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ENERGY TAXES: TRADITIONAL EFFICIENCY EFFECTS AND ENVIRONMENTAL IMPLICATIONS

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EXECUTIVE SUMMARY

This paper examines "traditional" (non-environmental) efficiency consequences and environmental effects of two energy tax policies: a tax on fossil and synthetic fuels based on Btu (or energy) content and a tax on consumer purchases of gasoline. It uses a model that uniquely combines attention to details of the U.S. tax system with a consolidated treatment of U.S. energy use and pollution emissions.

On traditional efficiency grounds, each of the energy taxes emerges as more costly to the economy than increases in personal or corporate income taxes of equal revenue yield. The time profiles of GNP and consumption are significantly lower under the energy taxes than under the alternatives.

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We perform a number of simulation experiments designed to isolate key structural features of energy taxes and identify which features account for their "excess costs"—the nonenvironmental welfare costs over and above those of an equal-revenue increase in the personal income tax. For both energy taxes, the relative narrowness of the tax base accounts for most of the excess cost. Differences in costs also are attributable to differences in the stage of activity or type of commodity represented in the tax base. The Btu tax's application to gross output (as compared with net output under an income tax) serves to expand the excess costs. In contrast, the gasoline tax's focus on consumption (as opposed to income) tends to mitigate the excess costs. The finding that energy taxes generate larger gross costs than the income tax alternatives is robust to a range of specifications for values of key parameters.

On the environmental side, we quantify the differences in the impacts of these tax alternatives for pollution emissions. For each of the eight major air pollutants considered, energy taxes induce emissions reductions that are at least nine times larger than the reductions under the income-tax alternatives. The differences in emissions impacts reflect the close connections between energy use and pollution generation. For the Btu tax, the largest percentage reductions in emissions are for CO_2 and NOX compounds. For the gasoline tax, the emissions reductions are spread somewhat more evenly across the eight major pollutants considered.

Overall, this study indicates that the Btu and gasoline taxes considered are inferior to the alternatives on narrow efficiency grounds but superior on environmental grounds. It remains an open question whether the environmental attractions of these taxes are large enough to offset their relatively high nonenvironmental costs.

1. INTRODUCTION

There is renewed interest in energy taxes as sources of public revenue. In February of this year the Clinton Administration proposed a Btu tax as a key component of its deficit-reduction package. Although this particular component was eventually removed from the budget package, the legislation passed by Congress several months later introduced in its place another (albeit smaller) energy tax—a tax on gasoline and other transportation fuels. Other energy taxes (such as carbon taxes) continue to be examined closely by policy makers.

There are many reasons for the intensified focus on energy taxes. Some are purely political. To many policy makers, certain types of energy taxes seem more acceptable to the voting public than typical tax increases, such as increments to personal or corporate income tax rates. Environmental considerations also are relevant here. Many have argued that the use of energy contributes disproportionately (in comparison with other activities) to major forms of pollution, and that taxing energy is a sensible way to discourage environmentally damaging activities. Efficiency concerns also apply. Some consider energy taxes to be relatively efficient instruments for obtaining government revenue in comparison with other plausible taxes.[1]

Despite the extensive debate on the attractions and drawbacks of energy taxes, there has been relatively little quantitative analysis of the gross efficiency costs[2] (the efficiency costs before netting out environmental benefits) and the environmental effects of these taxes in comparison with plausible alternatives such as increases in income taxes.[3] This paper provides a quantitative assessment.

We concentrate on two main types of energy taxes: a general tax on energy (a Btu tax) and a tax on consumer purchases of gasoline. For these taxes, we ask the following two sets of questions:

1. What are the (gross) efficiency costs of these energy taxes, and how do they compare with the efficiency costs of more traditional sources of revenue such as increases in income taxes? How can the different efficiency costs among energy taxes and between these and other taxes be explained?
2. How do these energy taxes differ from each other and from equal-revenue income taxes in terms of the impacts on emissions of important air pollutants? What are the sources of these differences?

[1] On the other hand, some analysts contend that energy taxes have larger efficiency costs than ordinary income taxes, and some would go so far as to maintain that any possible advantages of energy taxes in the environmental domain would be more than offset by the disadvantages in traditional cost dimensions.

[2] It is important to make clear what is meant by *efficiency costs* here. Among economists, the notion of efficiency customarily refers to the aggregate net benefit or cost to the economy from a policy change, as measured by adding up the dollar value of welfare impacts to each person. In its broadest sense, *efficiency* should encompass both environment-related as well as other welfare effects stemming from a given policy change. For convenience, in this paper we separate the environmental considerations from other efficiency considerations. Unless indicated otherwise, *efficiency costs* will mean the *gross* welfare costs, before netting out the benefits stemming from environmental changes.

