petroleum products are not taxed. Higher Armington elasticities imply greater substitution of foreign refined fuels for the domestic counterparts, and greater losses in profits and output in the domestic refined petroleum industry.

Higher values for other elasticities of substitution in production allow for easier substitution on two margins. First, oil and gas can be substituted more easily for coal, which experiences the largest relative price increase.

[35] In Goulder (1991a), we examine why carbon taxes tend to be more distortionary than many pre-existing taxes. The carbon tax has a much narrower tax base than that of such taxes as the personal and corporate income taxes. Because the base is narrower, it tends to generate larger gross distortions than those of these other taxes. It should be noted that gross distortions abstract from the efficiency gains associated with environmental (and other externality) effects.

In addition, non-energy inputs can be substituted more easily for energy inputs, which generally rise in price. Both effects contribute to the larger losses to the coal industry when elasticities of substitution are higher.[36] Interestingly, the domestic oil and gas industry fares better under higher production elasticities. Here it is important to note that imported oil and gas is the marginal source of supply, so that a tax-induced reduction in demand for oil and gas primarily affects the residual demand for imports. The importance of higher elasticities to the well-being of the domestic oil and gas industry is its effect on production costs, since there is little demand-side effect to the domestic industry. Under higher production elasticities, the domestic oil and gas industry can more easily contain costs by substituting nonenergy inputs for energy inputs. Thus the magnitude of the loss of profits and output is smaller when the elasticities are higher.

Different assumptions about oil and gas reserves are important mainly for the oil and gas and synthetic fuels industries. For the oil and gas industry, the percentage losses in profits and output tend to be larger in the case where initial reserves are assumed to be larger. Although the losses are greater in percentage terms, the absolute levels of profits and production are higher when higher values are assumed for initial reserves. For example, under the central case assumption of initial oil and gas reserves, the value of domestic oil and gas production in 2020 is $62.8 billion in the baseline and $62.4 billion under the policy change. When initial reserves are assumed to be twice the central value, production in 2020 has a value of $84.8 in the (different) baseline and $84.1 under the policy change. In the synfuels industry, the carbon tax yields somewhat larger losses when higher initial oil and gas reserves are assumed. Baseline levels of synfuels profits and output are also lower under this assumption.

V. CONCLUSIONS

Multilateral initiatives to reduce emissions of carbon dioxide may have many attractions relative to unilateral policies. Many of the "international competitiveness" problems that are so difficult to avoid under unilateral policies simply do not arise under policies that are introduced on a global basis. The advantages of multilateral policies do not eliminate the need for analysis of unilateral programs, however: in view of the difficulties inherent in reaching agreements for coordinated, interna-

[36] In the short run, coal profits fall less under the higher production elasticities. This reflects the fact that under this scenario, investment by the coal industry falls by a greater amount. In the short run, the larger drop in investment implies lower adjustment costs, a smaller reduction in retained earnings, and a smaller drop in recorded profits.

TABLE 8.
Sensitivity Analysis
(percentage changes from baseline).

	Coal mining		Oil & Gas extraction		Synthetic fuels	
	1990	2020	1990	2020	1990	2050[1]
1. Central Case						
Domestic Production	−37.14	−40.62	−1.39	−0.51	0.00	−13.18
Profits	−41.09	−38.19	−1.92	−2.51	0.00	−7.06
2. Armington Trade Elasticities						
a. 1.5 × Central Values						
Domestic Production	−36.96	−40.36	−1.38	−0.51	0.00	−13.24
Profits	−41.99	−39.33	−1.92	−2.52	0.00	−7.16
b. 0.5 × Central Values						
Domestic Production	−37.25	−40.86	−1.40	−0.52	0.00	−13.15
Profits	−40.38	−37.20	−1.92	−2.51	0.00	−7.02
3. Production Substitution Elasticities						
a. 1.5 × Central Values						
Domestic Production	−45.12	−49.03	−1.18	−0.39	0.00	−35.93
Profits	−36.60	−44.80	−1.83	−1.84	0.00	−39.15
b. 0.5 × Central Values						
Domestic Production	−32.12	−35.41	−1.67	−0.57	0.00	−11.09
Profits	−44.64	−33.41	−1.98	−2.73	0.00	−9.07
4. Domestic Oil/Gas Reserves						
a. 2.0 × Central Values						
Domestic Production	−37.14	−40.85	−1.39	−0.79	0.00	−13.50
Profits	−41.18	−38.46	−1.91	−3.02	0.00	−7.66
b. 0.5 × Central Values						
Domestic Production	−37.15	−40.37	−1.40	−0.14	0.00	−12.97
Profits	−41.01	−37.84	−1.92	−1.80	0.00	−6.67

tional action, it is worthwhile to investigate closely the potential of unilateral alternatives. This paper has examined various unilateral carbon tax policies, focusing on the distribution of the tax burdens across U.S. industries.

