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DO THE COSTS OF A CARBON TAX VANISH WHEN INTERACTIONS WITH OTHER TAXES ARE ACCOUNTED FOR?

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ABSTRACT

Previous analyses of U.S. carbon taxes have tended to ignore interactions between this tax and other, pre-existing U.S. taxes. This paper assesses the effects of the carbon tax using a model that addresses these interactions. The model is unique in integrating a detailed treatment of taxes and attention to nonrenewable resource supply dynamics within a disaggregated general equilibrium framework.

We find that the GNP and welfare costs of the carbon tax are significantly lower than what would be predicted if tax interactions were disregarded. When the revenues are used to finance reductions in marginal taxes at the personal or corporate level, the welfare costs are 25-32 percent lower than when the revenues finance lump-sum reductions in taxes. Pre-existing distortions -- specifically, the relatively light taxation of fossil-fuel-producing industries in comparison with other industries -- imply that the gross efficiency costs of carbon taxes are about 15 percent lower than would be the case if fossil-fuel-producing industries were not initially tax-favored.

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I. Introduction

A. Overview

In recent years policy makers and the general public have become increasingly concerned about the potential contributions of carbon dioxide (CO_2) emissions to the greenhouse effect and global climate change. Carbon dioxide now accounts for about half of the radiative warming associated with anthropogenic greenhouse gas emissions; under "business-as-usual" scenarios, carbon dioxide's contribution to global warming will rise (both absolutely and relative to other gases) over the next century as CO_2 emissions continue to increase.[1] The U.S. currently emits about 23 percent of global CO_2 emissions, and nearly all of the nation's CO_2 emissions are the result of the combustion of fossil fuels.[2] Hence fossil fuel burning in the U.S. is a potentially important contributor to the augmentation of the greenhouse effect.[3]

The recognition of these connections has generated support for policies to reduce or slow the growth of fossil fuel burning and, hence, of CO_2 emissions. One such policy is a carbon tax. This is a tax on fossil fuels -- oil, crude oil, and natural gas -- in proportion to their carbon content.[4] Since CO_2 emissions generally are proportionate to the amount of carbon content,[5] a tax based on carbon content

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[1]See U.S. Environmental Protection Agency (1989).

[2]See World Resources Institute (1990).

[3]U.S. demands for imports of fossil fuels and fossil-fuel-based products also contribute to CO2 emissions. The U.S. "responsibility" for CO_2 emissions might more be more closely related to its consumption, rather than production, of fossil fuels.

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

[5]The efficiency of the combustion process can affect somewhat the amount of carbon dioxide released per physical unit of fuel. However, this accounts for only slight variations in the ratio of CO_2 emissions to a fuel's carbon content.

is effectively a tax on CO_2 emissions.

A carbon tax would yield both benefits (avoided environmental damages) and costs, and responsible policy making requires attention to both. Assessing these effects is a formidable task. Recently a number of studies have sought to assess the economic costs which carbon taxes would impose on the U.S. and other nations. These studies have generated important insights into the costs of reducing CO_2 emissions. At the same time, the studies suffer from an important limitation in that they disregard interactions between carbon taxes and other taxes. Two important tax aspects are generally overlooked. First, the studies tend to assume that the revenues earned from carbon taxes are returned in lump-sum fashion to the economy. In fact, revenues from carbon taxes could be used to finance reductions in other, distortionary taxes.[6] The reductions in other taxes produce economic benefits by avoiding some of the distortions that other taxes would otherwise generate. Indeed, if the distortions produced by other taxes are large enough, then using carbon tax revenues to cut other taxes and reduce their distortions could yield gains that entirely offset the gross distortionary costs[7] of a carbon tax. Under these circumstances, a carbon tax could be justified on efficiency grounds even in the absence of environmental benefits. Advocates of "green" taxes would welcome such a result, since it provides an efficiency rationale for carbon taxes even under the most conservative assumptions about environmental benefits.

The second limitation stems from implicit assumptions about pre-existing taxes. With few exceptions,[8] studies of the costs of carbon taxes have assumed that these taxes are imposed on an economy without pre-existing taxes. This simplifying assumption can be critical to the cost assessment.

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[6]Of course, there are other options. The revenues could also be used to finance increases in Federal government spending or to reduce the Federal debt. The latter 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]).

[7]That is, the costs abstracting from the environmental benefits.

[8]An exception is the work of Jorgenson and Wilcoxen (1990a, 1990b).

It implies that, prior to the imposition of carbon taxes, the "playing field" is completely level. This case can be contrasted with the case where carbon taxes are imposed in an economy where fossil fuel producing industries initially enjoy relatively light taxation in comparison with other industries. In the former case, the efficiency costs of a carbon tax are likely to be considerably greater than in the latter: in the former case the carbon tax tilts the playing field (implying intersectoral efficiency losses), while in the latter it may help establish greater uniformity of taxation between fossil fuel and other industries (implying intersectoral efficiency gains).

Thus, how carbon tax revenues are used and the nature of pre-existing taxes may importantly influence the costs of a carbon tax. In this paper we address these issues in evaluating the costs carbon taxes. To assess these costs, we employ an intertemporal general equilibrium model of the U.S. economy. The general equilibrium framework is useful for addressing interactions among energy (fossil fuel) industries and beween these industries and other sectors of the economy. The intertemporal focus permits attention to how the effects of taxes change over time as households and firms alter saving and investment decisions.

The model employed here has three features that distinguish it from other economy-wide models applied to carbon taxes. These features make it uniquely well suited to evaluate the carbon tax in a realistic economic setting. First, it contains a detailed treatment of U.S. taxes. The model addresses effects of taxes on firms' investment incentives, equity values, and profits[9]; and on household consumption, saving and labor supply decisions. This permits attention to pre-existing tax distortions and allows one to consider various options for using carbon tax revenues to finance reductions in distortionary taxes.

Second, the model incorporates nonrenewable resource supply dynamics and transitions from

[9]Here the model applies the asset price approach to investment developed in Summers (1981) and previously employed in Goulder and Summers (1989).

conventional to synthetic fuels within a disaggregated general equilibrium framework. Previously such dynamics -- including the depletion of oil and gas stocks (and associated increases in production costs) and the eventual replacement of conventional fuels by a "backstop" technology -- have only been considered in optimization models, which involve highly aggregated treatments of industries and final goods. Recognizing the transition from conventional fossil fuels to synthetic fuels or backstop technologies is important for understanding the effects of a carbon tax, since there are significant differences in the carbon content of conventional fuels and synfuels.

Third, the model incorporates capital adjustment dynamics. In each industry, producers' investment decisions take account of the adjustment costs associated with the introduction of new capital. These costs render capital imperfectly mobile across industries and imply that firms will be less able to shift the burden of taxes to other sectors than would be the case under perfectly mobile capital. These dynamic considerations are important to understanding how industries adjust to the tax and the extent to which they bear or shift the tax burden.

Our simulations reveal that the GNP and welfare costs depend importantly on how the revenues from the tax are used and the nature of pre-existing tax distortions. When the revenues are used to finance reductions in marginal taxes at the personal or corporate level, the costs are 25-32 percent lower than when the revenues finance lump-sum reductions in taxes. Pre-existing tax distortions -- specifically, the relatively light taxation of fossil-fuel-producing industries in comparison with other industries -- imply that the gross efficiency costs of carbon taxes are about 15 percent lower than would be the case if the "playing field" were more level prior to the introduction of carbon taxes.

In the rest of this section, we discuss the relationship of this study to other empirical studies of the effects of carbon taxes. Section II describes the model, while Section III discusses the data and parameters. In Section IV we present and interpret simulation experiments involving different carbon tax alternatives. The final section concludes and lays out directions for further research.