[3] Studies by Goulder (1993) and Jorgenson and Wilcoxen (1993) have examined the overall costs of policies in which a carbon tax is combined in revenue-neutral fashion with cuts in income taxes. The overall costs of such policies implicitly indicate the relative costs of the carbon tax and the changes to income taxes. This paper differs from the earlier studies by concentrating on Btu and gasoline taxes, and examining more closely the mechanisms that account for the differences in costs between energy taxes and the income tax alternatives.

It should be noted that these questions focus on the aggregate economic and environmental impacts. Here we do not consider important distributional issues, namely, how these policies differ in the distribution of their impacts across household income groups, across geographical regions, or across nations (impacts on international competitiveness).

To address these questions, we first offer some theoretical considerations relevant to the choice between energy and income taxes. We then investigate these issues numerically using a simulation model of energy-economy-environment interactions in the United States. The numerical model projects paths of economic variables and pollution emissions under alternative tax regimes.

The simulation model adopts a dynamic, general equilibrium framework, which is especially useful for examining energy-tax options for at least two reasons. First, the general equilibrium structure addresses interactions across various sectors and industries. In contrast with partial equilibrium models, which consider a particular sector or industry in isolation, a general equilibrium model treats the different sectors and industries as part of a single interactive system. Thus, one can examine, for example, how the impacts of an energy tax are transmitted from energy markets to other markets and how responses in other markets feed back on energy markets. Second, a dynamic general equilibrium framework pays close attention to effects on saving and investment and other intertemporal adjustment issues. The taxes under consideration here can be expected to influence rates of return in different industries, thereby affecting incentives to invest and economic growth. A dynamic general equilibrium model is geared to address these effects.

Beyond the basic attractions of the general equilibrium framework, the particular model employed in this paper has features that make it especially well suited to the task at hand. First, the model uniquely combines a detailed treatment of the U.S. tax system with a close attention to sources and uses of energy in the United States. In contrast with other general equilibrium tax models, this model isolates important energy industries, takes account of substitution possibilities among energy fuels, incorporates the nonrenewable nature of oil and gas resources, and accounts for the transition from conventional fuels to "backstop" resources. And in contrast with other energy models (general equilibrium or otherwise), this model contains a detailed treatment of U.S. taxes. Building on earlier tax policy work,[4] it incorporates specific tax instruments and addresses tax incentive effects along a number of important

[4] See, for example, Goulder and Summers (1989), Goulder (1989), or Goulder and Thalmann (1993).

dimensions, including firms' investment incentives, equity values, and profits,[5] and household consumption, saving, and labor-supply decisions. The appeal of accounting for existing taxes is not simply that of comprehensiveness. A well-known principle of public finance is that the economic distortion or cost of a new tax depends fundamentally on what taxes already exist in the system: taxes interact. It is simply impossible to calculate the effects of new tax initiatives without accounting for pre-existing taxes.

Another distinguishing feature of the model is its consideration of environmental impacts.[6] Previous applications of the model have concentrated on the economic costs of a number of energy or environmental tax policies.[7] Recently, this model was extended to capture the impacts of tax policies on emissions of eight major air pollutants. This permits us to examine numerically a key dimension of the debate about energy taxes—the extent to which such taxes might yield environmental gains relative to other tax options. It should be recognized that attention to emissions represents only a first step along the environmental dimension. Ultimately, one would like to be able to assess the environment-related, *welfare impacts* of various tax policies. This would require one to capture all the links from (1) changes in emissions to (2) changes in concentrations, (3) changes in environmental impacts (such as human health), and (4) changes in welfare (evaluated in dollars). No economic model has yet consolidated all of these links on the national level for several major pollutants. The model applied in this paper takes a first step in this direction by connecting tax policy initiatives to changes in emissions for various pollutants.

The rest of the paper is organized as follows. Section 2 discusses some theoretical issues relevant to the choice between energy and income taxes. Section 3 provides an overview of the simulation model employed to assess these options numerically. The fourth section presents and interprets results from simulations of energy and income tax policies, and the final section offers conclusions.

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

[6] Perhaps the closest cousin to the current model is the intertemporal, general equilibrium model of Jorgenson and Wilcoxen (1990, 1993). However, the two models differ in some significant ways. The Jorgenson–Wilcoxen model stands out in having a stronger econometric foundation and in capturing price-responsive technological change within industries. The present model, on the other hand, contains considerably more detail on U.S. taxes, explicitly addresses the transition from exhaustible conventional fuels to backstop technologies, and captures effects of policies on emissions of a range of air pollutants.

[7] See, for example, Goulder (1992a, 1993).