Five main conclusions emerge from this study. First, the burden of a U.S. carbon tax is highly concentrated among a few industries. The coal, oil and gas, petroleum refining, and electricity industries bear the lion's share of the burden from a carbon tax. This reflects the fact that carbon—original and absorbed—is concentrated mainly in these industries.

Second, it makes a great difference to the U.S. coal, oil and gas, and

Petroleum refining		Electric utilities		Gas utilities		Nonenergy manufacturing		Nonenergy services	
1990	2020	1990	2020	1990	2020	1990	2020	1990	2020
−8.91	−5.10	−3.30	−3.99	−2.81	−1.93	−0.31	−0.59	−0.38	−0.58
−6.05	−2.43	−1.30	−1.49	0.55	−0.44	−1.29	−1.48	−1.06	−1.73
−9.45	−5.80	−3.16	−3.84	−2.58	−1.75	−0.30	−0.58	−0.37	−0.57
−7.18	−3.36	−1.37	−1.52	0.59	−0.47	−1.26	−1.49	−1.09	−1.76
−8.44	−4.62	−3.38	−3.99	−2.86	−1.92	−0.32	−0.61	−0.39	−0.59
−5.10	−1.73	−0.97	−1.25	0.66	−0.37	−1.33	−1.49	−1.03	−1.72
−9.94	−4.76	−4.14	−4.37	−3.63	−1.29	−0.41	−0.38	−0.48	−0.46
−2.71	−0.79	−0.36	−0.57	1.72	0.92	−1.28	−1.25	−0.94	−1.42
−8.21	−4.95	−2.76	−3.51	−2.35	−1.95	−0.25	−0.21	−0.32	−0.40
−9.03	−3.09	−2.19	−1.78	−0.56	−1.03	−1.28	−1.11	−1.16	−1.65
−8.90	−5.12	−3.30	−4.00	−2.81	−1.94	−0.30	−0.64	−0.38	−0.60
−6.06	−2.44	−1.31	−1.51	0.53	−0.45	−1.29	−1.54	−1.07	−1.78
−8.91	−5.05	−3.30	−3.95	−2.81	−1.88	−0.32	−0.50	−0.38	−0.54
−6.04	−2.40	−1.31	−1.45	0.55	−0.41	−1.30	−1.41	−1.05	−1.70

[1]For the synfuels industry, percentage changes for 2020 are not meaningful because baseline values are very small in that year. For this reason we report percentage changes for the year 2050.

petroleum refining industries whether the tax is introduced on an origin or destination basis. The reduction in profits to domestic oil and gas producers, for example, is over ten times larger under the origin-based tax, which does not involve tariffs on imported oil, than under the partial or full destination-based taxes, which do.[37]

[37] If the destination-based policy is introduced as a tax on final goods purchased domestically, then the tax will apply to goods of both domestic and foreign origin. Thus imported goods would face a tax, just as they would under the alternative approach involving import tariffs.

Third, for most U.S. industries it makes relatively little difference whether one introduces a partial or a full destination-based carbon tax. For the petroleum refining industry, however, the breadth of the application of the destination principle makes a dramatic difference: To avoid substantial costs to petroleum refiners, the carbon tax would have to apply not only to imported fossil fuels but to imported refined products as well. Extending the destination principle even further—widening the base of the tax to cover other carbon-based products—helps preserve international competitiveness for a broader range of industries, but makes administration of the tax more problematic. It is difficult to gauge where the appropriate balance between safeguarding competitiveness and limiting administrative costs is best struck. An examination of the distribution of carbon content across produced goods suggests, however, that the application of the destination principle to a relatively small number of carbon-intensive products would avert the most significant potential impacts on international competitiveness while avoiding the substantial administrative costs that the full destination-based carbon tax would entail.

