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ABSTRACT

This paper examines the optimal setting of environmental taxes in economies where other, distortionary taxes are present. We employ analytical and numerical models to explore the degree to which, in a second best economy, optimal environmental tax rates differ from the rates implied by the Pigovian principle (according to which the optimal tax rate equals the marginal environmental damages). Both models indicate, contrary to what several analysts have suggested, that the optimal tax rate on emissions of a given pollutant is generally *less* than the rate supported by the Pigovian principle. Moreover, the optimal rate is *lower* the larger are the distortions posed by ordinary taxes. Numerical results indicate that previous studies may have seriously overstated the size of the optimal carbon tax by disregarding pre-existing taxes.

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I. Introduction

Most economies feature levels of public spending that require more tax revenues than would be generated solely from pollution taxes set according to the Pigovian principle, that is, set equal to marginal environmental damages. As a consequence, tax systems generally rely on both environmental (corrective) and other taxes. However, the tradition among economists has been to analyze corrective and distortionary taxes separately: environmental taxes usually are examined without taking into account the presence of other, distortionary taxes. This omission is significant because the consequences of environmental taxes depend fundamentally on the levels of other taxes, including income and commodity taxes.

This paper examines optimal environmental taxation in a second-best setting. In particular, we explore how optimal environmental tax rates deviate from the rates implied by the Pigovian principle. The few previous investigations of this issue[1] include Sandmo (1975), Lee and Misiolek (1986) and Oates (1991). Sandmo demonstrated how the well-known "Ramsey" formula for optimal commodity taxes is altered when one of the consumption commodities generates an externality. Lee-Misiolek and Oates derive formulae indicating how the optimal rate for a newly imposed environmental tax is related to the marginal excess burden from existing taxes. The present paper extends this literature in three ways. First, in contrast with Sandmo's work, it derives analytical expressions for the optimal environmental tax in a more general setting that considers intermediate inputs as well as consumption commodities and incorporates both public and private goods in utility. Second, it differs from the papers of Lee and Misiolek and Oates in applying a general equilibrium analysis to link environmental and other taxes; distortionary costs of ordinary and environmental taxes are determined endogenously. Finally, in contrast with the earlier papers it combines the analytical work with numerical simulations that consider the implications of these principles for the U.S. economy.

The paper is organized as follows. Section II analytically investigates optimal environmental taxes using a simple general equilibrium model. The next two sections explore these issues numerically employing a disaggregated intertemporal general equilibrium model. Section III describes the numerical model; Section IV applies this model to evaluate the departures from Pigovian tax rules implied by second-best considerations. The final section offers conclusions.

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[1]A closely related issue is the extent to which the costs of environmental taxes are lowered when revenues from such taxes are devoted to reductions in existing distortionary taxes. A key question is whether "recycling" the revenues in this way can make the overall cost of the revenue-neutral policy zero or negative. For discussions of this issue in the context of carbon taxes, see Poterba (1993), Oates and Portney (1992), Pearce (1991), and Stavins (1991). For numerical investigations with carbon taxes see, for example, Weyant (1993) and Goulder (1994).

II. Theoretical Issues and Analytical Results

This section explores analytically how the presence of distortionary taxation affects the optimal setting of environmental taxes in the context of a simple model. Production is described by a constant-returns-to-scale production function $F(NL,X,Y)$ with inputs of aggregate labor (the product of the number of households N, and per capita labor supply, L), a "clean" intermediate good (X), and a "dirty" intermediate good (Y). Output can be used for public consumption (G), for clean or dirty intermediate inputs, or for household consumption of a "clean" and "dirty" consumption good (per capita clean and dirty consumption is denoted by C and D, *respectively*). Hence, commodity market equilibrium is given by

$$F(NL,X,Y) = G+X+Y+NC+ND \tag{1}$$

We normalize units so that the constant rates of transformation between the five produced commodities are unity.

The representative household maximizes private utility subject to the budget constraint:

$$(1+t_C)C + (1+t_D)D = (1-t_L)wL \tag{2}$$

where t_C and t_D denote, respectively, the tax rates on clean and dirty consumption. The labor tax rate t_L, and the producer (before-tax) wage, w, yield the consumption (after-tax) wage, $(1-t_L)w$. Environmental quality, E, deteriorates with the quantity used of dirty intermediate and dirty consumption goods; that is, $E=e(Y,ND)$ with $e_Y,e_{ND}<0$, where subscripts denote partial derivatives. Private decision makers ignore environmental externalities.

The government budget constraint is:

$$G = t_X X+t_Y Y+t_D ND+t_L wNL \tag{3}$$

where t_X and t_Y stand for the taxes on clean and dirty intermediate inputs, respectively. We assume (without loss of generality[2]) that the clean consumption commodity is untaxed.

[2]See footnote 5 below.

To derive the optimal tax rates, we solve the government's problem of maximizing household utility subject to the government budget constraint and decentralized optimization by firms and households. Private commodities are separable from public goods in household utility. Accordingly, the government adopts its four tax instruments (t_L, t_D, t_X, t_Y) to optimize:

$$NV[(1+t_D);\ (1-t_L)w] + NW[G, e(Y,ND)] + \mu(t_L wNL + t_D ND + t_X X + t_Y Y) \tag{4}$$

where V represents household indirect utility of private goods, $W(G,E)$ is utility from public goods, and μ denotes the marginal disutility of raising one unit of public revenue.

1. Optimal Taxes on Intermediate Goods

Appendix A derives the optimal tax rates. The analysis reveals that the clean intermediate inputs should not be taxed (i.e., $t_X=0$). Hence, in the absence of environmental externalities, net rather than gross output should be taxed. This an application of the well-known optimality of production efficiency derived by Diamond and Mirrlees (1971). They demonstrated that, if production exhibits constant returns to scale[3], an optimal tax system should not distort production. Intuitively, a tax on intermediate inputs is borne by the only primary factor of production, i.e. labor, and thus amounts to an implicit labor tax. From a revenue-raising point of view, the implicit labor tax is less efficient than an explicit tax on labor; whereas both taxes distort labor supply by reducing the consumption wage, only the input tax distorts the input mix into production.

The optimal tax on dirty inputs amounts to (see equation [A.7] in Appendix A):

$$t_Y = \left[\frac{u_E(-e_Y)}{u_C}\right]\frac{1}{\eta} \tag{5}$$

In contrast to the tax on clean inputs, the tax on dirty inputs is positive as long as households value environmental quality (i.e. $u_E>0$). The term between square brackets on the right-hand side of (5) corresponds to the textbook Pigovian tax. η is defined as the ratio of the marginal value of public revenue to the marginal utility of private income; it is often referred to as the marginal cost of public funds (MCPF). The MCPF term in (5) reveals how second-best considerations affect optimal environmental

[3]Under decreasing returns to scale, production efficiency continues to be optimal as long as a 100% profit tax is available.

taxation. It indicates in particular that the Pigovian tax is optimal only if η equals unity. A unitary MCPF means that public funds are not scarcer than private funds (as is the case when lump-sum taxes and subsidies are available or when labor supply is completely inelastic). However, in a second-best world without lump-sum taxation, the MCPF typically differs from one. In particular, the higher is the MCPF, the lower is the optimal environmental tax, *ceteris paribus*.

The inverse relationship between the MCPF and the optimal environmental tax may seem surprising since revenues from the environmental tax can be used to reduce distortionary taxes. However, the crucial consideration here is how the *presence* (as opposed to reduction) of distortionary taxes in the economy influences the costs of environmental taxes. The connection can be understood as follows. Abstracting from their environmental benefits, environmental taxes are more costly than alternative distortionary taxes. In particular, a tax on dirty intermediate inputs is more costly than a tax on net output (see Diamond and Mirrlees [1971]). This is the case because, in contrast to a tax on net output, the pollution tax "distorts"[4] the input mix into production. In this way, environmental taxes involve an excess cost over other distortionary taxes such as labor taxes, and this excess cost rises with the MCPF (see Bovenberg and de Mooij, 1994). Hence, the higher the MCPF, the higher the environmental benefits need to be to offset the excess costs of environmental taxes. The optimal pollution tax balances the social opportunity cost of additional tax revenue against the social benefit from reduced pollution. A higher MCPF means that the social opportunity cost of revenue is larger; hence the social benefits from pollution reduction have to be greater to justify a given environmental tax.

Another way of interpreting the negative impact of the MCPF on the optimal environmental tax is as follows. The government employs the tax system to accomplish simultaneously two objectives: namely, raising public revenues to finance public goods (other than the environment), and internalizing pollution externalities (thereby protecting the public good of the natural environment). If public revenues become scarcer, as indicated by a higher marginal cost of public funds, the optimal tax system focuses more on generating revenues (through non-environmental taxes, which are more efficient from a revenue-raising point of view) and less on internalizing pollution externalities.

High estimates for the marginal efficiency costs of the existing tax system (ie., the MCPF) have been used in support of pollution taxes (see, e.g., Oates [1991], and Pearce [1991]). However, these arguments ignore the costs of environmental taxes in terms of exacerbating pre-existing tax distortions.