2. EFFICIENCY EFFECTS OF ENERGY AND TRADITIONAL TAXES: THEORETICAL CONSIDERATIONS

This section examines, from a theoretical vantage point, the attractions and disadvantages of energy taxes in terms of their efficiency impacts. In its broadest sense, the notion of efficiency encompasses all of the aggregate welfare impacts of policy changes, including those that arise from policy-induced environmental changes. However, it is convenient to separate out the environmental and nonenvironmental impacts of policies. In this section we will start with nonenvironmental considerations and then turn to environmental issues.

One important qualification deserves attention at the outset. Here we are comparing pure tax policies. Real-world taxes usually are not pure. The U.S. income tax, for example, is actually a mix of a pure income tax and a pure consumption tax. Similarly, energy taxes often apply at different rates to different forms of energy and may have very specific exemptions and other special provisions. This section abstracts from such complications.

2.1 Traditional (Nonenvironmental) Considerations

2.1.1 Distortions in Labor, Capital, Intermediate Input and Commodity Markets To gauge the nonenvironmental efficiency impacts of energy and income taxes, it is necessary to consider the different dimensions along which these taxes generate economic distortions and excess burdens. We identify four main margins in which the principal distortions occur: the labor-leisure margin, the intertemporal margin, the margin of intermediate good choice, and the margin of consumer good choice. These margins are associated with labor, capital, intermediate good, and consumer good markets. The labor market is the domain in which the choice between working and enjoying leisure is made. The capital market is the domain for intertemporal choice, that is, the choice of how much to consume tomorrow (by saving and investing today) rather than consume today. Input and consumer good markets determine the allocation of producers' expenditures on inputs and of households' expenditures on consumer goods at given points in time.

Energy and income taxes have different effects along these margins, and these differences help explain their relative efficiency impacts. As is well known, the personal income tax—in particular, the component that applies to individual wage income—distorts the labor-leisure margin by driving a wedge between the marginal social value of labor (as indicated

TABLE 1.
Sites of Distortions Directly Generated by Energy and Income Taxes.

	Personal income tax increase	Corporate income tax increase	Btu tax	Consumer gasoline tax increase
Factor markets				
Labor-leisure choice	X		X	X
Intertemporal choice	X	X	X	
Product markets				
Intermediate input choice			X	
Consumer good choice				X

by the before-tax real wage) and the marginal private value of labor (as expressed by the after-tax real wage).[8] In addition, it distorts the intertemporal margin (capital market) through the tax on the return to capital: it drives a wedge between the marginal social value of a unit of capital (the pre-tax return to capital) and the marginal private value (the after-tax return). The corporate income tax likewise can introduce an intertemporal distortion.[9] Since the corporate tax does not apply to labor income, it has no direct impact on the labor-leisure margin.

These notions are summarized in Table 1. The Xs in the table indicate the markets where a given tax directly distorts resource allocation. For the income taxes, there are no Xs in the input and consumer good markets; these taxes do not directly affect input choice or the choice across consumer goods.

For the energy taxes, in contrast, there are direct impacts on input choice and consumer good choice. The Btu tax raises the cost of energy inputs (fuels) relative to other inputs, and in so doing affects firms' input choices. As shown by Diamond and Mirrlees (1971) and Stiglitz and Dasgupta (1971), the distortion of input choice corresponds to a (gross) efficiency loss. Similarly, a consumer-level gasoline tax alters the relative prices of gasoline and other consumer goods. Under fairly plausible assumptions, uniform taxation of consumer goods is optimal.[10] When these conditions apply, the gasoline tax distorts the choice among con-

[8] On this issue see, for example, Bradford (1984) and Auerbach and Kotlikoff (1987).

[9] Stiglitz (1976) points out that for certain combinations of interest deductibility and depreciation allowances, the tax rate on the marginal investment will be zero, and the corporate tax will function as a (nondistortionary) pure profits tax.

[10] Sufficient conditions are homotheticity of the utility function and weak separability between leisure and overall consumption. See Auerbach (1985).

sumer goods to the extent that it makes taxation of these goods less uniform.

This point might lead one to suppose that energy and income taxes introduce direct distortions in different markets—that energy taxes distort product (intermediate input and consumer good) markets while income taxes distort factor (labor and capital) markets. A closer look indicates that this is not the case. Even though energy taxes are not imposed directly on labor, they still distort labor-leisure choice: such taxes are *implicit* taxes on labor. To the extent that a Btu tax raises the costs of producing consumer goods, it raises the overall cost of commodities and thereby lowers the real after-tax wage. It therefore creates a labor market distortion by widening the gap between the marginal social value of labor (the real wage before taxes) and the private return to labor (the real wage after taxes). Correspondingly, a consumer-level gasoline tax raises the overall cost of the consumer's basket of commodities by raising the price of one commodity, gasoline. Thus it also serves to reduce the after-tax real wage.[11]