Fourth, destination-based U.S. carbon taxes are much more effective than origin-based taxes in reducing U.S. demands for carbon-based goods and the associated emissions. Under an origin-based tax, about 57% of the reduction in U.S.-source emissions is offset by increased net imports of emissions through substitution toward more carbon-intensive products. Under the destination-based alternatives, there is little substitution of this kind because in this case carbon-intensive imports gain no cost advantage relative to the domestically produced counterparts. A partial destination-based carbon tax achieves over 90 percent of the reduction in U.S. consumption of emissions that would occur under a full destination-based tax. The move from a partial to a full destination-based tax would have only a modest effect on emissions, yet the increase in administrative costs of such a move could be quite large. This calls in question the advisability of attempting to achieve a fully destination-based carbon tax.

Finally, using carbon tax revenues to finance cuts in other distortionary taxes reduces, but does not eliminate, the adverse consequences of the carbon tax policy for industry profits and investment. When the revenues are used this way, fossil fuel producers and producers of fossil-fuel-intensive products lose less than they would if revenues were returned in lump-sum fashion, but the losses do not vanish. Aggregate efficiency results suggest that a carbon tax must inevitably generate losses for at least some industries.

Although this analysis helps clarify the attractions and drawbacks of alternative types of carbon taxes, it leaves unanswered the question whether a carbon tax is preferable to other policies to achieve reductions in carbon dioxide emissions. The analysis also leaves open the question of what size (if any) carbon tax would be best. Answering this latter question requires attention to the value of the environmental benefits stemming from reduced carbon dioxide emissions. The magnitudes of these benefits are likely to remain highly uncertain for a long time. Still, policy choices—which may include the decision to avoid introducing a carbon tax—will have to be made in the short term, before the uncertainties are resolved. An analytical framework that could help guide today's choices is that of (sequential) decision making under uncertainty. There is considerable room for research that employs this framework to analyze the carbon tax and other environmental policy options in an uncertain world.

APPENDIX A: DETERMINING CARBON CONTENT AND DESIGNING A DESTINATION-BASED CARBON TAX

1. *Calculating the Carbon Content of Fossil-Fuel-Based Products*

Let n represent the number of industries, including the fossil-fuel-producing industries. Let b_i ($i = 1, \ldots, n$) denote the content of original carbon in the output of industry i. This is the amount of carbon that is found naturally in fossil fuels. Only fossil fuels have original carbon; for industries other than fossil fuels, b_i is zero. Let a_{ij} represent the required input of good i per unit of output produced by industry j.[38] Then e_j, the total embodied carbon content of product j, can be expressed as

$$e_j = b_j + \sum_{i=1}^{n} b_i a_{ij} + \sum_{k=1}^{n} \sum_{i=1}^{n} b_k a_{ki} a_{ij} + \sum_{m=1}^{n} \sum_{k=1}^{n} \sum_{i=1}^{n} b_m a_{mk} a_{ki} a_{ij} + \ldots \tag{1}$$

The first term on the right-hand side is the original carbon content. The other terms indicate *absorbed* carbon: the second term is the carbon content of the fuels used as inputs in the production of good j, the third is the carbon content of fuels used as inputs to the inputs to product j, etc.[39]

[38] Each element a_{ij} includes both domestic and foreign-made inputs of type i per unit of output j.

[39] Equation (1) indicates that the total carbon associated with a unit of processed or extracted fuel will generally exceed the fuel's original carbon content.

In matrix form, equation (1) can be written as:

$$e = b + bA + bA^2 + bA^3 + \ldots \tag{2}$$

where **e** and **b** are n-length row vectors, and **A** is an n by n matrix. This infinite series can be expressed as:

$$e = b[I-A]^{-1} \tag{3}$$

We employ equation (3) to calculate the total embodied (original plus absorbed) carbon content of each produced good.

2. *Calculating Import Levies and Export Subsidies for a Destination-Based Carbon Tax Policy.*

The purpose of import levies and export subsidies under a destination-based carbon tax is to eliminate the cost disadvantage which would otherwise occur as a result of a carbon tax. First consider the firms' costs in the absence of a carbon tax. Assuming a competitive environment in which price equals cost, the relationship between input prices, factor costs, and output prices can be expressed as:

$$p_j(1-t_{oj}) = \sum_{i=1}^{n} p_i(1+t_{ij})a_{ij} + v_j \tag{4}$$

where p_j is the price of product j (gross of output taxes), t_{oj} is the output tax on product j, t_{ij} is the tax on intermediate use of good i by industry j, and v_j is the unit factor (capital and labor) cost of good j.[40] This formulation assumes constant-returns-to-scale production: costs are independent of the scale of output.