[4] The word "distort" is in quotes to acknowledge the notion that the change in resource allocation may be justified once environmental benefits are taken into account.

These additional costs of environmental taxes are likely to be especially large if the marginal efficiency costs of the existing tax system are substantial. Therefore, the higher the efficiency costs of the existing tax structure are, the higher the environmental benefits need to be in order to justify the additional costs of environmental taxes in terms of a less efficient mechanism for financing public spending. High estimates for the efficiency costs of existing taxes *weaken* rather than *strengthen* the case for environmental taxation.

2. Optimal Taxes on Consumption

The optimal tax on dirty consumption consists of two parts (see also Sandmo [1975], Auerbach [1985], and Bovenberg and van der Ploeg [1994]). The first part, t_D^E, corrects for the environmental externality (see expression [A.6] in Appendix A):

$$t_D^E = \left[\frac{N u_E(-e_D)}{u_C}\right]\frac{1}{\eta} \tag{6}$$

This term looks very similar to (5). It amounts to the Pigovian tax divided by the MCPF. The second part of the optimal tax on polluting consumption, $t_D^D \equiv t_D - t_D^E$, is the distortionary (or revenue-raising) component of the tax. Together with the optimal labor tax, the optimal level of this distortionary component is determined on the basis of the familiar Ramsey formulas for raising revenues with the lowest costs to private incomes (see equations [A.12] and [A.13] in Appendix A). For example, if clean and dirty consumption are weakly separable from leisure and if utility is homothetic, uniform taxation of clean and dirty goods is optimal from the point of view of raising revenues with the smallest burden on private incomes. In this case, the optimal tax structure involves equal distortionary components of the two taxes on consumption. (In the case of the clean consumption commodity, the distortionary component is the only component.) Uniform distortionary taxes on consumption are equivalent to taxes on labor; thus the optimum is characterized by zero distortionary taxation of polluting consumption.[5] In this case, the only nonzero component of the optimal tax on dirty consumption is the externality-correcting part (6) (i.e., $t_D^D = 0$ *and* $t_D = t_D^E$).

With this particular utility structure, the MCPF is given by (see Bovenberg and van der Ploeg

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[5] Of course, since uniform consumption taxes are equivalent to labor taxes, the optimum can also be achieved through non-zero distortionary taxes on both consumption goods and lower labor taxes.

[1994]):

$$\eta = \left[1 - \frac{t_L}{1-t_L}\theta_L\right]^{-1} \tag{7}$$

The MCPF thus exceeds unity if (1) the uncompensated wage elasticity of labor supply, θ_L, is positive and (2) Pigovian taxes do not suffice to finance public consumption so that the distortionary tax on labor, t_L, is positive. These results are consistent with the literature on the MCPF surveyed in Ballard and Fullerton (1990). For public spending that is separable from consumer's choice on leisure and consumption, this literature finds that distortionary labor taxes raise the marginal costs of public spending above unity if the uncompensated wage elasticity of labor supply is positive. Combining (5), (6) and (7), we find that the same condition on the uncompensated elasticity determines whether distortionary labor taxes raise the marginal cost of (the collective good of) environmental protection above its social benefit. This result depends on the separability assumptions regarding utility. If environmental quality were a close substitute for private consumption, compensated rather than uncompensated elasticities would govern the effect on the marginal cost of environmental protection (see Wildasin [1984]).

III. Basic Features of the Numerical Model

The relatively simple analytical model discussed above abstracts from some important elements of actual economies. In particular, that model is static and disregards capital markets. Moreover, it treats all production as involving constant returns to scale. We consider these issues in the more complex numerical applied in this paper. This model has the attraction of capturing more realistically an actual economy.

This section sketches out the main features of the numerical model. Some details on the model's structure and parameters are offered in Appendix B. A more complete description is contained in Goulder (1992). Cruz and Goulder (1992) provide data documentation.

The model is an intertemporal general equilibrium model of the U.S. economy with international trade. It generates paths of equilibrium prices, outputs, and incomes for the U.S. economy and the "rest of the world" under specified policy scenarios. All variables are calculated at yearly intervals beginning in the 1990 benchmark year and usually extending to the year 2070.

The model is unique in combining a fairly realistic treatment of the U.S. tax system, a detailed representation of energy production and demand, and attention to stationary-source and mobile-source emissions of major air pollutants. It incorporates quite specific tax instruments and addresses effects of taxation along a number of important dimensions; these include firms' investment incentives, equity values, and profits,[6] and household consumption, saving and labor supply decisions. The specification of energy supply incorporates the nonrenewable nature of crude petroleum and natural gas and the transitions from conventional to synthetic fuels. The treatment of emissions is based on historical relationships between emissions and fuels used, processes employed, and levels of output.

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, crude petroleum and natural gas extraction, petroleum refining, synthetic fuels, electric utilities, and gas utilities. The model distinguishes the 17 consumer goods in Table 1.

B. Producer Behavior

1. General Specifications

In each industry, a nested production structure accounts for substitution between different forms of energy as well as between energy and other inputs. Each industry produces a distinct output (X), which is a function of the inputs of labor (L), capital (K), an energy composite (E) and a materials composite (M), as well as the current level of investment (I):

$$X = f[g(L,K),h(E,M)] - \phi(I/K) \cdot I \tag{8}$$

The energy composite is made up of the outputs of the six energy industries, while the materials composite consists of the outputs of the other industries:

$$E = E(\bar{x}_2, \bar{x}_3 + \bar{x}_4, \bar{x}_5, \bar{x}_6, \bar{x}_7) \tag{9}$$

$$M = M(\bar{x}_1, \bar{x}_8, ..., \bar{x}_{13}) \tag{10}$$

where $\bar{x}_i$ is a composite of domestically produced and foreign made input i.[7] Industry indices correspond to those in Table 1.

Managers of firms choose input quantities and investment levels to maximize the value of the firm. The investment decision takes account of the adjustment (or installation) costs represented by $\phi(I/K) \cdot I$

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[6]Here the model applies the asset price approach to investment developed in Summers (1981).

[7]The functions f, g, and h, and the aggregation functions for the composites E, M, and $\bar{x}_i$, are CES and exhibit constant returns to scale. Consumer goods are produced by combining outputs from the 13 industries in fixed proportions.

in equation (8). ϕ is increasing in the rate of investment.[8]

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

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:

$$X = \gamma(Z) f[g(L,K), h(E,M)] - \phi(I/K) \cdot I \tag{11}$$

where γ is a decreasing function of Z, the amount of cumulative extraction of oil and gas up to the beginning of the current period. This captures the idea 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 remove their capital from this industry.[9]

The model incorporates a synthetic fuel -- shale oil -- as a backstop resource, a perfect substitute for oil and gas.[10] The technology for producing synthetic fuels on a commercial scale is assumed to become known in 2010. Thus, capital formation in the synfuels industry cannot begin until that year.

All domestic prices in the model are endogenous, except for the domestic price of oil and gas. The path of oil and gas prices follows the assumptions of the Stanford Energy Modeling Forum.[11] The supply of imported oil and gas is taken to be perfectly elastic at the 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 then become the marginal source of supply, so that the

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[8]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) are diverted to install new capital.

[9]The attention to resource stock effects distinguishes this model several other general equilibrium energy environmental models. Many equilibrium models treat the domestic oil & gas industry as involving constant-returns-to-scale production, disregarding resource stock effects or fixed factors. In their global energy-environment model, Manne and Richels (1992) impose stock limits on resources such as oil and gas; however, these limits do not affect production costs prior to the point where the resource is exhausted.

[10]Thus, inputs 3 (oil&gas) and 4 (synfuels) enter additively in the energy aggregation function shown in equation (9).

[11]The world price is $24 per barrel in 1990 and rises in real terms by $6.50 per decade. See Gaskins and Weyant (1994).

cost of synfuels production rather than the world oil price dictates the domestic price of fuels.[12]

C. Household Behavior

Consumption, labor supply, and saving result from the decisions of a representative household maximizing its intertemporal utility, defined on leisure and overall consumption in each period. The utility function is homothetic and leisure and consumption are weakly separable (see Appendix B). The household faces an intertemporal budget constraint requiring that the present value of the consumption stream not exceed potential total wealth (nonhuman wealth plus the present value of potential labor income and net transfers). In each period, overall consumption of goods and services is allocated across the 17 specific categories of consumption goods or services shown in Table 1. Each of the 17 consumption goods or services is a composite of a domestically and foreign-produced consumption good (or service) of that type. Households substitute between domestic and foreign goods to minimize the cost of obtaining a given composite.

D. The Government Sector

The government collects taxes, distributes transfers, and purchases goods and services (outputs of the 13 industries). The tax instruments include energy taxes, output taxes, the corporate income tax, property taxes, sales taxes, and taxes on individual labor and capital income. In the benchmark year, 1990, the government deficit amounts to approximately two percent of GNP. In the reference case (or *status quo*) simulation, the debt-GNP ratio is approximately constant over time. In the policy experiments, we require that real government spending and the path of real government debt follow the same path as in the reference case. To make the policy changes revenue-neutral, we accompany the tax rate increases that define the various policies with reductions in other net taxes, either on a lump-sum basis (increased exogenous transfers) or through reductions in the marginal rates of other taxes.