Moreover, energy taxes can directly distort the intertemporal margin as well. Although energy taxes may not appear to be taxes on the return to capital, they function as capital taxes and affect the intertemporal margin insofar as they raise the costs of producing capital goods. Energy is an important input into the production of capital goods, and thus a tax imposed on the use of energy inputs into production (that is, a tax on fuels) will raise these costs.[12] The Btu tax is such a tax. Other things being equal, this tax will reduce the rate of return to investment, because the acquisition prices of capital goods will rise (without a compensating increase in the after-tax of the returns to the services from these goods). Thus, insofar as energy inputs are important to the production of capital goods, a Btu tax functions as a tax on investment, or a negative investment tax credit.[13] Not all energy taxes affect the intertemporal margin,

[11] The labor market distortion depends on the extent to which the after-tax real wage differs from its value in a no-tax situation. The after-tax real wage is (1) the after-tax nominal wage divided by (2) the gross of tax price of consumption. Income taxes directly affect the after-tax real wage by reducing (1), whereas energy taxes directly influence this wage by raising (2). For a further analysis of this and related labor market issues, see Bovenberg and de Mooij (1993) and Poterba (1993).

[12] Policy simulations indicate, however, that the effects on capital goods prices are relatively small. The Btu tax considered later in this paper ultimately raises oil and gas prices by about 14 percent and refined product prices by about 8 percent, but leads to real increases in capital goods prices of less than 0.4 percent.

[13] There is a difference between a Btu tax and personal income tax in their effects on "new" and "old" capital. The income tax reduces the return to all capital—whether previously installed (old) or just acquired (new); a Btu tax reduces the return only on new capital, that is, capital purchased since the introduction of the tax.

however. Consider a tax on consumer purchases of gasoline. This tax does not directly affect the cost of producing capital goods or directly alter the returns from investments in such goods. Hence it does not introduce a distortion on this margin.[14] In this respect, a *consumption-level* gasoline tax shares the attraction associated with a more general consumption tax of avoiding intertemporal distortions. These considerations indicate that energy taxes may have very different (nonenvironmental) efficiency impacts depending on whether they are imposed at the production stage or at the level of household consumption. We investigate this issue numerically later in this paper.

The locations of the Xs under the energy tax columns in Table 1 reflect these considerations. The central notion indicated by the table is that *energy taxes not only introduce distortions in product markets, but also induce the sort of factor market distortions generated by income taxes.* Of course, one cannot ascertain the relative efficiency costs of energy and income taxes merely by comparing the number of Xs associated with a given tax: the relative costs depend on the magnitude of the distortions as well as their number. It is tempting to suppose that energy taxes must generate much smaller-factor market distortions than income taxes do, since energy taxes have a much narrower tax base and generate less revenue. However, in assessing the relative gross costs of equal-revenue changes to energy and income taxes, the relevant consideration is the gross efficiency cost per dollar of revenue raised. As shown recently by Bovenberg and de Mooij (1993), the narrowness of the energy-tax base actually works toward *larger* gross distortions in factor markets from energy taxes in comparison with income taxes. In addition, the narrower the base of an energy tax, the larger the distortion introduced by the tax in the markets for intermediate goods or consumer goods (as applicable).[15] Hence, a narrower tax base serves to enlarge the gross efficiency costs of energy taxes relative to equal-revenue income taxes.

Based on these considerations, one might suspect that the Btu tax will involve larger gross efficiency costs than an equal revenue increment to income taxes. Its factor market distortions could be comparable to those generated by income taxes; at the same time it adds a distortion of its own along the margin for input choice. A consumer-level gasoline tax, in

[14] A consumer-level gasoline tax can have indirect, general equilibrium effects on the return to capital, despite the fact that it is not directly imposed on capital goods production or on capital income. In comparing the efficiency impacts of the different taxes, one can regard such indirect effects as second-order.

[15] A basic principle of public finance is that broader-based taxes tend to be more efficient than more narrow-based ones. With a narrow-based tax, the tax rates must be higher than under a broad-based tax to attain a given revenue target. Higher tax rates tend to imply larger efficiency costs.

contrast, might seem to have better prospects for involving lower gross costs than income taxes. Like income taxes, the gasoline tax directly distorts the labor market, but it avoids the capital market distortion introduced by income taxes and the Btu tax because the consumer-level gasoline tax does not raise the cost of producing capital goods.

Although these considerations may influence one's expectations of the rankings of income and energy taxes in terms of their gross efficiency costs, the rankings cannot be rigorously established a priori. Determining the rankings requires a numerical assessment.