B. Relationship to Other Studies

In the past few years several modeling efforts have been carried out with the aim of assessing the costs of reductions of carbon dioxide emissions.[10] A number of studies concentrate on the costs to particular industries -- mainly energy industries. These studies, which include Edmonds and Reilly (1983, 1985), and Morris (1991), provide important detail concerning abatement opportunities of particular sectors. However, the exclusive attention to certain industries prevents an assessment of the economy-wide effects of abatement policies.[11]

Economy-wide models that examine the costs of abatement fall into one of two general categories. One category consists of single-agent optimization models, of which Manne and Richels (1990a, 1990b, 1992) is a leading example.[12] The Manne-Richels model divides the world into five economic regions. In each region, a process model incorporating different technological options is linked to a one-sector macro model. Each region solves the problem of obtaining the path of aggregate consumption that maximizes intertemporal utility. The regions are linked through international trade in oil. The model is impressive in its attention to significant technological aspects of resource supply, including resource stock effects (increasing unit costs associated with depletion of resource stocks) and the possibility of resource exhaustion. Simulations with the model suggest that to stabilize U.S. emissions of CO2 at 1990 levels for the next 3-4 decades, carbon taxes in the range of $100-150 per ton would be necessary.

The other main category of economy-wide models consists of general equilibrium models. A leading example is the model of Jorgenson and Wilcoxen (1990a, 1990b), a dynamic general equilibrium

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[10]For a more comprehensive survey of models and results, see Nordhaus (1991) and Weyant (1991).

[11]The Edmonds-Reilly model currently is being extended to address economy-wide effects.

[12]Other optimization models include Nordhaus (1990) and Peck and Teisberg (1991). These models consider the environmental benefits, as well as the economic costs, of abatement of CO_2 (and other greenhouse gases). They have considerably less detail on production technologies than the Manne-Richels model.

model of the U.S.[13] The model has a more solid econometric foundation than most general equilibrium models; while many modelers borrow important parameters from other studies, the Jorgenson-Wilcoxen models's production and household demand parameters are estimated in time series using the model's own general equilibrium data set. The model's attention to forward-looking behavior and to technical change also distinguish it from many general equilibrium models. Jorgenson and Wilcoxen's analysis indicates that stabilizing U.S carbon emissions over the next three decades requires gradually increasing carbon tax rates that would reach a value of about $17 per ton by 2020. The required taxes are considerably lower than those which the Manne-Richels models suggests as necessary to meet the same objective.

The model employed in this paper offers a methodological advance in integrating some of the best features of the two categories of models. Like other general equilibrium models, this model can consider distortionary taxes. This is in contrast with optimization models, which assume no pre-existing tax distortions and which implicitly assume lump-sum recycling of carbon tax revenues.[14] As mentioned above, the consideration of distortionary taxes is important for evaluating the costs of a carbon tax. At the same time, and in contrast with other general equilibrium models, this model incorporates resource stock effects and a backstop technology. Previously, these have only been considered by optimization models. These resource features permit a richer exploration of dynamic adjustments than previously has been possible in a general equilibrium framework.

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[13]Other general equilibrium models that explore costs of emissions reductions include those by Whalley and Wigle (1991) and by Burniaux *et al.* (1991). The Jorgenson-Wilcoxen model is more closely related to the current investigation because of its focus on the U.S.

[14]Optimization models rely on the equivalence between the solution to the single-agent (planner's) maximization problem and the equilibrium outcome of a decentralized market economy. This equivalence requires the assumption of a first-best economy, that is an economy without pre-existing tax distortions.

II. The Model

The model generates an equilibrium path of prices and output for the U.S. economy. Equilibrium outcomes are calculated at yearly intervals over the 75-year period beginning in 1990.

A. Industry and Consumer Good Disaggregation

The model divides U.S. production into the 13 industries indicated in Table 1. The energy industries consist of coal mining, oil and gas, petroleum refining, and synthetic fuels. The synthetic fuels industry is a "backstop" industry: at constant returns to scale, it produces shale oil, a perfect substitute for oil and gas. Production of synfuels is not profitable at base year (1990) prices of inputs and outputs. Hence, as discussed in Section IV below, synfuels output becomes significant only in the future, when higher oil and gas prices could make synfuels economic.

The model also distinguishes the 17 consumer goods in Table 1. These goods are produced by combining the outputs of the 13 industries in given proportions.[15]

B. Production

In modeling the effects of a carbon tax, it is critical to account for potential substitutions between different forms of energy as well as between energy and other inputs. In the model, this is accomplished through a nested production structure in each industry. 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):

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

[15]We obtain these proportions by aggregating the translation matrix provided in the May 1984 *Survey of Current Business.*

The functions f, g, and h are CES in form. As indicated in Figure 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. The aggregation functions for E and M, and for the composites $\bar{x}_i$ are CES. This specification for production allows for input substitutions at several levels. Firms make these substitutions to minimize unit costs.

In equation (1), $\phi(I/K)\cdot I$ represents capital adjustment costs. The adjustment cost function, ϕ, is convex in I/K and has the form:

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

where δ is the rate of economic depreciation. This function 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.[16] ϕ denotes a rate per unit of investment; total adjustment costs (loss of output) are $\phi \cdot I$. Since the adjustment costs depend not only on I but also on K, the investment decision is fundamentally intertemporal: today's investment choices influence the costs of future investment through effects on future K.

Firms in each industry are regarded as price takers in the markets for inputs and outputs. Managers of firms are assumed to serve stockholders by maximizing the firm's equity value. As shown in Goulder (1991), the equity value of the firm at time t, V_t, can be expressed as:

[16]Here adjustment costs are internal to the firm. For a discussion of this and other adjustment cost specifications, see Mussa (1978).

(2) $$V_t = \sum_{s=t}^{\infty} \left[\left(\frac{1-\tau_e}{1-\tau_v}\right) DIV_s - VN_s \right] d(t,s)$$

where DIV_s and VN_s are dividends and new share issues at time s, τ_e and τ_v are the marginal tax rates on dividend income and capital gains, and *d(t,s)* is a discounting operator, defined as

(3) $$d(t,s) = \prod_{u=t+1}^{s} (1+r_u)^{-1}$$

where r_u is the after-tax rate of return the firm must offer to stockholders for period u. Equation (2) expresses the equity value of the firm as the discounted value of after-tax dividends less new share issues.

In each period, the firm's choice variables are the levels of labor and intermediate inputs and the level of investment. Optimal investment involves balancing the current costs of investment (both the acquisition costs of new capital and the adjustment costs) against the future benefits (the higher dividends made possible by a higher future capital stock). The solution to this problem is fully described in Goulder (1991).

C. Special Treatment of Oil and Gas: Depletion of Stocks, the Emergence of a Backstop Technology, and the Role of Imports

Because of the long-term nature of the climate change issue, most carbon tax policies under consideration are long-term as well. For this reason, it seems reasonable to investigate the effects of carbon taxes over an extended time horizon -- 75-100 years. Over a time horizon of this length, many standard assumptions of computable general equilibrium (CGE) models become difficult to sustain. The consensus view is that, despite new discoveries, identified oil and gas reserves will significantly diminish in the first half of the 21st century.[17] The real costs of producing oil and gas are likely to rise as

[17]See Masters *et al.* (1987) for estimates of undiscovered crude oil and natural gas reserves. If current rates of extraction were to continue into the next century, reserves would significantly diminish even under

marginal production involves more costly methods of extraction. To capture this phenomenon, one needs to model *resource stock effects* -- the increasing difficulty and cost of extracting given ores as their stocks are drawn down. Existing CGE models do not consider these effects.[18] Rather, they apply the same formal treatment for the supply of nonrenewable resources (e.g., oil and gas) as for the supply of ordinary produced goods (e.g., steel and clothing). Such a treatment implies that the supplies of oil and gas are inexhaustible; their production is limited only by the availability of capital and labor.

Another important phenomenon that is likely to occur over the next half century is the emergence of a synthetic fuels substitute for oil and gas. The current synfuels technology is not sufficiently advanced to make synfuels production economic at current oil and gas prices. However, as oil and gas resource stocks are depleted and the real prices of these resources rise, synfuels can be expected to gain an important share of the market for conventional energy.[19]

The model employed here considers important interactions between domestic oil and gas production, imports of oil and gas, and the emergence of a synthetic fuel substitute -- shale oil. We discuss these interactions below.