E. Foreign Trade

Except for oil and gas imports, imported intermediate and consumer goods are imperfect substitutes for their domestic counterparts.[13] Import prices are exogenous in foreign currency, but the domestic-currency price changes with variations in the exchange rate. Export demands are modeled as

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[12]For details, see Goulder (1992).

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

functions of the foreign price of U.S. exports and the level of foreign income (in foreign currency). The exchange rate adjusts to balance trade in every period.

F. Modeling Pollution Emissions

Recent extensions of the model enable it to project emissions of eight important pollutants: total suspended particles (TSP), sulphur oxides (SOX), nitric oxides (NOX), volatile organic compounds (VOC's), carbon monoxide (CO), lead (Pb), particulate matter (PM10), and carbon dioxide (CO_2).

The key parameters used to project emissions levels (under baseline assumptions or in response to a change of policy) are *emissions factors*. These factors are calculated based on detailed U.S. data on emissions rates for specific industrial processes and fuels.[14]

G. 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[15], that firms' demands for loanable funds match 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 marginal tax rates.[16]

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 an exogenous rate.[17]

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[14]The model includes fuel-based, output-based, and mobile-source based emissions factors. The *fuel-based* emissions factor $e\_f_{i,j,k}$ represents the rate of emissions of pollutant i per unit of input of fuel j used industry k. Fuel-based emissions factors do not account for all of the emissions of a given pollutant from a given industry. Industrial emissions over and above those that can be attributed to given fuels are deemed output-based. The *output-based* emissions factor $e\_o_{i,k}$ denotes the ratio of output-related emissions of pollutant i to the quantity of gross output from industry k. The *mobile-source* emissions factors e_m_{ik} express the ratio of emissions i from a given mobile source k to the level of use of that source (vehicle). For details on data and methodology, see Goulder (1993).

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

[16]Since agents are forward-looking, equilibrium in each period depends not only on current prices and taxes but on future magnitudes as well.

[17]The growth of potential labor services is due to population growth and exogenous Harrod-neutral (labor-embodied) technical progress. The latter is consistent with a steady state because we assume that technical progress applies both to the production of goods and the enjoyment of leisure.

IV. Optimal Environmental Taxes in a Second-Best Setting: Numerical Results

This section uses the model described in Section III to investigate numerically how second-best considerations influence optimal rates for environmentally motivated taxes. We compare the numerical results with optimal rates implied by the Pigovian formula and by the analytical model of Section II.

A. The Simulations

We focus on the policy of a carbon tax. This is a tax on fossil fuels -- oil, crude oil, natural gas, and synfuels -- in proportion to their carbon content. Since carbon dioxide (CO_2) emissions generally are proportional to the carbon content of these fuels[18], a tax based on carbon content is effectively a tax on CO_2 emissions.[19]

We compare results under a carbon tax with results from a reference case or baseline simulation. In the reference case, all tax rates and other policy variables are maintained at the benchmark (1990) values. In the long run, the economy reaches a steady state: all quantities increase at a rate of two percent (governed by the exogenous growth rate of effective labor), while relative prices are constant. Two features of the model prevent balanced growth in the short and medium run. First, the depletion of oil and gas reserves causes unit costs of domestic oil and gas supply to rise. In addition, as indicated in the previous section, the real prices of imported oil and gas increase in real terms. These features reduce over time the share of oil and gas consumption relative to overall consumption. As indicated in Figure 1, rising costs of domestic oil and gas production lead to diminishing output of domestic oil and gas, while rising import prices eventually cause synfuels to replace conventional fuels.

B. Marginal Costs and Benefits from Emissions Reductions

Figure 2a shows the marginal welfare costs of CO_2 emissions reductions. The emissions reductions are achieved through carbon taxes of different magnitudes. The marginal costs are obtained by dividing the change in welfare costs (as measured by the equivalent variation) by the change in emissions over successive increments to carbon taxes. The marginal costs are calculated for two alternative uses of the revenues: namely, additional lump-sum transfers and reductions in the marginal

[18]The efficiency of the combustion process can affect somewhat the ratio of carbon dioxide emissions to the carbon content of a given fuel. However, this accounts for only slight variations in this ratio.

[19]Atmospheric CO_2 is considered a principal anthropogenic contributor to the greenhouse effect. The carbon tax thus has the potential to reduce the rate of greenhouse warming by curtailing CO_2 emissions and slowing the rate of increase in atmospheric CO_2 concentrations.

rates of the personal income tax. The horizontal axis in the figure is the percentage reduction in CO_2 emissions from the baseline path. Obviously, a given tax generates different percentage reductions at different times; we "average" these reductions by first taking the present value of the reductions (over an infinite time horizon). We then convert this number into the annual emissions reduction which, if increased every year at the steady-state rate of growth, yields the same present value.[20] Figure 2b shows the carbon tax rates necessary to achieve given emissions reductions.[21,22] Several findings emerge from the figures. First, marginal welfare costs rise with increases in carbon tax rates. This reflects rising costs of carbon abatement. Second, the marginal welfare cost curve is lower in the case of personal income tax replacement: using the revenues to cut personal income tax rates decreases the distortionary costs of the income tax, thereby lowering the cost of this revenue-neutral policy relative to the alternative policy with lump-sum replacement.

Third, emissions reductions from the carbon tax entail positive marginal costs -- even when carbon tax revenues are returned to the economy through cuts in marginal rates of the personal income tax. This indicates that, at the margin, a carbon tax is more costly than the personal tax it replaces. This result is consistent with the analysis of Section II. Further experiments with the numerical model consistently yield this outcome.[23]

Fourth, the marginal welfare cost curves in Figure 2a intersect the horizontal axis at a positive value. In other words, incremental carbon taxes (or incremental emissions reductions) involve non-incremental costs. This result contrasts with what one would obtain from a traditional Pigovian tax analysis, which implicitly assumes an economy without any pre-existing taxes. The Pigovian analysis

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[20]The approach is as follows. Let *EE* represent the present value of emissions reductions over the infinite horizon, where reductions are discounted at the household's real after-tax rate of return. Then the annualized reduction is given by $EE^*(r-g)/(1+r)$, where r is the long-run real after-tax interest rate and g is the long-run real growth rate.

[21]If environmental damages are related to concentrations, rather than emissions, it will generally be preferable to have rising, rather than constant, carbon tax rates. On this see Peck and Teisberg (1992).

[22]In fact we obtain two relationships between carbon tax rates and emissions reductions: one in the case of lump-sum replacement and one in the case of personal tax replacement. But the two are so similar they are virtually indistinguishable when plotted. The relationships differ (albeit slightly) because the method of revenue replacement has a slight influence on emissions. A given carbon tax rate implies slightly larger emissions reductions when revenue replacement is lump sum (because aggregate income and output fall more).

[23]In Goulder (1994), the numerical model of this paper is employed to examine the sources of the excess cost of a carbon tax over personal or corporate income taxes. That study identifies the carbon tax's focus on intermediate inputs as a key determinant of its excess costs, thus reinforcing the analytical results from Section II of the present paper.

asserts that the marginal welfare cost from an environmental tax is equal to the tax rate; hence, the marginal cost approaches zero as the tax rate becomes small. Our finding that marginal welfare costs are non-zero for infinitesmal carbon tax rates reflects the presence of other tax distortions. We return to this issue below.

C. Comparing the Pigovian Prescription with Results from the Analytical and Simulation Models

An important result from Figure 2 is that under both forms of revenue replacement, the optimal rate for the environmental tax differs substantially from the rate that would prescribed by the Pigovian principle. Suppose, for example, that the marginal environmental *benefits* from reductions in CO_2 were equal to $75.[24] The Pigovian principle would support a carbon tax of the same value. Our analysis indicates, however, that in the presence of distortionary taxation, such a tax is too high under either form of revenue replacement: the marginal welfare costs exceed the marginal benefits. With revenues used to cut personal tax rates, the optimal tax is about $48 per ton. The optimal tax is even lower (about $13 per ton) when revenues are replaced through lump-sum payments. In fact, under lump-sum replacement, it is never efficiency-improving to introduce a (non-negative) carbon tax if marginal benefits are below $55 per ton!

Further comparisons of implied optimal tax rates are offered in Table 2. The first column of this table indicates alternative possible values for the marginal environmental damages from CO_2 emissions. The other columns contain the optimal carbon tax rates corresponding to these environmental damages.