In matrix form we can express this relationship as:

$$pT_1 = p\tilde{A} + v \tag{5}$$

where **p** is a 1 by n vector of prices, $\mathbf{T_1}$ is an n by n diagonal matrix consisting of diagonal elements $1-t_{oj}$ ($j = 1, \ldots, n$), $\tilde{A}$ is an n by n matrix consisting of elements $(1+t_{ij})a_{ij}$, and v is a 1 by n vector of unit factor costs. The solution to the system represented by (5) is:

$$p = v[T_1-\tilde{A}]^{-1} \tag{6}$$

[40] Equation (4) implicitly assumes that there are no tariffs on imported inputs. The extension to incorporate tariffs is straightforward and involves distinguishing the domestic and foreign inputs required per unit of production.

Now consider the cost increase which would result from an origin-based carbon tax. Let t_{cj} represent the carbon tax levied on industry j. In contrast with the *ad valorem* output tax t_{oj}, the carbon tax is a per-unit tax. The tax is proportional to original carbon content, b_j. Thus t_{cj} is nonzero only for the fossil-fuel-producing industries. With the carbon tax, the relationship between price and cost becomes:

$$p_j(1-t_{oj}) - t_{cj} = \sum_{i=1}^{n} p_i(1+t_{ij})a_{ij} + v_j \tag{7}$$

In matrix form this is:

$$pT_1 - t_c = p\tilde{A} + v \tag{8}$$

The solution to this system is:

$$p = (v+t_c)\,(T_1-\tilde{A})^{-1} \tag{9}$$

The cost effect of the carbon tax is given by the difference between the prices in equations (6) and (9).[41] The difference is $\mathbf{t}_c(\mathbf{T}_1-\tilde{\mathbf{A}})^{-1}$. This can be rewritten as:

$$t_cT_1^{-1} + t_c(T_1^{-1}\tilde{A})T_1^{-1} + t_c(T_1^{-1}\tilde{A})^2T_1^{-1} + \ldots \tag{10}$$

The first term in equation (10) is nonzero only for the fossil-fuel-producing industries; it is the cost increase associated with the direct application of the carbon tax to the output of that industry. The second term (generally nonzero in all industries) represents the cost increase stemming from higher-priced fossil fuel inputs used by the industry. The remaining terms represent the effect from higher-priced fossil fuels used indirectly by the industry, that is, from higher prices of other inputs to the industry as a result of the carbon tax having raised the costs of these inputs.

To neutralize the effect of a carbon tax on the costs of exported goods, it is necessary to introduce a per-unit subsidy to each exported product j equal to $\Sigma_{i=1}^{n} t_{ci}X_{ij}$, where $\mathbf{X} \equiv (\mathbf{T}_1-\tilde{\mathbf{A}})^{-1}$ from (9). This restores the after-tax cost of the exported good to its original value given in (6).[42] Similarly, an

[41] This analysis assumes that the carbon tax does not alter the technical coefficients that make up the matrix **A**. To the extent that firms can change input intensities to reduce the use of the taxed inputs, the cost effect will be smaller than that given here.

[42] The subsidy allows domestic producers to continue to devote products to the export market. The subsidy has no direct impact on domestic producers' decisions to sell on the export market as opposed to the domestic market. Although producers enjoy the subsidy

import levy equal $\Sigma_{i=1}^{n} t_{ci}X_{ij}$ for imported good j would cause imported fossil-based products to increase in price by the same amount as domestically-produced goods of the same type.[43]

In the special case where there are no prior output taxes t_j or intermediate good taxes t_{ij}, $\mathbf{X}$ reduces to $[\mathbf{I} - \mathbf{A}]^{-1}$, indicating that the cost increase of a carbon tax in a given industry is proportional to the quantity of original and absorbed carbon embodied in a unit of output.

APPENDIX B: FUNCTIONAL FORMS AND PARAMETERS USED IN THE MODEL[44]

1. *Industry Production Functions and Elasticities*

a. Production Structure (see text for definitions of variables):

—industries other than oil and gas industry:

$$X = f[g(L,K), h(E,M)] - \phi(I/K) \cdot I$$

—oil and gas industry:

$$X = \gamma(Z) \cdot f[g(L,K),h(E,M)] - \phi(I/K) \cdot I$$

—all industries:

$$E = \mathrm{E}(\bar{x}_2, \bar{x}_3+\bar{x}_4, \bar{x}_5, \ldots, \bar{x}_7)$$
$$M = \mathrm{M}(\bar{x}_1, \bar{x}_8, \ldots, \bar{x}_{13})$$

where $\bar{x}_i$ is a composite of domestically produced and foreign made input i. Industry indices correspond to those of the first table under c.

b. Functional Forms:

—f, g, h, E, M, and $\bar{x}$ functions (all industries): CES

—ϕ adjustment cost function (all industries):

only for exported goods, they cannot enjoy higher profits from exports unless they raise export prices. The latter would reduce foreign demands for the exported goods. At unchanged export prices, the subsidy simply permits exporters to maintain their profit margins.