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the authors' most optimistic scenarios regarding potential discoveries.

[18]Optimization models, as distinct from general equilibrium models, have proven capable of addressing stock effects. Optimization models identify economic outcomes with the solution to a "planner's problem" involving the maximization of a single objective function, where typically the arguments of this function are levels of present and future consumption. See, for example, Manne and Richels (1990a, 1990b, 1992) and Peck and Teisberg (1991).

[19]This is the consensus opinion embodied in the climate-change-related modeling work now being undertaken by the Energy Modeling Forum at Stanford University. See Weyant (1991).

1. Stock Effects in the Oil and Gas Industry

The model employed here deals with stock effects in the oil and gas industry.[20] We sketch out the treatment here; a detailed discussion is provided in Goulder (1991).

In the oil and gas industry, the production specification is:

$$X = \gamma(Z) \cdot f[g(L,K), h(E,M)] - \phi(I/K) \cdot I \tag{4}$$

where γ is a decreasing function of Z, the amount of cumulative extraction (or output) of oil and gas as of the beginning of the given period. Z is a stock variable that is augmented according to the relationship, $Z_{t+1} = Z_t + X_t$.

The presence of 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).

The resource stock effect introduces two important production considerations. First, it introduces another intertemporal element: optimizing producers must account for the effects of current output decisions on future costs through the effects on cumulative extraction, Z. Second, the stock effect raises the possibility that costs of production will ultimately rise enough to warrant the shutting down of operations. The presence of a synthetic fuels backstop for oil and gas implies that there is an upper limit on the price that oil and gas producers can charge for their output. As shown in Goulder (1991), an oil and gas producer should shut down if the internal rate of return from remaining in operation permanently falls below the after-tax return that stockholders could earn on alternative investments. Under these circumstances stockholders are best served if the firm liquidates its remaining assets, enabling stockholders

[20]Coal is also a nonrenewable resource. However, coal reserves are very large relative to current output levels: at current rates of extraction, coal reserves could satisfy domestic demands for well over 100 years. See Edmonds and Reilly (1985). Over a 75-100 year horizon, it is reasonable to ignore stock effects for this resource.

to invest the proceeds from the liquidation at the market rate of return.

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 one difference, however. 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 on the availability and price of oil and gas, as discussed in II.G below.

3. Oil and Gas Imports and the Resource Price Path

We treat the U.S as a price taker in the world market for oil and gas. In standard scenarios, the world price begins at $24 per barrel (1990 dollars) and rises in real terms by $6.50 per decade.[21] 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.

However, 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 are the marginal source of supply, and the cost of synfuels production rather than the world oil price dictates the

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

domestic price of fuels. We discuss this issue further in section II.G below.

D. Household Behavior

Consumption, labor supply, and saving result from the decisions of an infinitely-lived representative household maximizing its intertemporal utility with perfect foresight. In year t it chooses a path of "full consumption" C to maximize

$$(5) \qquad U_t = \sum_{s=t}^{\infty} (1+\omega)^{t-s} \frac{\sigma}{\sigma-1} C_s^{\frac{\sigma-1}{\sigma}}$$

where C is CES a composite of consumption of goods and services G and leisure L:

$$(6) \qquad C_s = \left[G_s^{\frac{\upsilon-1}{\upsilon}} + \delta^{\frac{1}{\upsilon}} L_s^{\frac{\upsilon-1}{\upsilon}} \right]^{\frac{\upsilon}{\upsilon-1}}$$

In the equations above, ω is the rate of time preference, σ is the intertemporal elasticity of substitution, υ is the elasticity of substitution between goods and leisure, and δ is an intensity parameter for leisure. The household maximizes utility subject to the intertemporal budget constraint requiring that the present value of the consumption stream not exceed potential total wealth (current nonhuman wealth plus the present value of potential labor income and net transfers). In each period, overall consumption of goods and services *(G)* is allocated across the 17 specific consumption categories of Table 1 according to fixed expenditure shares. Each of the 17 consumption goods is a composite of a domestically and foreign-produced consumption good of that type. Households substitute between domestic and foreign goods to minimize the cost of obtaining a given composite good.

The aggregate endowment of time is exogenous: it grows at a constant rate, g, which determines the long-run (steady-state) growth rate of the economy. This growth represents Harrod-neutral technical progress in producing labor or leisure services per unit of actual time. Labor is perfectly mobile across sectors.

E. The Government Sector

The government collects taxes, distributes transfers, and purchases goods and services (outputs of the 13 industries). Overall government expenditure is exogenous and increases at a constant rate, g, equal to the steady-state growth rate of the model.[22]

The model incorporates a wide array of tax instruments. These include carbon taxes, output taxes, the corporate income tax, property taxes, sales taxes, and taxes on individual labor and capital income. A complete description of the taxes in the model is provided in Goulder (1991).

In the benchmark year, 1990, there is a government deficit equal to approximately two percent of GNP. In the baseline (*status quo*) simulation, the deficit-GNP ratio is approximately constant.[23] In the policy experiments in this paper, we require that the deficit follow the same path as in the baseline simulation. Consistency requires that total tax revenues be 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.

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[22]Public goods are not included in the household's utility function. This reflects the difficulty of assessing a household's utility from (or demand for) public goods. The omission is innocuous for welfare evaluations if public and private goods are separable in utility and if the path of provision of public goods is kept constant across simulation experiments.

[23]We assume that the real deficit grows at the steady-state growth rate, g. Along the baseline path and the economic path corresponding to policy changes, the growth rate of GNP generally differs from g in the short run but converges to g in the long run (steady state). Hence the deficit-GNP ratio is strictly constant only in the long run.

F. Foreign Trade

Except for oil and gas imports, which are perfect substitutes for domestically produced oil and gas, imported intermediate and consumer goods are imperfect substitutes for their domestic counterparts.[24] As indicated above, demands for foreign intermediate inputs stem from cost-minimizing producer behavior, while demands for foreign consumer goods derive from household utility maximization. Import prices are exogenous in foreign currency, but the domestic-currency price changes with changes in the exchange rate.

Export demands are modeled as functions of the foreign price of U.S. exports and the level of foreign income (in foreign currency). The foreign price is the price in U.S. dollars plus tariffs or subsidies, converted to foreign currency through the exchange rate. We impose the assumption of zero trade balance at each period of time. The exchange rate variable adjusts to reconcile the value of U.S. import demands with the value of foreign export demands.

G. Equilibrium

Equilibrium in each period satisfies four types of conditions:

(1) the aggregate demand for labor equals the aggregate supply;

(2) the demand for each industry output equals its supply;[25]

(3) the aggregate demand by firms for loanable funds equals the aggregate supply by households; and

(4) government tax revenues equal government spending less the government deficit.

[24] Thus, we adopt the assumption of Armington (1969).