The third column of Table 2 includes optimal rates implied by the analytical model. That model indicates that the optimal environmental tax rate is equal to the marginal environmental benefits from emissions reduction (or marginal damages from emissions) divided by the marginal cost of public funds (η). It presumes a world in which other (distortionary) taxes are set optimally. This assumption differs from the realistic benchmark conditions of the economy to which the numerical model applies; nevertheless, it is instructive to observe the "optimal" rate implied by the analytical model for the U.S. economy. Simulation experiments with the numerical model indicate that the marginal cost of public

[24] To facilitate the discussion of optimal taxes, we drastically simplify the time dimension. We disregard dynamic issues such as changes through time in benefits and costs, and dynamic choices such as optimal changes through time in tax rates. Time aggregation makes it easier to isolate key relationships that should continue to hold when dynamic elements are given fuller consideration.

funds is approximately 1.12.[25] Suppose once again that the marginal environmental benefit from reductions in CO_2 has a value of \$75. In that case, the analytical model calls for a carbon tax of about \$67 (\$75/1.12) if the entire tax system is optimal.[26]

The fourth and fifth columns of Table 2 show the optimal values generated by the simulation model. These optimal values are the tax rates that equate marginal costs and benefits from emissions reductions, using the information shown in Figure 2.

Importantly, both the analytical and numerical models yield optimal tax rates dramatically lower than those implied by the Pigovian principle. The explanation for these differences was provided in Section II. In a second-best setting, a given environmental tax generates larger non-environmental costs than it would in the absence of other, distortionary taxes: environmental taxes compound the distortions that existing factor taxes generate. Hence, the optimal environmental tax is lower than the rate implied by the Pigovian principle.

The numerical model yields optimal rates even lower than those endorsed by the analytical model. The complexity of the numerical model makes it difficult to identify the cause of this difference. However, an important potential source is the nature of the benchmark. The analytical model's formula for optimal environmental taxes presumes an economy in which *all* taxes are set optimally. The numerical model, in contrast, employs a benchmark which approximates the actual U.S. tax system in 1990. This benchmark is suboptimal (in an efficiency sense) because the marginal efficiency costs of various taxes are not equal. It is worthwhile exploring the extent to which numerical simulations of the carbon tax under more efficient benchmark conditions would involve lower marginal costs of given emissions reductions and thus generate optimal carbon taxes closer to those predicted by the analytical model.

We do this by constructing a counterfactual benchmark involving an "improved" initial configuration of taxes, and then deriving the optimal carbon tax in this counterfactual setting. Specifically, we create a counterfactual benchmark that is optimal according to the principles inherent in the analytical model. The optimized benchmark involves two changes relative to the original benchmark: (1) taxes on intermediate inputs, industry outputs, and consumer goods are eliminated, and (2) marginal tax rates on

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[25]We calculate the marginal cost of public funds by scaling up the exogenous path of government spending by a factor slightly greater than 1 (namely, 1.005), and calculating the welfare impact when this spending increase is financed through increased personal income taxes. The MCPF is equal to $EV/PV(\Delta G)$, where EV is the welfare change (as measured by the equivalent variation) and $PV(\Delta G)$ is the present value of the change in government spending.

[26]Perhaps more precisely, this is the optimal tax rate that arises when the analytical model's optimal tax rule is applied using the marginal cost of public funds from the numerical model.

capital and labor are adjusted so that the marginal welfare cost per dollar are the same for each tax. Thus, under the optimized benchmark, all existing taxes involve the same marginal excess burden per dollar of revenue ($0.22).

Figure 2 and Table 2 include results from a carbon tax that is imposed on this optimized benchmark. Figure 2a shows that under this counterfactual scenario the marginal welfare costs of given emissions reductions are significantly lower than under the realistic case. Correspondingly, in Table 2 the optimal carbon tax associated with given marginal environmental damages is higher than the optimal tax arising in the realistic benchmark case. By comparing the results in the third and last columns of Table 2, we find that under the optimized benchmark the simulation model yields optimal tax rates quite close to those endorsed by the analytical model. This indicates that most of the differences between the analytical and simulation model results are due to the "suboptimal" nature of the ordinary benchmark for the simulation model.[27]

D. Sensitivity Analysis

Table 3 indicates the sensitivity of optimal tax rates to key parameters. These simulations involve changes relative to the realistic (as opposed to optimized) benchmark. The table reports results based on a posited value of $75/ton for the marginal environmental benefits from the carbon tax. All results in the table are for simulations in which carbon tax revenues are returned to the economy through reductions in personal income tax rates.

The general result from Table 3 is that, under the range of parameter values considered, the analytical and numerical models call for optimal tax rates below the Pigovian optimum. The analytical optimum is below the Pigovian optimum because the MCPF consistently exceeds unity. The numerical optimum is always below the analytical optimum; as discussed previously, this seems to reflect the suboptimal nature of the benchmark.

To consider the significance of pre-existing tax rates (heading 2), we reduce or increase all marginal tax rates for pre-existing tax rates by 50 percent. The MCPF approaches unity as the pre-existing

[27]One could argue that in fact the current tax system is less imperfect than suggested by the non-zero intercept of the middle line in Figure 2a. The analytical model indicates that the optimal second-best tax system has zero taxes on intermediate goods and on clean consumer goods. However, in the real world non-zero taxes on intermediate goods and clean consumer goods need not constitute departures from optimality. To the extent that certain consumer good taxes are in fact user fees or are aimed at internalizing other environmental externalities, the additional marginal welfare costs they generate may be justified by the benefits of the specific goods, services, or environmental improvements they finance. Because the simulation model does not capture these benefits, it may overstate the marginal welfare costs of carbon emissions reductions.

tax rates are reduced; accordingly, the optimal tax rates from the analytical and simulation models approach the Pigovian rate of $75/ton.

The intertemporal elasticity of substitution in consumption regulates the sensitivity of household savings to the after-tax return. Larger values for this elasticity raise the MCPF (and thus decrease the optimal tax from the analytical model). The optimal tax from the simulation model is also lower in this case, implying that the revenue-neutral carbon tax package exacerbates distortions of the capital market, despite the fact that its revenues are returned (in part) through reductions in capital income taxes.

The uncompensated elasticity of labor supply regulates the potential for distortions in labor markets. A higher value for this elasticity raises the MCPF (and reduces the optimal tax from the analytical model). However, a higher elasticity of labor supply implies a higher optimal tax from the numerical model. Hence, the revenue-neutral combination of a carbon tax and a personal tax cut tends to reduce labor market distortions. This suggests that the carbon tax primarily distorts the intertemporal margin while the personal tax (for which labor income contributes 70 percent of the revenues) distorts mainly the labor-leisure margin.

Higher values for energy substitution elasticities enlarge the potential for distortions in energy markets. With higher elasticities the MCPF is higher and the analytical optimum is lower. The numerical model's optimum is also lower in this case. The revenue-neutral combination of carbon tax and personal tax cut thus exacerbates inefficiencies (abstracting from environmental benefits) in energy markets.

V. Conclusions

This paper has employed analytical and numerical models to examine the general equilibrium interactions between environmentally motivated taxes and distortionary taxes. Our results indicate that accounting for pre-existing taxes yields optimal tax rates considerably below the rates suggested by the Pigovian principle. This may seem to contradict the notion, expressed by several authors, that optimal tax rates can be *higher* if environmental tax revenues are returned to the economy through cuts in distortionary taxes, rather than in lump-sum fashion. In fact, there is no contradiction here; different reference points apply. We too find that (for given marginal environmental benefits) the optimal tax is higher with revenue replacement through cuts in distortionary taxes than with replacement through increased lump-sum transfers (larger lump-sum tax reductions). But we also find that the optimal rate under either type of revenue replacement is considerably lower in a second-best economy compared with the result for the same type of revenue replacement in an economy without distortionary taxes.

In this connection, estimates of optimal carbon taxes in integrated climate-economy models (e.g., Nordhaus [1993][23], and Peck and Teisberg [1992]) are biased upward. For example, Nordhaus (1993) considers how recycling carbon tax revenues through cuts in distortionary taxes raises the optimal carbon tax. When revenues from the carbon tax are returned in lump-sum fashion, the optimal tax rate for the first decade is about $5 per ton; the optimal rate rises to $59 per ton when revenues are devoted to reducing distortionary taxes. Importantly, that study does not consider how pre-existing taxes increase the gross costs of the carbon tax itself (before the revenues are recycled). While the Nordhaus study accounts for the efficiency gains connected with the *reduction* (through recycling) of initial distortionary taxes, it does not consider the efficiency costs stemming from the interactions between *remaining* distortionary taxes and the newly imposed carbon tax. The analytical and simulation models in this paper indicate that the costs associated with (remaining) pre-existing distortions are greater than the benefits from reductions in distortionary taxes made possible by the carbon tax revenues. Hence, pre-existing taxes reduce the optimal tax rate.

These results provide some guidelines on the setting of environmental taxes. At the same time, it should be emphasized that in many circumstances a key ingredient in the optimal tax formulation -- the marginal environmental benefits -- is very uncertain. Further research that narrows the uncertainty bands will be of great value to policy analysts.

[23]Nordhaus has pioneered the integration of (environmental) benefits and (non-environmental) costs in simulation modeling of carbon taxes.

References

Armington, P.S., 1969. "A Theory of Demand for Products Distinguished by Place of Production," *I.M.F. Staff Papers*, 159-76.

Auerbach, A.J., 1985. "The Theory of Excess Burden and Optimal Taxation," in A.J. Auerbach and M.S. Feldstein (eds.), *Handbook of Public Economics* 1, North-Holland, Amsterdam.