[43] Note that if the technology employed in producing imports differed from that used in producing the corresponding domestic goods, then this import levy will not generally imply the same tax rate per unit of carbon content as that applied to domestic goods through the carbon tax.

[44] See Cruz and Goulder (1991) for documentation of data and parameter sources.

$$\phi(I/K) = \begin{cases} \frac{1}{2} \cdot \beta \cdot (I/K - \delta)^2 / (I/K), & I/K > \delta \\ 0 & , I/K \leq \delta \end{cases}$$

δ represents the rate of economic depreciation.

—γ stock effect function (oil and gas industry):

$$\gamma(Z_t) = \gamma_0 - (Z_t/\bar{Z})^{\epsilon}$$
$$Z_t = Z_0 + \sum_{s=1}^{t-1} X_s$$

Z_t is cumulative extraction (output) of oil/gas up to the beginning of period t and $\bar{Z}$ is total discovered reserves.

c. Parameter Values:

—elasticities of substitution in production:

	Substitution Margin:				
Producing Industry	*g-h*	*L-K*	*E-M*	*E components*	*M components*
1. Agriculture and Non-coal Mining	0.7	0.68	0.7	1.45	0.6
2. Coal Mining	0.7	0.80	0.7	1.08	0.6
3. Oil and Gas Extraction	0.7	0.82	0.7	1.04	0.6
4. Synthetic Fuels	0.7	0.82	0.7	1.04	0.6
5. Petroleum Refining	0.7	0.74	0.7	1.04	0.6
6. Electric Utilities	0.7	0.81	0.7	0.97	0.6
7. Gas Utilities	0.7	0.96	0.7	1.04	0.6
8. Construction	0.7	0.95	0.7	1.04	0.6
9. Metals and Machinery	0.7	0.91	0.7	1.21	0.6
10. Motor Vehicles	0.7	0.80	0.7	1.04	0.6
11. Miscellaneous Manufacturing	0.7	0.94	0.7	1.08	0.6
12. Services (except electric utilities, gas utilities, and housing)	0.7	0.98	0.7	1.07	0.6
13. Housing Services	0.7	0.80	0.7	1.81	0.6

—elasticities of substitution between domestic and foreign inputs (parameter of $\tilde{x}$ functions)

Input Type	*elasticity*
1. Agriculture and Non-coal Mining	2.31
2. Coal Mining	1.14
3. Oil and Gas Extraction	(infinite)
4. Synthetic Fuels	(not traded)
5. Petroleum Refining	2.21
6. Electric Utilities	1.0
7. Gas Utilities	1.0
8. Construction	1.0
9. Metals and Machinery	2.74
10. Motor Vehicles	1.14
11. Miscellaneous Manufacturing	2.74
12. Services (except electric utilities, gas utilities, and housing)	1.0
13. Housing Services	(not traded)

—stock effect function parameters:

parameter:	Z_0	$\bar{Z}$	γ_0	ϵ
value:	0	450	1	2

Note: This function is parameterized so that γ approaches 0 as Z approaches $\bar{Z}$. The value of $\bar{Z}$ is 450 billion barrels (about 100 times the 1990 production of oil and gas, where gas is measured in barrel-equivalents). $\bar{Z}$ is based on estimates from Masters *et al.* (1987). Investment in new oil and gas capital ceases to be profitable before reserves are depleted: the value of ϵ implies that, in the baseline scenario, oil and gas investment becomes zero in the year 2031.

2. *Household Utility Function*

a. Utility Function:

$$U_t = \sum_{s=t}^{\infty} (1+\omega)^{t-s} \frac{\sigma}{\sigma-1} C_s^{\frac{\sigma-1}{\sigma}}$$

where ω is the subjective rate of time preference, σ is the intertemporal elasticity of substitution in consumption, and C is CES, a composite of consumption of goods and services G and leisure L:

$$C_s = \left[G_s^{\frac{v-1}{v}} + \eta^{\frac{1}{v}} L_s^{\frac{v-1}{v}} \right]^{\frac{v}{v-1}}$$

b. Parameter Values:

parameter:	ω	σ	v	η
value:	0.007	0.5	0.69	0.84

REFERENCES

Barro, Robert (1979). "On the Determination of the Public Debt." *Journal of Political Economy* 87, 940–971.