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

These conditions are met through adjustments in output prices, in the market interest rate, and in lump-sum taxes or tax rates.[26]

In general, output prices serve as equilibrating variables. However, in the market for "fuel resources" (oil/gas and synfuels), the equilibrating variable depends on the supply circumstances. Let p_R represent the fuel resource price -- the price of oil/gas or of synfuels. Let $\bar{p}_W$ denote the (exogenous) price of imported oil/gas and let p_S represent the synfuels price that would be necessary to generate a quantity of synfuels sufficient to satisfy the domestic demand for resources net of domestic oil and gas production. Thus, p_S is the price that would induce sufficient synfuels supply to drive oil and gas imports to zero. For the "resources" market, the following relationships hold:

$$(7) \qquad p_R = \begin{cases} \bar{p}_W , & p_S \geq \bar{p}_W \\ p_S , & p_S < \bar{p}_W \end{cases}$$

These relationships are suggested by Figure 2. When p_S exceeds $\bar{p}_W$, domestic oil/gas production and synfuels are not sufficient to satisfy domestic resource demand. In this event, imports are the marginal source of supply, and the price received for a unit of resources is the exogenously specified world price, $\bar{p}_W$ (adjusted for tariffs). Under these conditions, the model employs the *quantity* of oil imports as the equilibrating variable that helps bring supplies and demands for resources into balance. In contrast, once synfuels production expands sufficiently to meet the entire domestic demand, oil/gas imports are zero and synfuels represent the marginal source of supply. Under these circumstances, the synfuels *price* p_S is the

[26]By Walras's Law, the required number of equilibrating variables is one less than the number of equilibrium conditions. The numeraire is the nominal wage, which is specified as growing exogenously at an annual rate of four percent. The growth rate of nominal wages determines the steady-state inflation rate, although the growth rates of all prices other than the wage rate are endogenous during the transition. Incorporating inflation in the model enables us to capture non-neutralities of the U.S. tax system with respect to the rate of inflation. The non-neutral features include deductibility of nominal interest payments and depreciation deductions based on historical cost.

equilibrating variable for the resource market. This is the price that brings synfuels supply plus domestic oil and gas supply into balance with the total domestic demand.

Since agents are forward-looking, equilibrium in each period depends not only on current prices and taxes but on future magnitudes as well. To obtain perfect foresight expectations, we repeatedly solve the model forward (usually for 75 one-year periods), each time generating a path of equilibria under a given set of expectations. After each path of equilibria is obtained, we revise the expectations and solve for a new path. In this iterative fashion, we ultimately obtain expectations that match actual outcomes and generate the consistent intertemporal path. Details on the solution method are provided in Goulder (1991).

III. Data and Parameters

A. Data

The data for the model 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. To convert 1986 values to 1990 (benchmark year) values, we scaled up the 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 1990 values accord closely with values projected by the OECD (1991).

Another important element of the data set is the carbon content of particular fossil fuels and of synfuels. This information is summarized in Table 2. As mentioned earlier, carbon content is proportional to carbon dioxide emissions. We calculated the carbon content of different fuels by multiplying the amount of carbon per unit of heat content (expressed in exajoules[27]) times the heat content per unit of fuel. Sources of this information are indicated in the table. It may be noted that synfuels contain more carbon per unit of heat content than oil, gas, or coal.

B. Parameters

Production function elasticities of substitution for the model were derived from estimates by Dale Jorgenson and Peter Wilcoxen. The Jorgenson-Wilcoxen estimates of parameters for translog cost functions were transformed to elasticities of substitution more compatible with the CES form of our model.[28]

For the oil and gas industry, it is necessary to specify the function $\gamma(Z)$ which relates the costs of production to cumulative extraction, Z. There is not sufficient information to estimate this function with precision; broad sensitivity analysis is critical here. For the central case specification, we specify the following quadratic relationship:

$$\gamma(Z) = \gamma_0 - (Z/\bar{Z})^2 \qquad (8)$$

with $\gamma_0 = 1$ and $\bar{Z} = 450$ billion barrels (about 100 times the 1990 production of oil and gas, where gas is measured in barrel-equivalents). The initial value for Z is 0.

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[27]An exajoule is 10^{18} joules or approximately 10^{15} British Thermal Units (BTU's); a BTU is the amount of heat energy required to raise the temperature of one pound of water one degree Fahrenheit (under specified conditions of pressure and temperature).

[28]There are several differences between the specifications of the Jorgenson-Wilcoxen model and this model which limit the reliability of the Jorgenson-Wilcoxen estimates in the present model. Beyond the differences in functional forms, there are differences in industry classifications. In addition, the Jorgenson-Wilcoxen production specification assumes that capital is perfectly mobile in every period, whereas our production specification allows for short-run capital immobility. It would be preferable to employ parameters that are estimated under the same specification as that in the model. Such work is in progress.

Other important parameters apply to the household side of the model. The elasticity of substitution in consumption between goods and leisure, υ, is set to yield an compensated elasticity of labor supply of 0.5: $\upsilon = 0.69$. The intensity parameter δ is set to generate a ratio of labor time to the total time endowment equal to .44.[29] The intertemporal elasticity of substitution, σ, equals .5.[30] Calibrating the model to 1990 flows leads to a value of 0.007 for time preference, ω. These parameters imply a value of 0.18 for the elasticity of savings with respect to the rate of interest between the current period and the next.

III. Simulations

A. Reference Case Simulation

To analyze the effects of carbon taxes, we first perform a reference case simulation. This simulation assumes *status quo* or "business-as-usual" conditions and forms a reference path for measuring effects of policy shocks.

In the reference case, all tax rates and other policy variables are kept constant at their benchmark (1990) values. The aggregate labor endowment (in efficiency units) grows at an exogenously specified rate of two percent. Real government expenditure also is specified to grow at the two percent rate.

In the long run, the economy reaches a steady state; all quantities increase at a rate of two percent

[29]In calibrating the model, we assume the representative consumer works 1920 hours out of a potential 4638 hours each year. The latter figure is based on the assumption that the consumer's work hours could not exceed 12 hours per day on average over the entire year.

[30]Econometric estimates of σ vary considerably; see, for example, Hall (1988) and Lawrance (1991). The value of 0.5 falls between the lower estimates from time-series analyses and the higher ones from cross-sectional studies.

(governed by the growth rate of effective labor), and relative prices do not change. There are two features of the model which prevent steady-state or balanced growth in the short and medium run along the reference path. First, the depletion of oil and gas reserves implies lower productivity or, equivalently, rising unit costs of domestic oil and gas supply. In addition, the real prices of imported oil and gas are exogenously specified as increasing in real terms. These features lead to reductions, over time, in the share of oil and gas consumption relative to overall consumption. As indicated in Figure 3, rising costs of domestic oil and gas production lead to diminishing output of domestic oil and gas, and rising import prices eventually cause synfuels to replace conventional fuels in the "resource" (oil/gas and its equivalent) market. Synfuels technology is introduced in 2010, and by 2040 synthetic fuels enjoy more than a 75 percent share of the fuels resource market. In the steady state, synthetic fuels entirely replace conventional oil and gas.

B. Effects of Carbon Taxes

1. Lump-Sum Revenue Adjustments

We now consider the effects of carbon taxes imposed unilaterally by the U.S. We consider taxes of $25, $50, and $100 per ton in 1990 dollars, with the tax applying to domestically produced fossil fuels and to imported fossil fuels.[31] At 1990 prices, a $25/ton carbon tax amounts to a tax of $13.40 per short ton of coal, of $2.93 per barrel of oil, and $0.35 per thousand cubic feet of natural gas. If there were no effect on pre-tax prices, a $25/ton tax would raise the prices of coal, oil, and natural gas by 72, 13, and 24 percent, respectively.[32]

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[31]More precisely, the tax applies to fossil fuels that are consumed domestically. Exported fuels are exempt from the tax. For a discussion of alternative carbon tax designs, see Goulder (1992).

[32]The price increases reflect not only the direct impact of the tax but also an indirect effect associated with higher-priced fossil fuel inputs used in the production (extraction) of fossil fuels. See Goulder (1992) for an analysis of these effects.

These policies bring in government revenue. Since real government expenditure and the real deficit are exogenously specified, it is necessary to adjust some other tax in these experiments so that tax revenues plus the exogenous government borrowing are consistent with the exogenous level of government spending. In these first experiments we reduce personal taxes in *lump-sum* fashion to satisfy the consistency requirement. The lump-sum reduction in taxes represents a reduction in the household's average tax rate. The marginal tax rates applicable to individual labor and capital income are unchanged.

Figure 4 displays the effects of these taxes on carbon emissions.[33] The solid line represents emissions growth in the reference case. Emissions grow steadily over the 60-year interval displayed. Larger carbon taxes lead to more substantial emissions reductions. However, doubling the magnitude of the tax leads to less than a doubling of the emissions reduction. This reflects rising marginal costs to producers of reducing the use of fossil fuels and to consumers of substituting for fossil-fuel-intensive goods and services.