Ballard, C.L. and D. Fullerton, 1990. "Wage Tax Distortions and Public Good Provision, National Bureau of Economic Research Working Paper No. 3506, Cambridge, MA.

Bovenberg, A.L. and F. van der Ploeg, 1994. "Environmental Policy, Public Finance and the Labor Market in a Second-Best World," *Journal of Public Economics*, forthcoming.

Bovenberg, A.L. and R.A. de Mooij, 1994. "Environmental Levies and Distortionary Taxation," *American Economic Review*, forthcoming.

Cruz, Miguel and Lawrence H. Goulder, 1992. "An Intertemporal General Equilibrium Model for Analyzing U.S. Energy and Environmental Policies: Data Documentation." Unpublished manuscript, Stanford University.

Diamond, P.A., and J.A. Mirrlees, 1971. "Optimal Taxation and Public Production, *American Economic Review* 61, 8-27 and 261-278.

Gaskins, Darius and John Weyant, 1994. *The Costs of Controlling Greenhouse Gas Emissions*. Stanford, CA: Stanford University Press, forthcoming.

Goulder, Lawrence H., November 1992. "An Intertemporal General Equilibrium Model for Analyzing U.S. Energy and Environmental Policies: Model Structure." Unpublished manuscript, Stanford University.

__________, 1993. "Energy Taxes: Traditional Efficiency Effects and Environmental Implications." In James M. Poterba, ed., *Tax Policy and the Economy 8*. Cambridge, MA, MIT Press, forthcoming.

__________, 1994. "Effects of Carbon Taxes in an Economy with Prior Tax Distortions: An Intertemporal General Equilibrium Analysis." Working Paper, Stanford University.

__________, and Philippe Thalmann, 1993. "Approaches to Efficient Capital Taxation: Leveling the Playing Field vs. Living by the Golden Rule." *Journal of Public Economics* 50, 169-196.

Lee, Dwight R., and Walter S. Misiolek, 1986. "Substituting Pollution Taxation for General Taxation: Some Implications for Efficiency in Pollution Taxation." *Journal of Environmental Economics and Management* 13:338-347.

Manne, Alan S., and Richard G. Richels, 1992. *Buying Greenhouse Insurance: The Economic Costs of CO_2 Emissions Limits*. Cambridge, MA, MIT Press.

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.

Nordhaus, William D., 1993. "Optimal Greenhouse-Gas Reductions and Tax Policy in the "DICE" Model." *American Economic Review (Papers and Proceedings)* 83 (2), 313-317.

Oates, W.E., 1991. "Pollution Charges as a Source of Public Revenues," Resources for the Future Discussion Paper No. QE92-05, Washington, D.C.

Oates, W.E., and Paul R. Portney, 1992. "Economic Incentives and the Containment of Global Warming." *Eastern Economic Journal* 18(1), 85-98.

Pearce, D.W., 1991. "The Role of Carbon Taxes in Adjusting to Global Warming," *Economic Journal* 101, 938-948.

Peck, Stephen C. and Teisberg, Thomas J., 1992. "CETA: A Model for Carbon Emissions Trajectory Assessment." *Energy Journal* 13 (1), 55-77.

Poterba, James M. and Lawrence H. Summers, 1985. "The Economic Effects of Dividend Taxation." In Edward I. Altman and Marti G. Subramanyam, eds., *Recent Advances in Corporate Finance*. Homewood, IL, Irwin.

Poterba, James M., 1993. "Global Warming: A Public Finance Perspective." *Journal of Economic Perspectives* 7(4), 47-63.

Sandmo, A., 1975. "Optimal Taxation in the Presence of Externalities," *Swedish Journal of Economics* 77, 86-98.

Stavins, Robert N., 1991. *Project 88 -- Round II. Incentives for Action: Designing Market-Based Environmental Strategies*. Washington, D.C., May.

Summers, Lawrence H., January 1981. "Taxation and Corporate Investment: A q-Theory Approach." *Brookings Papers on Economic Activity*, 67-127.

Weyant, John P., 1993. "Costs of Reducing Global Carbon Emissions." *Journal of Economic Perspectives* 7(4), 27-46.

Wildasin, D.E., 1984. "On Public Good Provision with Distortionary Taxation," *Economic Inquiry* 22, 227-243.

Appendix A: Analytical Results

Firms maximize profits under perfect competition and thus equalize the marginal product of each factor to its user cost.

$$\begin{aligned} F_{NL}(1, X/NL, Y/NL) &= w \\ F_X(1, X/NL, Y/NL) &= 1 + t_X \\ F_Y(1, X/NL, Y/NL) &= 1 + t_Y \end{aligned} \tag{A.1}$$

The last two first-order conditions yield the demands for the two intermediate inputs conditional on the level of employment.

$$X = NLx(1+t_X; 1+t_Y); \quad Y = NLy(1+t_X; 1+t_Y) \tag{A.2}$$

Substituting (A.2) into the first first-order condition in (A.1), we find the producer wage in terms of t_X and t_Y :

$$w = \omega(1+t_X; 1+t_Y) \tag{A.3}$$

where

$$\omega_{t_X} = -\frac{X}{NL}; \qquad \omega_{t_Y} = -\frac{Y}{NL} \tag{A.4}$$

To find the optimal tax rates, we substitute (A.2) into (4) to eliminate X and Y. Maximizing with respect to t_L, we find the following first-order condition (after dividing through by $-wN$).

$$(\lambda-\mu)L + \mu\left[t_D\frac{\partial D}{\partial w_N} + (t_L w + t_X + t_Y)\frac{\partial L}{\partial w_N}\right] + Nu_E e_{ND}\frac{\partial D}{\partial w_N} + u_E e_Y \frac{\partial L}{\partial w_N} = 0 \tag{A.5}$$

where we have used $\frac{\partial V}{\partial w_N} = \lambda L$ (Roy's identity) and where $w_N \equiv (1-t_L)w$. Define

$$t_D^E = \frac{Nu_E(-e_D)}{\mu} \tag{A.6}$$

$$t_Y^E = \frac{u_E(-e_Y)}{\mu} \tag{A.7}$$

Substitution of (A.6) and (A.7) into (A.5) yields

$$(\lambda-\mu)L = \mu\left[(t_D-t_D^E)\frac{\partial D}{\partial w_N}+t_L w\frac{\partial L}{\partial w_N}\right] + \mu\left[t_X+(t_Y-t_Y^E)\right]\frac{\partial L}{\partial w_N} \tag{A.8}$$

The first-order condition for maximizing (4) with respect to t_X is given by:

$$\mu\left[X+t_X NL\frac{\partial x}{\partial t_X}+(t_Y-t_Y^E)NL\frac{\partial y}{\partial t_x}\right] \tag{A.9}$$

$$+\mu\, w_{t_Y} NL\left[t_X\frac{\partial x}{\partial w}+(t_Y-t_Y^E)NL\frac{\partial y}{\partial w}\right] - w_{t_x}\mu NL = 0$$

where we have used (A.6), (A.7) and (A.8). Substitution of (A.4) yields:

$$t_X\left[\frac{\partial x}{\partial t_X}-\frac{X}{NL}\frac{\partial x}{\partial w}\right] + (t_Y-t_Y^E)\left[\frac{\partial y}{\partial t_Y}-\frac{X}{NL}\frac{\partial y}{\partial w}\right] = 0 \tag{A.10}$$

In an analogous way, we derive the first-order condition for t_Y as:

$$t_X\left[\frac{\partial x}{\partial t_Y}-\frac{Y}{NL}\frac{\partial x}{\partial w}\right] + (t_Y-t_Y^E)\left[\frac{\partial y}{\partial t_Y}-\frac{Y}{NL}\frac{\partial y}{\partial w}\right] = 0 \tag{A.11}$$

(A.10) and (A.11) together imply $t_X = 0$ and $t_Y = t_Y^E$. With (A.7), this implies (5), where $\eta = \mu/u_C$.

Substitution of these results into (A.8) and the first-order condition for t_D yields:

$$(\lambda-\mu)L + \mu\left[(t_D-t_D^E)\frac{\partial D}{\partial w_N}+t_L w\frac{\partial L}{\partial w_N}\right] = 0 \tag{A.12}$$

$$(\lambda-\mu)D + \mu\left[(t_D-t_D^E)\frac{\partial D}{\partial t_D}+t_L w\frac{\partial L}{\partial t_D}\right] = 0 \tag{A.13}$$

(A.12) and (A.13) are the familiar Ramsey equations in which the term t_D is replaced by the distortionary part of the tax on polluting consumption, $t_D^D = t_D - t_D^E$. The non-distortionary part is given by (A.6), which can be written as (6) by using the definition of η ($\equiv\mu/u_C$).