2.1.2 A Note on the Monopsony Power Argument The monopsony power argument has been invoked to support energy taxes. The United States is a major demander of oil on the world market. To the extent that an energy tax discourages U.S. demands for oil, it can help drive down the world price of oil. Other things being equal, reductions in the pre-tax price of imported oil are beneficial to domestic welfare, and compensate for the costs of the tax to consumers of oil.

This argument does indeed provide a basis for policies to reduce U.S. demands for imported oil. Provided that the United States exerts monopsony power and the tax is not too high, a tax on oil can provide efficiency gains. On the other hand, this issue does not provide support for a broader energy tax such as the Btu tax we have discussed. The United States is a net exporter of coal and its net imports of natural gas are not large. The monopsony power argument does not apply to these fuels.

2.1.3 A Closer Look at the Issue of Commodity Market Distortions We have asserted that by altering the relative rates of taxation of different commodities, energy taxes introduce an efficiency cost on this margin, a cost that is avoided by income taxes. Strictly speaking, whether the effect on the intercommodity margin detracts from or adds to the appeal of energy taxes in comparison with income taxes depends on two issues that, to preserve the flow of the previous discussion, were glossed over initially.

Is energy relatively lightly taxed initially? The first issue is whether, under the status quo, energy is taxed relatively lightly in comparison with other commodities. If so, then the energy tax could in fact lead to a more efficient allocation of consumption between energy and other commodities, and the "intercommodity efficiency effect" of the energy tax could be positive.[16] It turns out, however, that it is difficult to make the

[16] This issue relies on the central notion from public finance that the distortionary cost of a given tax is an increasing function of the rate of pre-existing taxes in the market in ques-

case that energy is more lightly taxed than other commodities. Favorable tax rules had applied to depreciation and resource depletion in the oil and gas extraction industries, but these rules were eliminated under the Tax Reform Act of 1986. Moreover, specific forms of energy (such as gasoline) face federal and state excise taxes that do not apply to most other commodities. There is little basis for expecting that differences in pre-existing tax rates would cause the intercommodity effect to contribute to rather than detract from the appeal of a new energy tax.

Is the supply of energy relatively inelastic? The other consideration is whether energy supply and demand are relatively inelastic in comparison with other commodities. A basic principle of public finance is that, other things being equal, for a given tax rate the excess burden (or efficiency cost) is smaller the more inelastic the supply or demand of the good upon which the tax is applied.[17]

This principle can be related to the intercommodity efficiency effect. If energy is supplied more inelastically than other commodities, then a given tax rate can potentially lead to a smaller efficiency cost when applied to energy than when applied to other commodities. Under these circumstances a tax on energy can potentially improve efficiency on the intercommodity margin.[18]

Some analysts claim that the supply of energy is relatively inelastic. A common argument is that, to a large extent, stocks of fossil fuels are essentially fixed, so that the long-run supply of such fuels is highly inelastic. This argument ignores an important distinction between the natural supply of unrecovered reserves and the quantity of economically recoverable (and thus extractable) reserves. Although the supply of unrecovered reserves may be fixed, the quantity of economically recoverable reserves may nonetheless be very elastic. Consider in particular the case of crude

tion. Abstracting from differences in elasticities of demand and supply across commodities, if pre-existing taxes on energy were lower than those on other commodities, then the distortionary cost of an incremental increase in the energy tax would be less than that of an incremental increase in other commodity taxes.

[17] This principle is consistent with the well-known Ramsey Rule of optimal commodity taxation (Ramsey, 1927) that endorses taxes on commodities in inverse relation to the elasticities of demand. The "inverse elasticity rule" is often misleading, however, because it ignores cross-price elasticities of demand and adding-up restrictions that apply to consumer demand systems. Indeed, Deaton (1979) and Auerbach (1985) have shown that optimal commodity taxation involves *uniform* tax rates when utility functions are homothetic and leisure and consumption are weakly separable. (See also Atkinson and Stiglitz, 1980, chapter 12.) For comprehensiveness, we include here a discussion of the relative inelasticity of energy supply, but it should be recognized that under certain conditions this issue has no bearing on whether higher taxes are justified on efficiency grounds.

[18] See Bovenberg and de Mooij (1993).

oil. There is considerable heterogeneity across producers in terms of the costs of extracting given amounts of fuel, reflecting the differences in geological characteristics of different fields (oil depth, types of subsurface minerals, etc.). When producers have different production costs, the "rents" on produced oil will differ as well. Producers with especially low production costs will earn large rents, while others, with high extraction costs, will earn small ones. For some marginal producers, taxes on oil can reduce the rent just enough to turn marginally profitable production uneconomic, meaning that the supply of oil is sensitive to taxes on oil, even in the very long run. In other words, the commercial supply of nonrenewable resources is not completely inelastic.