None of the taxes causes emissions to remain permanently below the 1990 levels from the reference case. Under the $25/ton tax, emissions return to 1990 levels after about 22 years; under the $100/ton tax, this occurs after approximately 43 years.

Figures 5a and 5b display the effects of the tax on GDP. Consider first the upper figure. A $25/ton tax reduces GDP (relative to the reference path) by about 0.7-0.8 percent in the first five years and by about 1.4 percent in the long run; a $100/ton tax reduces GDP by about 2.9-3.3 percent initially and by about 5.8 percent in the long run. The costs increase more than in proportion to the magnitude of the carbon tax. This is in keeping with standard excess burden analyses that suggest that efficiency costs increase with the square of the tax rate. It should be kept in mind that in discussing GDP costs and

[33]These are the carbon emissions associated with U.S. demands for (consumption of) goods and services. An alternative emissions measure relates to U.S. supplies of (production of) goods and services. The U.S. is a net importer of emissions in the sense that consumption-related emissions are higher than production-related emissions. In other words, the goods which the U.S. imports involve more emissions than the goods which it exports.

efficiency costs, we are abstracting from the beneficial effects on GDP in the form of avoided environmental damages. A broader notion of efficiency would encompass both sides of the cost and benefit evaluation.

In percentage terms, the GDP losses are larger in the long run than in the short run. This reflects the fact that, in the long run, conventional oil and gas resources are replaced by synthetic fuels. The latter are more carbon-intensive than the energy-equivalent volume of oil and gas; hence, synfuels face higher carbon taxes per unit of energy. In the long run, the real tax burden on energy therefore rises with the move to synfuels. Although carbon taxes discourage consumption of synfuels as well as other fossil-based fuels, they do not prevent the shift to synfuels: the dwindling of domestic oil and gas reserves and rising real prices of imported oil make this shift necessary. These results attest to the importance of considering stock effects and the conversion to backstop technologies in assessing carbon tax policies over a long time horizon.

Table 3 shows the effects of the taxes on welfare. The welfare measure here is the equivalent variation expressed as a percentage of the households' after-tax income (over the infinite horizon).[34] Thus the welfare loss from the $25/ton carbon tax, for example, is equivalent to a 0.71 percent reduction in the household's initial financial and human wealth -- the present value of its current and future after-tax labor and capital income as measured from 1990. As with GDP, the welfare costs rise more than in proportion to the magnitude of the tax.

2. Alternative Revenue Adjustments: Reducing Pre-existing Distortionary Taxes

Included in Figure 5b (for GDP) and Table 3 (for welfare) are results from simulations involving

[34]The equivalent variation is the lump-sum payment which would enable the household to achieve the same level of intertemporal utility in the reference case (facing reference case prices and policy parameters) as under the policy change. Thus a positive equivalent variation implies that the policy change is welfare-improving.

alternative methods of revenue adjustment. In contrast with the previous simulations, where carbon tax revenues financed lump-sum reductions in other taxes, in the new simulations the carbon tax revenues finance reductions in distortionary taxes. These simulations consider a tax rate of $25/ton.

Three alternative revenue adjustments are considered. In the personal income tax adjustment simulation, the carbon tax revenues finance reductions in marginal tax rates on labor and capital (interest, dividend, and capital gains) income at the personal level. Marginal taxes on labor and on capital are reduced in the same proportion. The revenues are large enough to reduce the marginal tax on labor from .259 to .255 and the marginal tax on capital from .262 to .258. In the corporate income tax adjustment simulation, the carbon revenues finance reductions in the corporate profits tax. The carbon tax revenues can support a reduction in this tax from .507 to .450.[35] A third alternative simulation reduces indirect labor taxes (payroll taxes) by the same proportion in each industry.

The results reveal smaller GDP and welfare losses than in the corresponding lump-sum adjustment simulation. The welfare loss is approximately 25 percent smaller when marginal taxes are reduced at the personal level, 32 percent smaller when the profits tax is reduced, and 28 percent smaller when payroll taxes are reduced. Using the carbon revenues to finance cuts in distortionary taxes significantly reduces the overall economic losses. At the same time, the cuts in distortionary taxes do not entirely eliminate the GDP or welfare costs.[36] This indicates that the gross distortion[37] from a carbon tax is greater than

[35]The corporate rate accounts for profits taxes at both the Federal and state levels.

[36]It is possible to use the revenues in a way that ultimately yields an increase in GDP relative to the reference case. Specifically, in an alternative simulation in which revenues finance investment tax credits, the capital stock expands enough to allow GDP to rise relative to the reference case after about 25 years. However, this simulation does not yield a welfare increase: the longer-term increases in consumption are not large enough to offset the nearer-term reductions in consumption which were necessary to finance the increases in investment.

[37]That is, the efficiency cost abstracting from environmental benefits.

that generated by equal-revenue changes in the personal income tax, corporate profits tax, or payroll tax.[38]

These results suggest that the carbon taxes cannot be justified on the basis of (narrow) efficiency considerations alone. If there were no environmental benefits associated with these taxes, they would appear to generate reductions in welfare. Since the carbon tax is a type of commodity tax, this finding may seem contrary to the view that increased reliance on commodity taxes instead of income taxes would improve the overall efficiency of the U.S. tax system. This view has fairly wide support among public finance economists.[39] In fact, these carbon tax results do not contradict this view. Advocates of commodity taxation generally promote *broad-based* commodity taxes. Carbon taxes, in contrast, apply to a fairly narrow portion of the overall economy: in 1990, for example, the fossil-fuel industries (which form the base of a carbon tax) produced less than three percent of the nation's value-added. Greater reliance on broad-based commodity taxes might well improve the efficiency of the U.S. tax system, but adopting a carbon tax is not a move in this direction, since the carbon tax is not broad-based.

To what extent is the narrowness of the carbon tax base responsible for its large efficiency costs relative to other taxes? To address this issue, we simulated a uniform, across-the-board output (commodity) tax with the same revenue yield as the $25 per ton carbon tax. We use the revenues to finance reductions in marginal rates on individual capital and labor income, as in carbon tax simulation involving reductions in the personal tax. As Table 3 indicates, this policy combination leads to an efficiency gain. This contrasts with the result from carbon tax simulation employing the same specification for revenue adjustment. This suggests that the breadth of the tax base is critical.

However, the broad-based output tax differs from a carbon tax in two ways: its base is broader

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[38]A potential bias against carbon taxes in the model is its treatment of the world oil price as exogenous. If the model accounted for U.S. monopsony power, the costs would be offset to some degree through downward pressure exerted on the (net-of-tax) world oil price.

[39]See, for example, Jorgenson and Yun (1990), and Ballard, Scholz, and Shoven (1987).

and its rates are uniform across sectors. To separate out the effect of rate uniformity from the effect of the breadth of the tax base, we perform another simulation. Here we introduce a tax with the same tax base as the carbon tax -- it applies only to fossil fuels and synthetic fuels -- but with uniform rates across the industries within the tax base. Again the tax rates are scaled so as to yield the same revenue as the $25 per ton carbon tax. As the final row of Table 3 indicates, this experiment leads to only a modest reduction in the magnitude of the welfare loss. In other words, the uneven taxation of different fuels under the carbon tax only accounts for a small portion of its efficiency loss. Taken together, the last two experiments in Table 3 indicate that it is the narrowness of the tax base, rather than the unevenness of its tax rates on fuels, that is most responsible for the large gross efficiency costs of a carbon tax.

3. Significance of Pre-Existing Distortions

To consider the importance of prior taxes, we perform additional simulations which incorporate counterfactual assumptions about the the initial conditions of the economy in which the carbon tax is introduced. The fuel producing industries -- coal, oil and gas, and synthetic fuels -- face taxes on labor and capital prior to the introduction of carbon taxes. Because of depletion allowances and relatively favorable depreciation rules, these industries together face somewhat lower taxes on capital than other industries.[40] The marginal indirect labor tax rates are also slightly lower than the average marginal rates for other industries. In an additional simulation experiment, we assume, contrary to fact, that prior taxes on capital and labor in the fuel-producing industries are exactly the same as the weighted-average marginal rates on capital and labor in other industries. We thus assume a "level playing field" between the fuel-producing industries and other industries. It should be noted that these assumptions are incorporated in an alternative reference case as well as the policy change case now considered.