Appendix B: Structure and Parameter Values of the Numerical Model[1]

I. Structure

A. Production

1. Technology

a. General Features

Table A1 indicates the nested production structure. In each industry i, gross output X_i is produced using inputs of labor (L_i), capital (K_i), an energy composite $(\bar{E}_i)$ and a materials composite $(\bar{M}_i)$. The production function has the following form:

1) $$X_i = f_i\left[g_{1i}(L_i,K_i)\ ,\ g_{2i}(\bar{E}_i,\bar{M}_i) \right] - \phi_i(I/K_i)I_i$$

The functions f_i, g_{1i}, and g_{2i} are CES. Hence the function f can be written as:

2) $$f(g_1, g_2) = \gamma_f\left[\alpha_f\, g_1^{\rho_f} + (1 - \alpha_f)g_2^{\rho_f}\right]^{1/\rho_f}$$

where the industry subscript has been suppressed and where γ_f, α_f, and ρ_f are parameters. The parameter ρ is related to σ_f, the elasticity of substitution between g_1 and g_2: $\rho = (\sigma - 1)/\sigma$. Analogous expressions apply for the functions g_1 and g_2.

The second term in equation (1) represents the loss of output associated with installing new capital (or dismantling existing capital). Per-unit adjustment costs, ϕ, are given by:

3) $$\phi(I/K) = \frac{(\xi/2)\ (I/K - \delta)^2}{I/K}$$

where I represents gross investment (purchases of new capital goods) and ξ and δ are parameters. The parameter δ denotes the rate of economic depreciation of the capital stock.

The energy composite $(\bar{E}_i)$ in equation (1) is a CES function of the specific energy products of the different energy industries:

4a) $$\bar{E} = \bar{E}(E_1, E_2, \ldots, E_5)$$

4b) $$= \gamma_{\bar{E}}\left[\sum_{j=1}^{5} \alpha_{\bar{E}j}\, E_j^{\rho_{\bar{E}}}\right]^{1/\rho_{\bar{E}}}$$

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[1] A more comprehensive description of the structure of the model is in Goulder (1992). Detailed documentation of the data and parameters for the model is provided in Cruz and Goulder (1992).

Table A1: Nested Production Structure

X	=	$f(g_1, g_2) - \phi(I/K)I$	
g_1	=	$g_1(L, K)$	
g_2	=	$g_2(E, M)$	
E	=	$E(E_1, \ldots, E_5)$	
M	=	$M(M_1, \ldots, M_7)$	
E_i	=	$E_i(ED_i, EF_i)$	$i = 1,\ldots,5$
M_i	=	$M_i(MD_i, MF_i)$	$i = 1,\ldots,7$

Note: All functions are CES in form except for $\phi(I/K)$, which is quadratic in I/K.

Table A2: Nested Utility Structure

Function:	Functional Form:
$U_t(C_t, C_{t+1}, \ldots, C_s, \ldots)$	constant intertemporal elasticity of substitution
$C_s(\tilde{C}_s, \ell_s)$	CES
$\tilde{C}_s(\bar{C}_{1,s}, \ldots, \bar{C}_{i,s}, \ldots, \bar{C}_{17,s})$	Cobb-Douglas
$\bar{C}_{i,s}(CD_{i,s}, CF_{i,s})$	CES

Key:

U_t	= intertemporal utility evaluated from period t
C_s	= full consumption in period s
$\tilde{C}_s$	= overall goods consumption in period s
ℓ_s	= leisure in period s
$\bar{C}_{i,s}$	= consumption of composite consumer good i in period s
$CD_{i,s}$	= consumption of domestically produced consumer good i in period s
$CF_{i,s}$	= consumption of foreign produced consumer good i in period s

where $\sum_{j=1}^{5} \alpha_{\bar{E}j} = 1$. The subscripts to E in equations (4a) and (4b) correspond to energy industries as follows:

Subscript	Energy Industry
1	Coal mining
2	Oil&gas extraction and synthetic fuels
3	Petroleum refining
4	Electricity
5	Processed natural gas

Oil&gas and synthetic fuels combine as one input in the energy composite, reflecting the fact that these fuels are treated as perfect substitutes in production.[2]

Similarly, the materials composite $(\bar{M}_j)$ in equation (1) is a *CES* function of the specific materials products of the 7 non-energy industries:

5a) $$\bar{M} = \bar{M}(M_1, M_2, ..., M_7)$$

5b) $$= \gamma_{\bar{M}} \left[\sum_{j=1}^{7} \alpha_{\bar{M}j} M_j^{\rho_{\bar{M}}} \right]^{1/\rho_{\bar{M}}}$$

where $\sum_{j=1}^{7} \alpha_{\bar{M}j} = 1$. The subscripts to M in equations (5a) and (5b) correspond to materials (non-energy) industries as follows:

Subscript	Materials Industry
1	Agriculture and mining (except coal mining)
2	Construction
3	Metals and machinery
4	Motor vehicles
5	Miscellaneous manufacturing
6	Services (except housing services)
7	Housing services

The elements E_j $(j = 1,...,5)$ and M_j $(j = 1,...,7)$ in the $\bar{E}$ and $\bar{M}$ functions are themselves *CES* composites of domestically produced and foreign made inputs:

6) $$E_j = \gamma_{Ej} \left[\alpha_{Ej} ED_j^{\rho_{Ej}} + (1 - \alpha_{Ej}) EF_j^{\rho_{Ej}} \right]^{1/\rho_{Ej}} , \quad j = 1, ..., 5$$

7) $$M_j = \gamma_{Mj} \left[\alpha_{Mj} MD_j^{\rho_{Mj}} + (1 - \alpha_{Mj}) MF_j^{\rho_{Mj}} \right]^{1/\rho_{Mj}} , \quad j = 1, ..., 7$$

[2] E_2 denotes the total quantity (in energy-equivalent units) of oil&gas plus synfuels:
$$E_2 = E_{og} + E_{sf}$$

where ED_j and EF_j denote domestic and foreign energy inputs of type j, and MD_j and MF_j denote domestic and foreign materials inputs of type j.

b. Endogeneity of γ in the Oil&Gas Production Function

In industries other than oil&gas, the element γ_f in the production function is parametric. In the oil&gas industry, γ_f is a decreasing function of cumulative oil&gas extraction:

$$\gamma_{f,t} = \varepsilon_1 \left[1 - (Z_t/\bar{Z})^{\varepsilon_2}\right] \tag{8}$$

where ϵ_1 and ϵ_2 are parameters, Z_t represents cumulative extraction as of the beginning of period t, and $\bar{Z}$ is the original estimated total stock of recoverable reserves of oil&gas (as estimated from the benchmark year). The following equation of motion specifies the evolution of Z_t:

$$Z_{t+1} = Z_t + X_t \tag{9}$$

Equation (8) implies that the production function for oil and gas shifts downward as cumulative oil&gas extraction increases. This addresses the fact that as reserves are depleted, remaining reserves become more difficult to extract and require more inputs per unit of extraction.

2. **Behavior of Firms**

In each industry. managers of firms are assumed to serve stockholders in aiming to maximize the value of the firm. The objective of firm-value maximization determines firms' choices of input quantities and investment levels in each period of time.

The value of the firm can be expressed in terms of dividends and new share issues, which in turn depend on profits in each period. The firm's profits during a given period are given by:

$$\pi = (1 - \tau_a)\left[pX - w(1 + \tau_L)L - EMCOST - iDEBT - TPROP\right] + \tau_a(DEPL + DEPR) \tag{10}$$

where τ_a is the tax rate on profits, p is the output price net of output taxes, w is the wage rate net of indirect labor taxes, τ_L is rate of the indirect tax on labor, $EMCOST$ is the cost to the firm of energy and materials inputs, i is the gross-of-tax interest rate paid by the firm, $DEBT$ is the firm's current debt, $TPROP$ is property tax payments, $DEPL$ is the current gross depletion allowance, and $DEPR$ is the current gross depreciation allowance. $TPROP$ equals $\tau_p p_{K,s-1} K_s$, where τ_p is the property tax rate, p_K is the purchase price of a unit of new capital, and s is the time period. Current depletion allowances, $DEPL$, are a constant fraction β of the value of current extraction: $DEPL = \beta pX$. Current depreciation allowances, $DEPR$, can be expressed as $\delta^T K^T$, where K^T is the depreciable capital stock basis and δ^T is the depreciation rate applied for tax purposes.[3]

In equation (10), *EMCOST* is given by:

$$11)\quad EMCOST = \sum_{j=1}^{5} (1 + \tau_{Ej})(p_{ED,j}ED_j + p_{EF,j}EF_j) + \sum_{j=1}^{7} (1 + \tau_{mj})(p_{MD,j}MD_j + p_{MF,j}MF_j)$$

where the subscripts for energy and materials correspond to industries as indicated above; and where τ_E and τ_M denote the tax rates applying to the firm's use of intermediate inputs, and p_{EDj} and p_{EFj} (p_{MDj} and p_{MFj}) are the pre-tax prices of domestic and foreign energy (materials) inputs of type j.[4]

The following accounting or cash-flow identity links the firm's sources and uses of revenues:

$$12)\quad \pi + BN + VN = DIV + IEXP$$

The left-hand side is the firm's source of revenues: profits, new debt issue *(BN)*, and new share issues *(VN)*. The uses of revenues on the right-hand side are investment expenditure *(IEXP)* and dividend payments *(DIV)*. Negative share issues are equivalent to share repurchases, and represent a use rather than source of revenue.