Thus, it remains an open question whether supplies of energy are more or less elastic than other commodities in general. The answer depends, in each fossil-fuel industry, on the distribution of production costs across producers, now and in the future. The empirical verification of this notion has not yet been accomplished.[19]

In sum, though it is possible for energy taxes to improve efficiency on the intercommodity margin, the conditions that would allow this result to hold either do not apply or require a degree of empirical verification that has yet to be established.

Overall, the theoretical considerations from this subsection do not produce a clear winner on (nonenvironmental) efficiency grounds. There are many dimensions along which energy taxes can be expected to be more costly than increased income taxes. But there are at least some dimensions in which energy taxes might be less costly. To gauge how these different efficiency impacts add up, we need to adopt an empirical analysis. We perform such an analysis in Section 4.

2.2 Environmental Considerations

2.2.1 Connections between Pollution Intensity and Environmental Improvement Environmental considerations might seem to favor energy taxes. The argument is simple. If energy use is generally more damaging to the environment than other activities, then an energy tax may be

[19] Jones and Bremmer (1990), considering supply effects for Texas wells over the period 1973–1983, report elasticities ranging from .13 to .38. Walls (1991) uses information on the price responsiveness of exploration and drilling activity to project a supply elasticity of .15. Interpreting these elasticities is inherently problematic because it is difficult to discern whether the observed changes in supply represent permanent increments to the total amount to be extracted from given reserves or temporary increases that, because of rising extraction costs, will eventually be offset by future reductions in supply (so that there is no increase in the total amount ultimately extracted). The supply elasticities relevant to the efficiency discussion should measure permanent increments.

superior to the other taxes considered here because it targets the source of the damage.

Later in this paper (Table 9) we provide evidence that supports the conventional wisdom that energy use contributes disproportionately to economy-wide emissions of important air pollutants. However, environmental regulations complicate the connection between energy taxes and changes in energy use. To the extent that pre-existing regulations constrain emissions of certain pollutants, higher energy taxes need not always lead to further reductions in these pollutants below the levels mandated by regulations. Consider, for example, the sulphur dioxide emissions from coal-fired electric power plants. Such emissions are regulated through provisions of the 1990 Clean Air Act Amendments. To the extent that an energy tax reduces demands for electricity, power plants whose output levels fall can comply with the limits on total sulphur dioxide with higher ratios of sulphur dioxide per unit of output. Such plants need not "ratchet down" their emissions-output ratios as far as they would if no tax were implemented. We return to this issue in the next section.

2.2.2 Do We Know That "Small" Taxes Are Superior to the Alternatives? The previous discussion suggested that energy taxes are likely to be more costly than the alternatives in the nonenvironmental dimensions. Thus, even if energy taxes are more environmentally beneficial than the alternatives, the question remains as to whether they are more efficient overall. One line of reasoning would suggest that they must be, provided that the tax rate is not too high. Figure 1 is a typical diagram indicating the costs and benefits from an environmental tax. The supply S and demand D curves can be interpreted as the marginal private cost and marginal benefit from energy use. The marginal external (or environmental) cost from energy use is represented by MEC. Adding this marginal cost to private marginal cost yields the social marginal cost curve, MSC. The shaded area in the diagram indicates the efficiency loss from excessive use of energy when purchasers of energy do not face the external costs. Here, introducing a small energy tax (for example, t_1 in diagram) helps reduce the differential between marginal social cost and marginal private cost and shrinks the efficiency loss. So long as t_1 does not greatly exceed the marginal external cost, the tax will lead to benefits in excess of costs. This suggests that so long as the energy tax rate is conservative, that is, falls short of (or at least does not vastly exceed) the marginal environmental cost, then the energy tax will pay for itself. An energy tax will not only be more attractive than the alternatives; it will improve efficiency!

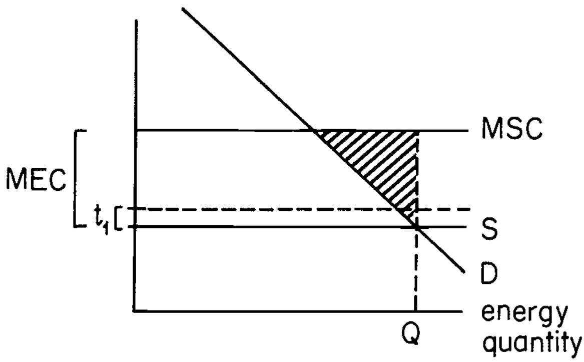

FIGURE 1. *Are "Small" Energy Taxes Guaranteed to Confer Efficiency Gains?*

This argument, though appealing, is not entirely valid. If no other taxes are present in the economy, then the case can be made that a small energy tax pays for itself. But in an economy with pre-existing taxes—whether in the energy markets or in other markets—there is no guarantee that small energy taxes will generate environmental gains larger than the nonenvironmental efficiency costs. The issue here is reminiscent of the notion, presented in subsection 2.1 above, that energy taxes can generate large efficiency costs because they not only affect energy markets but also introduce distortions in labor markets (the dimension of labor-leisure choice) and capital markets (the intertemporal dimension). In general equilibrium, even small environmentally motivated taxes can generate large efficiency costs through the distortions they introduce in other markets. This notion receives support from analytical work by Bovenberg and de Mooij (1993) and simulation work by Goulder (1993).