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[40]The weighted average effective marginal tax rate on capital is 0.18 for these industries, as compared with 0.28 for all the non-residential industries.

Table 3 shows that the assumptions about prior taxes are important: the welfare cost of a $25/ton carbon tax with lump-sum use of the revenues is 0.71 under our central case values for prior taxes. This cost is about 15 percent less than the cost (0.84) when the fuel-producing industries face the same indirect labor and capital tax rates as do other industries. When prior taxes favor fuel-producing industries, the playing field *after* carbon taxes is more level than would be the case if the prior tax burdens were uniform. Consequently, the efficiency costs are smaller when prior taxes favor fuel-producing industries. Models that disregard prior taxes implicitly assume a level playing field prior to the introduction of the carbon tax. Hence they are biased toward exaggerating the costs of carbon taxes.

4. Industry Effects

Table 4 shows the effects of a $25/ton carbon tax on the output levels and output prices for the different industries. These results are for the simulation with lump-sum tax adjustment. The coal mining industry suffers the greatest output loss, in keeping with the fact that coal is the most highly taxed (per unit of energy or per dollar of fuel) of the fossil fuels. In most industries, output falls by a greater percentage in the long run than in the short run. This reflects the transition from oil and gas to coal and synfuels, both of which are more carbon intensive per dollar than oil and gas. Thus the base of the carbon tax, and the corresponding tax burden, increase over time. This increase is reflected in growing output losses.

Coal prices rise by 64 percent in the short run and about 70 percent in the long run. The carbon tax induces producers to reduce coal supplies.[41] In so doing they are able to shift an increasing share

[41]Table 2 indicated that a $25/ton carbon tax would increase the price of coal by 57.2 percent if pre-tax prices remained unchanged. The percentage increases from our simulations are higher than this. The reason is that the carbon tax leads to increases in the prices of many of the inputs used to produce coal. In Goulder (1992), we take these effects into account and show that a $25/ton carbon tax would raise the price of coal by 72.0 percent if the cost of the tax were entirely shifted onto the purchasers of coal. Table 4 shows that the actual price increase is about 64 percent in the short run and 69 percent in the long run. Thus, consumers bear about 89 percent of the tax burden on impact and about 96 percent

of the tax burden to consumers of coal.

5. Sensitivity Analysis

Our final simulations examine the sensitivity of results to important model parameters. Table 5 displays the significance of these parameters for the effects of a $25/ton carbon tax whose revenues are returned in lump-sum fashion to the households. We use the equivalent variation measure to gauge the costs of this policy. The numbers in the left-hand column account for the welfare effects along the entire path of transition as well as in the new steady state. The figures in the right-hand column consider only the changes in steady-state welfare.

In the central case, the parameters of the synfuels production function imply unit costs of $50 per barrel-equivalent when real input prices are at 1990 levels. Specifying lower synfuels costs implies a higher *level* of welfare under a carbon tax than in the central case. However, the welfare *change* -- the difference between reference case and policy change case for a given set of parameter assumptions -- is greater when the synfuels cost is lower. The reason is that lower synfuels costs imply faster introduction of the new technology. (Synfuels drive out oil imports by 2032 in the low-cost scenario, as compared to 2044 in the central case scenario.) A given path of world oil prices yields greater profit opportunities for synfuels the lower is the cost of synfuels production. Since synfuels are more carbon-intensive than conventional fuels, the government collects more in carbon taxes sooner when synfuels penetrate the market sooner. Hence, the welfare change relative to the no-tax case is greater. Correspondingly, when higher synfuels production costs are assumed, the welfare change is smaller since the pace of synfuels introduction is slower (imports are eliminated by 2051) and the carbon tax base expands more slowly.

The economy reaches a steady state only after synfuels have entirely replaced conventional oil and gas. The nature of the steady state is largely independent of transition issues such as the speed of synfuels

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of the burden in the long run.

market penetration. For this reason changes in assumptions about synfuels costs make relatively little difference to the steady-state welfare impacts.

Larger reserves of domestic oil and gas imply that domestic production will maintain larger shares of U.S. consumption for a longer time. This implies a higher *level* of domestic welfare than under central case assumptions. The larger the share of consumption represented by domestic production, the smaller the import share and the smaller the terms of trade losses from rising oil prices. At the same time, larger domestic reserves have very little effect on the timing of synfuels introduction. The reason is that, even under optimistic assumptions regarding domestic reserves, oil imports are the marginal source of supply and determine the market price until synfuels eliminate them. Thus the domestic reserve assumptions have no effect on the oil/gas price path, and the incentives for synfuels production are largely unaffected.[42] For this reason, the welfare impact of a carbon tax does not change much under different assumptions about the extent of domestic oil/gas reserves. Welfare effects change significantly with changes in assumed elasticities of substitution in production. The welfare costs are roughly proportional to the elasticities. Higher elasticities imply greater opportunities to substitute for higher-priced fuels; hence the lower welfare costs.

Lower adjustment costs make possible more rapid reallocations of industry capital stocks following a policy shock. As with greater substitutability, less costly adjustment implies smaller welfare losses. Adjustment costs are primarily important during the transition. By definition, the steady state is reached after full adjustment. Hence assumptions about adjustment cost parameters are not significant to changes in steady-state welfare.

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[42]The model assumes that world oil prices are exogenous. An alternative assumption would attribute some monopsony power to the U.S. In this event, increased domestic production of oil and gas could drive down the world price by reducing import demands.

IV. Conclusions

For advocates of carbon taxes, the news from these simulations is both good and bad. The good news is that the gross distortionary cost (i.e., the cost exclusive of environmental benefits) of carbon taxes can be significantly reduced when the revenues are used to finance reductions in other distorting taxes. The bad news is that, for the alternatives considered in this paper, "recycling" the revenues does not bring the gross distortionary cost to zero. When the environmental benefits of carbon taxes are ignored, carbon taxes generally appear more distortionary (because of their narrow tax base) than the taxes they are likely to replace.[43] To justify a carbon tax, one needs to invoke the environmental benefits.

The magnitudes of these benefits, unfortunately, are quite uncertain. Partly as a result of these uncertainties, the issue of whether to introduce a carbon tax remains highly controversial.[44] Although the results in this paper do not answer this question, they do indicate how the gross costs of such taxes can be reduced.

The results also indicate the importance of taking pre-existing distortions into account in evaluating the costs of carbon taxes. Because fossil fuel industries tend to be tax favored, the costs of new taxes like carbon taxes are considerably smaller than would be the case if the new taxes were imposed in an economy with more even prior taxation.

The results in this paper should be interpreted with caution. There are important limitations in the model which should be recognized. The homothetic nature of the consumer demand functions in the model tends to imply a more persistent reliance on energy-based products than is warranted by recent

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[43]The prospects may be more favorable in some other industrialized nations. For example, in many European countries, marginal tax rates on labor are much higher than in the U.S. Hence the distortions from labor taxes are likely to be greater. In these countries, using carbon tax revenues to finance reductions in labor tax rates might well generate gross efficiency gains. The issue is complicated by the fact that a carbon tax itself is, to a degree, an implicit tax on labor. On this issue see Bovenberg (1992).

[44]To date, there has been more economic analysis of the cost side than the benefit side. The payoffs to research on the benefit side may be quite large. The U.S. Environmental Protection Agency has recently begun a major research effort to evaluate the potential environmental benefits.

empirical work. Econometric work could improve the production function parameters used in the model. There is substantial uncertainty regarding the parameters that determine the scope of resource stock effects and the cost of the backstop technology, and further work to narrow the uncertainty bands would be most worthwhile.