Firms pay dividends equal to a constant fraction, a, of profits net of economic depreciation, and maintain debt equal to a constant fraction, b, of the value of the existing capital stock. Thus:

$$13)\quad DIV_s = a\left[\pi_s + (p_{K,s} - p_{K,s-1})K_s - \delta p_{K,s}K_s\right]$$

$$14)\quad BN_s \equiv DEBT_{s+1} - DEBT_s = b(p_{K,s}K_{s+1} - p_{K,s-1}K_s)$$

Investment expenditure is expressed by:

$$15)\quad IEXP_s = (1 - \tau_K)p_{K,s}I_s$$

where τ_K is the investment tax credit rate. Of the elements in equation (12), new share issues, *VN*, are the

[3]For convenience, we assume that the accelerated depreciation schedule can be approximated by a schedule involving constant exponential tax depreciation.

[4]To simplify the exposition, we have not included in equations (10) and (11) subscripts identifying the given industry for which profits or input costs are calculated. It may be noted that the intermediate good taxes, τ_{Ej} and τ_{Mj}, may differ across industries using a particular good as well as across intermediate goods.

In equation (11), for $j = 2$ the expression $p_{Ej}\,(1 + \tau_{Ej})\,E_j$ is short-hand for $p_{og}\,(1 + \tau_{og})\,E_{og} + p_{sf}\,(1 + \tau_{sf})\,E_{sf}$, where "*og*" refers to oil and gas and "*sf*" refers to synfuels. Since oil&gas and synfuels are perfect substitutes, it is always the case that gross-of-tax costs of these fuels to the firm are the same: that is, $p_{og}\,(1 + \tau_{og}) = p_{sf}\,(1 + \tau_{sf})$. However, when $\tau_{og} \neq \tau_{sf}$, the net-of-tax prices p_{og} and p_{sf} will differ.

residual, making up the difference between $\pi + BN$ and $DIV + IEXP$.[5]

Arbitrage possibilities compel the firm to offer its stockholders a rate of return comparable to the rate of interest on alternative assets.

16) $$(1 - \tau_e)\, DIV_t + (1 - \tau_v)\,(V_{t+1} - V_t - VN_t) = (1 - \tau_b)\, i_t\, V_t$$

The parameters τ_e, τ_v, and τ_b are the personal tax rates on dividend income (equity), capital gains, and interest income (bonds), respectively. The return to stockholders consists of the current after-tax dividend plus the after-tax capital gain (accrued or realized) on the equity value (V) of the firm net of the value of new share issues. This return must be comparable to the after-tax return from an investment of the same value at the market rate of interest, i.

The firm's decision problem is completed by the equation of motion for the capital stock:

17) $$K_{t+1} = (1 - \delta)K_t + I_t$$

Capital is augmented by net investment. Cumulative extraction is augmented by the level of current output (or extraction). In the oil&gas industry, the equation of motion (9) also applies.

B. Household Behavior

Consumption, labor supply, and saving result from the decisions of an infinitely-lived representative household maximizing its intertemporal utility with perfect foresight. The nested structure of the household's utility function is indicated in Table A2. In year t the household chooses a path of "full consumption" C to maximize

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

where ω is the subjective rate of time preference and σ is the intertemporal elasticity of substitution in full consumption. C is a CES composite of consumption of goods and services $\bar{C}$ and leisure ℓ:

19) $$C_t = \left[\bar{C}_t^{\frac{\upsilon - 1}{\upsilon}} + \alpha_C^{\frac{1}{\upsilon}}\, \ell_t^{\frac{\upsilon - 1}{\upsilon}}\right]^{\frac{\upsilon}{\upsilon - 1}}$$

υ is the elasticity of substitution between goods and leisure; α_C is an intensity parameter for leisure.

The variable $\bar{C}$ in (25) is a Cobb-Douglas aggregate of 17 composite consumer goods:

20) $$\bar{C}_t = \prod_{i=1}^{17} \bar{C}_{i,t}^{\alpha_{C,i}}$$

where the $\alpha_{C,i}\,(i = 1,\ldots,17)$ are parameters. The 17 types of consumer goods identified in the model are shown

[5] For a discussion of alternative specifications, see Poterba and Summers (1985).

in Table 2 of the main text.

Consumer goods are produced domestically and abroad. Each composite consumer good $\bar{C}_i$, $i = 1,...,17$, is a CES aggregate of a domestic and foreign consumer good of a given type:

21) $$\bar{C} = \gamma_{\bar{C}} \left[\alpha_{\bar{C}} CD^{\rho_{\bar{C}}} + (1 - \alpha_{\bar{C}}) CF^{\rho_{\bar{C}}} \right]^{1/\rho_{\bar{C}}}$$

In the above equation, CD and CF denote the household's consumption of domestically produced and foreign made consumer good of a given type at a given point in time. For simplicity, we have omitted subscripts designating the type of consumer good and the time period.

The household maximizes utility subject to the intertemporal budget constraint given by the following condition governing the change in financial wealth, WK :

22) $$WK_{t+1} - WK_t = \bar{r}_t WK_t + YL_t + GT_t - \tilde{p}_t \bar{C}_t$$

In the above equation, $\bar{r}$ is the average after-tax return on the household's portfolio of financial capital, YL is after-tax labor income, GT is transfer income, and p is the price index representing the cost to the household of a unit of the consumption composite, C .

C. Government Behavior

A single government sector approximates government activities at all levels -- federal, state, and local. The main activities of the government sector are purchasing goods and services (both non-durable and durable), to transferring incomes, and to raising revenue through taxes or bond issue.

1. Components of Government Expenditure

Government expenditure, G , divides into nominal purchases of nondurable goods and services (GP) , nominal government investment (GI) , and nominal transfers (GT) :

23) $$G_t = GP_t + GI_t + GT_t$$

In the reference case, the paths of *real* GP , GI , and GT all are specified as growing at the steady-state real growth rate, g . In simulating policy changes we fix the paths of GP , GI , and GT so that the paths of *real* government purchases, investment and transfers are the same as in corresponding years of the reference case. Thus, the expenditure side of the government ledger is largely kept unchanged across simulations. This procedure is expressed by:

(24a) $$GP_t^P \ / \ p_{GP,t}^P = GP_t^R / p_{GP,t}^R$$

(24b) $$GI_t^P \ / \ p_{GI,t}^P = GI_t^R / p_{GI,t}^R$$

(24c) $GT_t^P \; / \; p_{GT,t}^P \; = \; GT_t^R / \, p_{GT,t}^R$

The superscripts P and R denote policy change and reference case magnitudes, while p_{GP}, p_{GI} and p_{GT} are price indices for GP, GI, and GT. The price index for government investment, p_{GI}, is the purchase price of the representative capital good. The price index for transfers, p_{GT}, is the consumer price index. The index for government purchases, p_{GP}, is defined below.

2. Allocation of Government Purchases

GP divides into purchases of particular outputs of the 13 domestic industries according to fixed expenditure shares:

25) $$\alpha_{G,i} GP = GPX_i p_i \qquad i = 1,...,13$$

GPX_i and p_i are the quantity demanded and price of output from industry i, and $\alpha_{G,i}$ is the corresponding expenditure share. The ideal price index for government purchases, p_{GP}, is given by:

26) $$p_{GP} = \prod_{i=1}^{13} p_i^{\alpha_{G,i}}$$

II. Parameter Values

A. Elasticities of Substitution in Production

Parameter:	σ_f	σ_{g1}	σ_{g2}	σ_E	σ_M	σ_x
Substitution margin:	g_1-g_2	L-K	E-M	E components	M components	dom-foreign inputs
Producing Industry:						
1. Agric. & Non-coal Mining	0.7	0.68	0.7	1.45	0.6	2.31
2. Coal Mining	0.7	0.80	0.7	1.08	0.6	1.14
3. Oil & Gas Extraction	0.7	0.82	0.7	1.04	0.6	(infinite)
4. Synthetic Fuels	0.7	0.82	0.7	1.04	0.6	(not traded)
5. Petroleum Refining	0.7	0.74	0.7	1.04	0.6	2.21
6. Electric Utilities	0.7	0.81	0.7	0.97	0.6	1.0
7. Gas Utilities	0.7	0.96	0.7	1.04	0.6	1.0
8. Construction	0.7	0.95	0.7	1.04	0.6	1.0

9. Metals & Machinery	0.7	0.91	0.7	1.21	0.6	2.74
10. Motor Vehicles	0.7	0.80	0.7	1.04	0.6	1.14
11. Misc. Manufacturing	0.7	0.94	0.7	1.08	0.6	2.74
12. Services (except housing)	0.7	0.98	0.7	1.07	0.6	1.0
13. Housing Services	0.7	0.80	0.7	1.81	0.6	(not traded)

B. Parameters of Stock Effect Function in Oil and Gas Industry

Parameter:	Z_0	$\bar{Z}$	ε_1	ε_2
Value:	0	450	1.27	2.0

Note: This function is parameterized so that γ_t approaches 0 as Z approaches $\bar{Z}$ (see equation (8)). 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 values of ε_1 and ε_2 imply that, in the baseline scenario, oil and gas investment becomes zero in the year 2031.