Cruz, Miguel, and Lawrence H. Goulder (1991). "An Intertemporal General Equilibrium Model for Analyzing U.S. Environmental and Energy Policies: Data Documentation." Working paper, Stanford University, June.

Goulder, Lawrence H. (1990). "Using Carbon Charges to Combat Global Climate Change." Stanford University Center for Economic Policy Research Discussion Paper No. 226, December.

——— (1991b). "Second-Best Taxation and Non-Renewable Resource Supply: An Integrative Approach." Working paper, Stanford University, March.

——— (1991a). "Effects of Carbon Taxes in an Economy with Prior Tax Distortions: An Intertemporal General Equilibrium Analysis for the U.S." Working paper, Stanford University, June.

Goulder, Lawrence H., and Lawrence H. Summers (1989). "Tax Policy, Asset Prices, and Growth: A General Equilibrium Analysis." *Journal of Public Economics* 38, 265–296.

Jorgenson, Dale W., and Peter J. Wilcoxen (1990). "Reducing U.S. Carbon Dioxide Emissions: The Cost of Different Goals." Working paper, Harvard University, November.

Lave, Lester (1991). "Formulating Greenhouse Policies in a Sea of Uncertainty" *The Energy Journal* 12(1), 9–21, January.

Manne, Alan S., and Richard G. Richels (1990a). "CO_2 Emission Limits: An Economic Analysis for the USA." *The Energy Journal* 11 (2), 51–85.

———(1990b). "Global CO_2 Emission Reductions—The Impacts of Rising Energy Costs." Working paper, Stanford University, February.

——— (1992). *Buying Greenhouse Insurance: The Economic Costs of CO_2 Emissions Limits*. Cambridge, Mass.: The MIT Press, forthcoming.

Masters, Charles D., et al. (1987). "World Resources of Crude Oil, Natural Gas, Natural Bitumen, and Shale Oil." In *Proceedings of the 12th World Petroleum Congress* 5, 3–27.

Mussa, Michael (1978). "Dynamic Adjustment in a Heckscher-Ohlin-Samuelson Model." *Journal of Political Economy* 86 (5), 775–791.

Nordhaus, William (1990). "To Slow or Not to Slow: The Economics of the Greenhouse Effect." Paper prepared for the 1990 annual meeting of the American Association for the Advancement of Science.

_____ (1991). "The Cost of Slowing Climate Change: A Survey." *The Energy Journal* 12 (1), January.
OECD/IEA (1990). *Energy Balances of OECD Countries: 1987–1988.* Paris: OECD.
_____ (1991). *Oil and Gas Information, 1988–1990.* Paris: OECD.
Peck, Stephen C., and Thomas J. Teisberg (1991). "CETA: A Model for Carbon Emissions Trajectory Assessment." Working paper, Electric Power Research Institute, February.
Poterba, James M. (1991). "Tax Policy to Combat Global Warming: On Designing a Carbon Tax." National Bureau of Economic Research Working Paper No. 3649, March.
Sandmo, Agnar (1975). "Optimal Taxation in the Presence of Externalities." *Swedish Journal of Economics* 77, 86–98.
Shiells, Clinton R., Robert M. Stern, and Alan V. Deardorff (1986). "Estimates of the Elasticities of Substitution between Imports and Home Goods for the United States." *Weltwirtschaftliches Archiv* 122: 497–519.
U.S. Department of Commerce (1984). *Survey of Current Business*, May.
_____ (1991). *Survey of Current Business*, February.
U.S. Department of Energy, Energy Information Administration (1989). *Annual Energy Outlook 1989, Long Term Projections.*
U.S. Environmental Protection Agency (1989). *Policy Options for Stabilizing Global Climate.* Draft Report to the Congress, Daniel Lashof and Dennis Tirpak, eds., February.
Weyant, John (1991). "Global Climate Change: Energy Sector Impacts of Greenhouse Gas Emission Control Strategies," Working paper, Energy Modeling Forum, Stanford University, March.
World Resources Institute (1990). *World Resources: 1990–91.* New York: Oxford University Press.