Notwithstanding the limitations, the model offers a unique and useful framework for examining interactions between environmental initiatives and tax distortions. It would be worthwhile to employ it to evaluate taxes on other greenhouse gases and other tax policies serving environmental objectives. More broadly, the general framework introduced here -- one which integrates nonrenewable resource supply with distortionary taxation -- has several natural applications in the areas of energy policy and land use policy.

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Table 1
Industry and Consumer Good Categories

Industries

1. Agriculture and Non-Coal Mining
2. Coal Mining
3. Crude Petroleum and Natural Gas
4. Synthetic Fuels
5. Petroleum Refining
6. Electric Utilities
7. Gas Utilities
8. Construction
9. Metals and Machinery
10. Motor Vehicles
11. Miscellaneous Manufacturing
12. Services (except housing)
13. Housing Services

Consumer Goods

1. Food
2. Alcohol
3. Tobacco
4. Utilities
5. Housing Services
6. Furnishings
7. Appliances
8. Clothing and Jewelry
9. Transportation
10. Motor Vehicles
11. Services (except financial)
12. Financial Services
13. Recreation, Reading, & Misc.
14. Nondurable, Non-Food Household Expenditure
15. Gasoline and Other Fuels
16. Education
17. Health

Figure 1

Nested Structure of Production

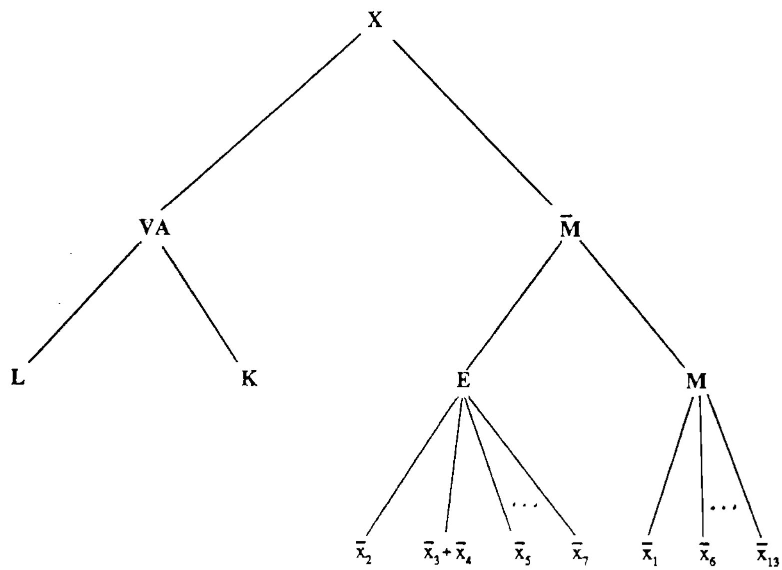

Figure 2
Relationship between World Oil Price and Backstop Price

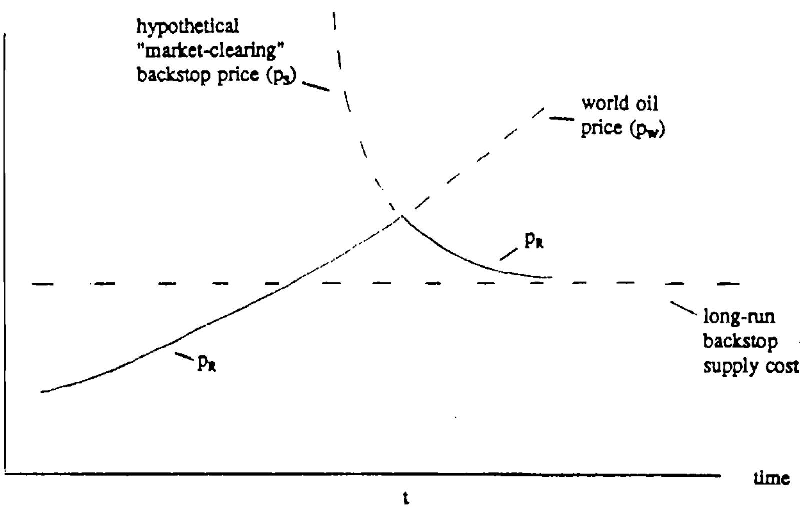

Table 2

Carbon Content of Fossil Fuels

	Coal	Oil	Natural Gas	Synfuels
1. fuel unit	short ton	barrel	kcf[1]	barrel-equivalent
2. metric tons of carbon per exajoule[2]	24.12×10^{6}	19.94×10^{6}	13.74×10^{6}	40.0×10^{6}
3. exajoules per fuel unit[3]	22.29×10^{-9}	5.89×10^{-9}	1.04×10^{-9}	5.89×10^{-9}
4. metric tons of carbon per fuel unit [(2) × (3)]	537.6×10^{-3}	117.4×10^{-3}	14.3×10^{-3}	235.6×10^{-3}
5. 1990 price of fuel unit	$23.50	$24.00	$1.60	NA
6. metric tons of carbon per dollar of fuel in 1990 [(4) / (5)]	.0229	.0049	.0089	NA
7. Percent increase in price implied by $25/ton carbon tax [25 × (6) × 100][4]	57.2	12.2	22.2	NA

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[1]"kcf" means 1000 cubic feet.

[2]Following from Weyant (1991). Weyant's rates are expressed as metric tons per quadrillion BTU's.

[3]Based on figures in Department of Energy, Energy Information Administration, *Annual Energy Outlook* 1989.

[4]This assumes the tax has no effect on the pre-tax price. Effects on pre-tax prices are analyzed in Section IV of text.

Figure 3
Consumption of Oil & Gas and Synthetic Fuels
(evaluated at 1990 prices)