The upshot is that the existence of a net efficiency gain from an energy tax—even a small one—cannot be established on a priori grounds. Determining whether the tax yields net benefits and ascertaining the magnitude of the net benefit or cost relative to the net benefits or costs of alternative policies requires empirical investigation.

2.2.3 National Security Benefits A potential benefit from energy taxes is increased national security associated with reduced reliance on oil imports. Under a broad definition of *environmental*, this might be considered an environmental benefit because it is external to the private benefits underlying oil purchase and supply decisions.

The argument for national-security benefits turns on the idea that reduced importation of oil implies smaller economic costs in the event of a supply disruption. This benefit is extremely difficult to quantify, in part because of the difficulty of calculating the probability and magnitude of oil supply disruptions. In the spirit of comprehensiveness, we mention this potential benefit here, but we do not attempt to quantify the benefit in this paper.

2.3 Summary

All in all, the theoretical issues from this section paint a mixed picture regarding the attractiveness of energy taxes in comparison with income taxes. On the one hand, theory points out several ways in which energy taxes might be more costly than the alternatives on nonenvironmental (traditional macroeconomic) grounds. On the other hand, energy taxes appear likely to have the advantage in the environmental domain. The overall efficiency impact cannot be determined from theory alone. In Section 4 we use a general equilibrium model to explore the magnitudes of the traditional nonenvironmental impacts and evaluate some of the environmental consequences.

3. BASIC FEATURES OF THE SIMULATION MODEL

We assess the effects of energy and income taxes using a general equilibrium model of the United States that incorporates international trade. Here we sketch out some main features of the model. Details about the model's structure and parameters are offered in the Appendix. A more complete description is in Goulder (1992b).

The model generates paths of equilibrium prices, outputs, and incomes for the U.S. economy 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 (1) a detailed treatment of the U.S. tax system, (2) a close treatment of energy production and demand, and (3) attention to stationary-source and mobile-source emissions of major air pollutants. The representation of taxes incorporates very specific tax instruments and addresses effects along a number of important dimensions. These include effects on firms' investment incentives, equity values, and profits, and impacts on household consumption, saving, and labor-supply decisions.[20] The specification of energy supply includes an attention to the nonrenewable nature of crude petroleum and natural gas and a treatment of the transitions from conventional to synthetic fuels. The treatment of emissions is based on historical relationships between emissions and fuel used, processes employed, and levels of output.

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

TABLE 2.
Industry and Consumer Good Categories.

Industries
1. Ariculture and Noncoal 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, and Miscellaneous
14. Nondurable, Non-food household expenditure
15. Gasoline and other fuels
16. Education
17. Health

3.1 Industry and Consumer Good Disaggregation

The model divides U.S. production into the 13 industries indicated in Table 2. The energy industries consist of coal mining, crude petroleum and natural-gas extraction, synthetic-fuels production, petroleum refining, electric utilities, and gas utilities. The model also distinguishes the seventeen consumer goods in Table 2.

3.2 Producer Behavior

3.2.1 General Specifications In each industry, a nested production structure accounts for potential substitutions 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 inputs of labor L, capital K, an energy composite E, and a materials composite M, as well as the current level of investment I:

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

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

$$E = E(\bar{x}_2, \bar{x}_3 + \bar{x}_4, \bar{x}_5, \ldots, \bar{x}_7) \tag{2}$$

$$M = M(\bar{x}_1, \bar{x}_8, \ldots, \bar{x}_{13}), \tag{3}$$

where $\bar{x}_i$ is a composite of domestically produced and foreign made input i. Industry indices correspond to those provided in Table 2.[21]

Managers of firms are assumed to serve stockholders in aiming to maximize the value of the firm; this objective guides the choices of input quantities and investment levels in each period of time. The model incorporates capital adjustment dynamics. In equation (1), $\phi(I/K) \cdot I$ represents capital adjustment (or installation) costs; these are an increasing function of the rate of investment.[22]

3.2.2 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

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

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

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

where γ is a decreasing function of Z, the amount of cumulative extraction (or output) of oil and gas up to the beginning of the current period. This equation captures the fact that as Z rises (or, equivalently, as reserves are depleted), it becomes increasingly difficult to extract oil and gas resources, so that greater quantities of K, L, E, and M are required to achieve any given level of extraction (output). Increasing production costs ultimately induce oil and gas producers to remove their capital from this industry.[23]

The model incorporates a synthetic fuel, shale oil, as a backstop resource, a perfect substitute for oil and gas.[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.