C. Utility Function Parameters

Parameter:	ω	σ	ν	η
Value:	0.007	0.5	0.69	0.84

Figure 1

Consumption of Oil & Gas and Synthetic Fuels

(evaluated at 1990 prices)

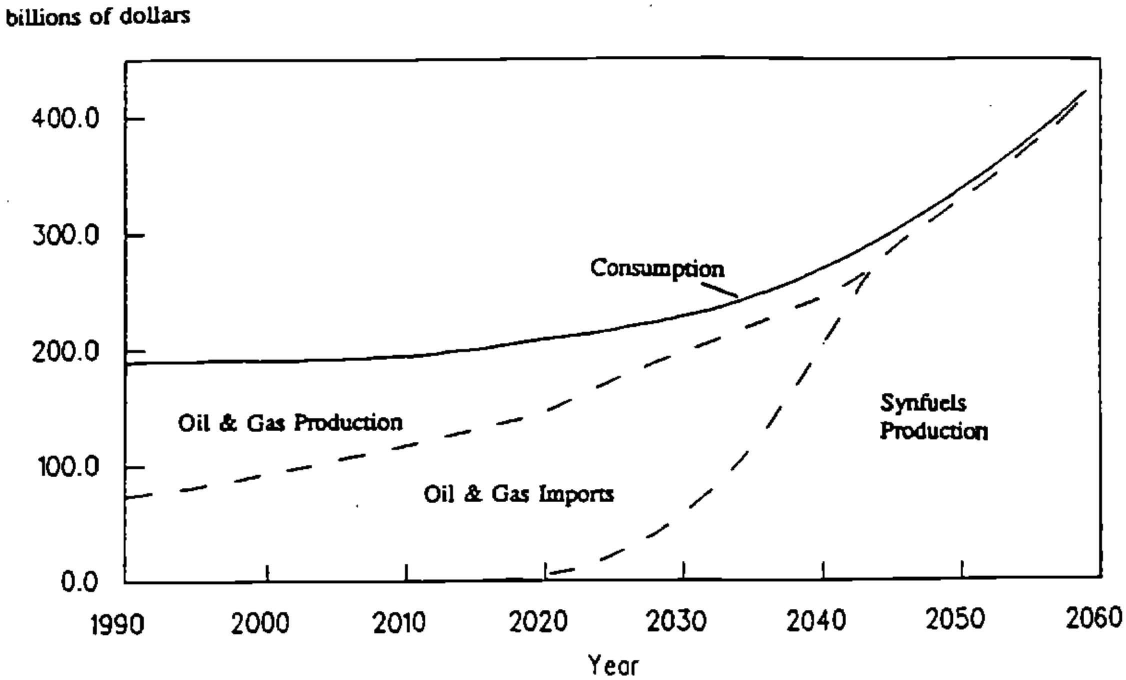

Figure 2

Marginal Welfare Costs, Emissions Reductions and Carbon Tax Rates

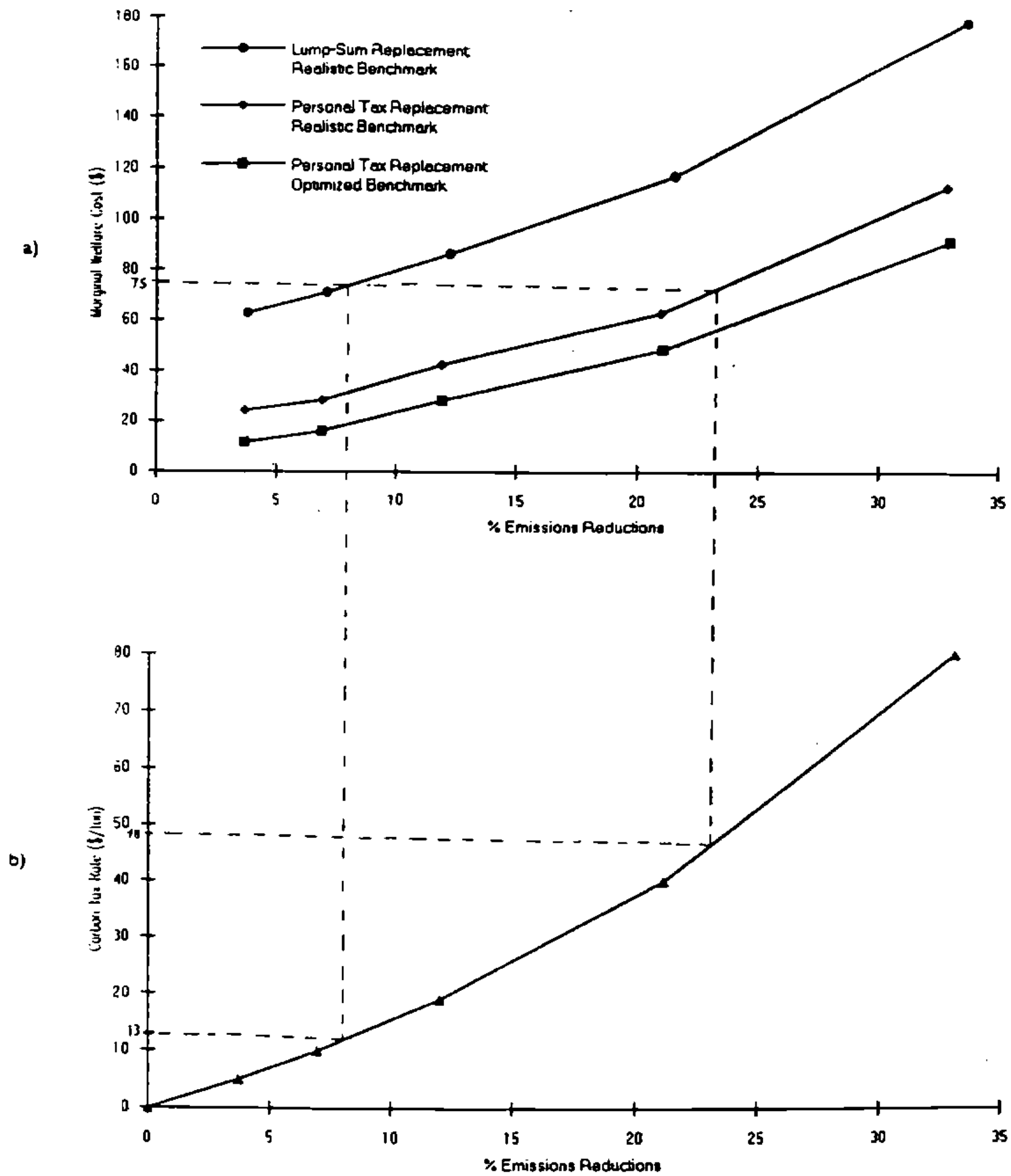

Table 1

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

Table 2

Differences between Pigovian and Second-Best Taxes
(All tax rates in dollars per ton)

	"Optimal" Pigovian Tax	Optimal Tax Implied by Analytical Model (PIT Replacement)	Optimal Tax from Numerical Model		
			Realistic Benchmark, Lump-Sum Replacement	Realistic Benchmark, PIT Replacement	Optimized Benchmark, PIT Replacement
Assumed Marginal Environmental Damages: ($/ton)					
25	25	22	0	7	17
50	50	45	0	27	41
75	75	67	13	48	64
100	100	89	31	68	85

Table 3: Sensitivity Analysis[1]

	MCPF	Optimum Implied by Numerical Model	Optimum from Simulation Model
1. Central Case	1.121	67	48
2. Marginal Rates for Pre-existing Taxes			
-- lowered 50%	1.036	72	64
-- raised 50%	1.194	63	34
3. Intertemporal Elasticity of Substitution in Consumption[2]			
-- low (.33)	1.102	68	52
-- high (.66)	1.146	65	45
4. Uncompensated Elasticity of Labor Supply[3]			
-- low (-0.03)	1.109	68	44
-- high (0.16)	1.149	65	54
5. Energy Substitution Elasticities[4]			
-- lowered by 50%	1.107	68	50
-- raised by 50%	1.173	64	44

[1]Marginal environmental benefits are assumed to be $75/ton. Results for the numerical model are from simulations of a carbon tax with revenue-preserving reductions in marginal rates of the personal income tax.

[2]Central case value is 0.5.

[3]These simulations involve changes in υ, the goods-leisure elasticity of substitution. The central case value of υ is 0.69, implying an uncompensated labor supply elasticity of 0.06. υ is 0.64 and 0.74 in the low and high elasticity cases. The compensated elasticities in the low, central and high cases are 0.45, 0.52, and 0.63, respectively.

[4]In the low (high) elasticity simulation, the elasticity of substitution between composite energy ($\bar{E}$) and composite materials ($\bar{M}$) is lowered (raised) in all industries by 50 percent.