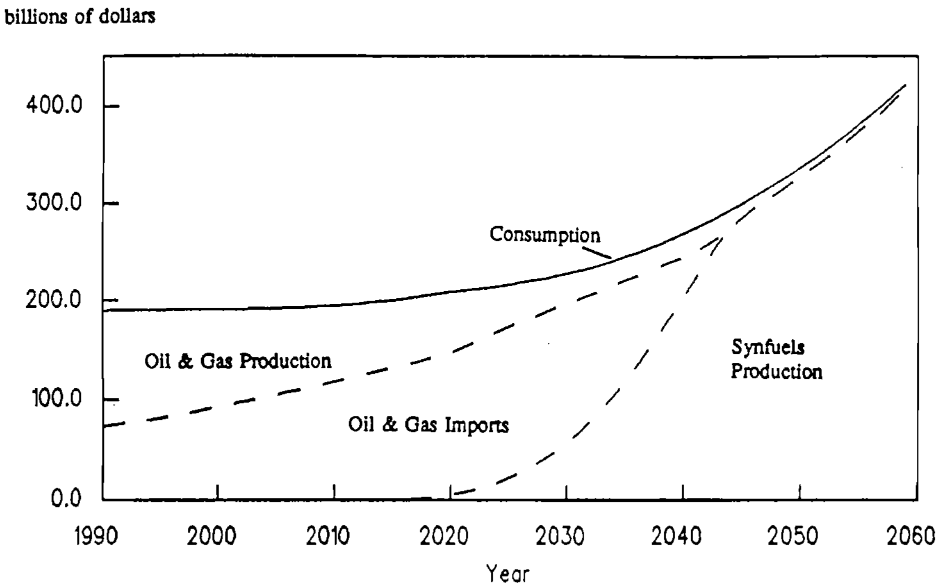


Figure 4
Carbon Emissions

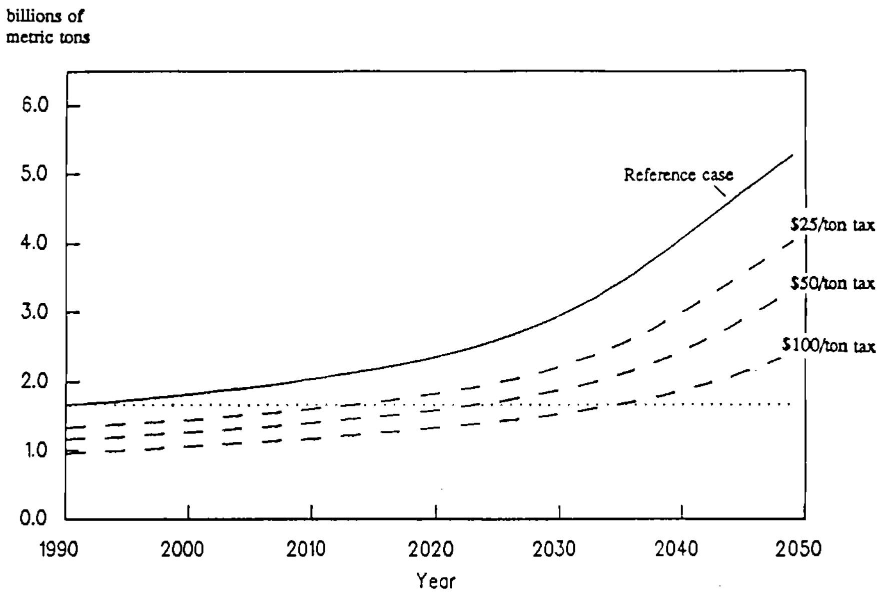
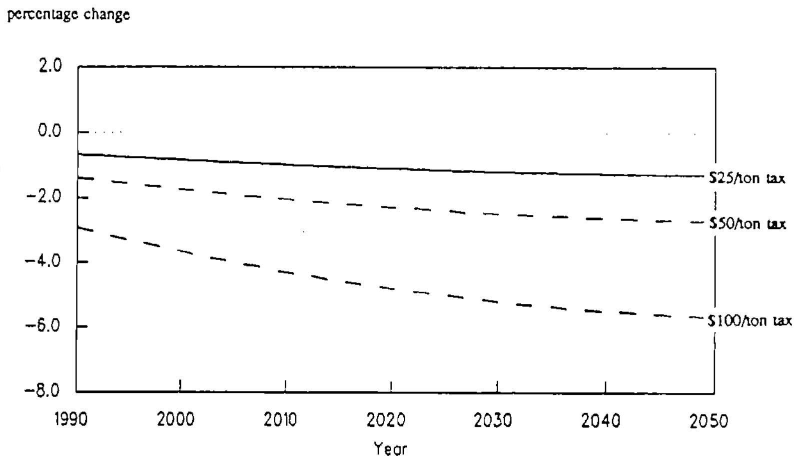


Figure 5
Effects on GDP
(percentage changes from reference case)

(a)



(b)

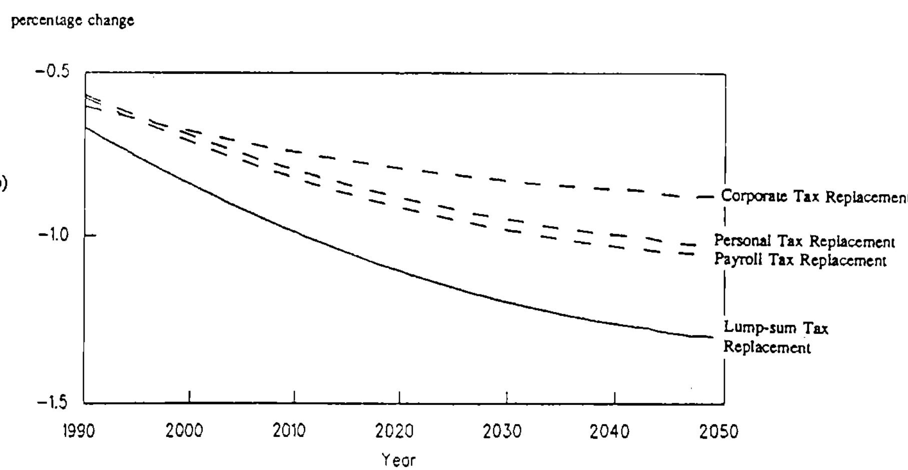


Table 3
Welfare Effects[1]

	Welfare Change
I. Carbon Tax	
Initial Simulation ($25/Ton Tax, Lump-Sum Rev. Adjustment)	-0.712
Alternative Tax Rates	
$50/Ton	-1.494
$100/Ton	-3.103
Alternative Revenue Adjustments	
Cut Personal Income Taxes	
-- all marg. rates reduced	-0.536
-- labor marg. rates reduced	-0.539
-- capital marg. rates reduced	-0.530
Cut Corporate Taxes	-0.482
Cut Payroll Taxes	-0.513
Alternative Pre-Existing Taxes[2]	
No Prior Tax Preference to Fossil Fuel Industries	-0.840
II. Alternative Output Taxes (with Personal Income Tax Reduction)	
Broad-Based Uniform Output Tax	0.118
Uniform Output Tax, Fossil and Synfuels Industries Only	-0.510

Notes:

1. The measure of the welfare change is the equivalent variation as a percentage of the present value of household income over the infinite horizon.
2. The counterfactual assumption for this simulation applies in both the reference case and under the policy change (carbon tax).

Table 4
Effects of $25/ton Carbon Tax on Industry Output and Prices
(percentage changes from reference case)

	Output		Prices	
	Short Run	**Long Run**	**Short Run**	**Long Run**
Industry				
1. Agriculture and Non-Coal Mining	-0.08	-0.67	-1.19	-1.02
2. Coal Mining	-37.14	-42.61	64.10	69.51
3. Crude Petroleum and Natural Gas	-1.39	--	13.92	--
4. Synthetic Fuels	--	-10.53	--	12.57
5. Petroleum Refining	-8.91	-7.24	7.23	8.04
6. Electric Utilities	-3.30	-4.64	4.01	4.93
7. Gas Utilities	-2.81	-3.26	4.59	4.01
8. Construction	-0.27	-0.86	-0.60	-1.02
9. Metals and Machinery	-0.50	-0.62	-1.14	-1.46
10. Motor Vehicles	0.03	-0.54	-0.62	-1.14
11. Miscellaneous Manufacturing	-0.36	-0.73	-0.71	-1.02
12. Services (except housing)	-0.43	-0.91	-0.70	-1.14
13. Housing Services	-0.01	-0.76	-0.50	-1.13

Note: "Short Run" and "Long Run" refer to the first simulation period and the steady state, respectively. Prices include carbon taxes and are expressed relative the producer price index.

Table 5

Sensitivity Analysis
$25/ton Carbon Tax, Lump-Sum Tax Adjustment

			Equivalent Variation as Percent of Lifetime Income	
			Transition Considered	Steady State Only
1.	Central Case		-0.712	-0.781
2.	Long-Run Backstop Cost[1]			
	a.	$40 per barrel-equivalent	-0.764	-0.855
	b.	$70 per barrel-equivalent	-0.625	-0.733
3.	Reserves of Domestic Oil & Gas[2]			
	a.	$\bar{\bar{Z}} = 900$	-0.681	-0.788
	b.	$\bar{\bar{Z}} = 225$	-0.894	-0.792
4.	Production Function Elasticities			
	a.	High (2 × reference values)	-0.577	-0.662
	b.	Low (0.5 × reference values)	-0.881	-1.105
5.	Capital Adjustment Costs[3]			
	a.	Low (zero)	-0.602	-0.763
	b.	High (2 × reference values)	-0.883	-0.808

Notes:

(1) This is the long-run unit cost of backstop production when real input prices are at 1990 levels. In the central case, the long-run backstop cost is $50 per barrel-equivalent.

(2) Units for $\bar{\bar{Z}}$ are billions of barrels of oil. Central case value for $\bar{\bar{Z}}$ is 450.

(3) In the high adjustment cost scenario, we double the β parameter of the quadratic adjustment cost function (see Section II.B). In the low adjustment cost scenario, $\beta = 0$ for all industries except for synfuels. In the synfuels industry, the value of β is halved. Zero adjustment costs for synfuels would imply implausibly rapid market penetration.