All domestic prices in the model are endogenous, except for the domestic price of oil and gas. The latter is given by the exogenous world price of oil and gas plus whatever oil tariff may apply. According to the baseline assumptions of the Stanford Energy Modeling Forum, this world price is specified as $24 per barrel in 1990 and rising in real terms by $6.50 per decade.[25] 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 the domestic supply of oil and gas satisfy all of domestic demand. Synfuels then become the marginal source of supply, and the cost of synfuels production rather than the world oil price dictates the domestic price of fuels.[26]

[23] The attention to resource stock effects distinguishes this model from several other general equilibrium, energy-environmental models. Many equilibrium models treat the domestic oil-and-gas industry as a constant-returns-to-scale production, disregarding resource stock effects or fixed factors (see, for example, Jorgenson and Wilcoxen [1990, 1993]). In their global energy-environment model, Manne and Richels (1992) impose stock limits on resources such as oil and gas, but these limits have no effect on production costs prior to the point where the resource is exhausted.

[24] Thus, inputs 3 (oil and gas) and 4 (synfuels) enter additively in the energy aggregation function shown in equation (2).

[25] See Gaskins and Weyant (1993).

[26] For details, see Goulder (1993).

3.3 Household Behavior

Consumption, labor supply, and saving result from the decisions of a representative household maximizing its intertemporal utility. 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 is allocated across the seventeen specific consumption categories of Table 2. Each of the seventeen 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.

3.4 The Government Sector

The government collects taxes, distributes transfers, and purchases goods and services (outputs of the thirteen industries).

The model incorporates a wide array of tax instruments, including 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, there is a government deficit equal to approximately 2 percent of GNP. In the reference case (or status quo) simulation, the deficit-GNP ratio is approximately constant. In the policy experiments in this paper, we require that real government spending and the real deficit follow the same path as in the reference case, implying that, to meet the cash flow requirement, the real tax revenues collected under the various policies must be the same as in the reference case. Ordinarily, the policies considered in this paper—new energy taxes or increases to income taxes—would lead to an increase in tax revenue (relative to the reference case) in the absence of some other tax adjustment. To make these policies revenue neutral, we accompany the rate increases that define the various policies with reductions in other taxes, either on a lump-sum basis or through reductions in other tax rates.

3.5 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.[27] As

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

indicated above, demands for foreign intermediate inputs stem from cost-minimizing producer behavior, whereas demands for foreign consumer goods derive from household utility maximization. Import prices are exogenous in foreign currency, but the domestic-currency price changes with 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 achieve trade balance, that is, to reconcile the value of U.S. import demands with the value of foreign export demands.

3.6 Modeling Pollution Emissions

Recent extensions of the model enable it to project emissions of important pollutants under different policy circumstances. The model considers eight major pollutants: total suspended particles (TSP), sulphur oxides (SOX), nitric oxides (NOX), volatile organic compounds (VOCs), carbon monoxide (CO), lead (Pb), particulate matter (PM_{10}), and carbon dioxide (CO_2).

The extension of the model to project emissions was accomplished through close collaborations with personnel at the U.S. Environmental Protection Agency and the Environmental Law Institute. We have made use of detailed, highly disaggregated data on emissions rates for specific industrial processes and fuels.[28]

The key parameters used to project emissions levels (under baseline assumptions or in response to a change of policy) are *emissions factors*. The model includes three types of emissions factors: fuel-based factors, output-based factors, and mobile-source-based 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 in industry k.[29] Fuel-based emissions factors do

[28] These data come from a wide variety of sources, including the Annual Survey of Manufacturers from the U.S. Department of Census, the Quarterly Coal Report and Petroleum Supply Report from the U.S. Department of Energy, and the Minerals Yearbook. Personnel at the Environmental Law Institute (ELI) organized the detailed emissions data and aggregated these data to conform to the thirteen-industry and seventeen-consumer good aggregation of this model.

[29] In each industry, we take the ratio of the fuel-associated emissions to the quantity of fuel used in a given industry to obtain the fuel-based emissions factor for each pollutant from that industry. We calculate this ratio in 1990, based on ELI data on fuel-associated emissions and the general equilibrium model's data on fuel use. Thus, for example, the emissions factor defining the rate of emissions of TSP per unit of coal input in the electric

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.[30] The mobile-source emissions factors e_m_{ik} are expressed as the ratio of emissions i from a given mobile source to the level of use of that source (vehicle).[31]

By applying the emissions factors to the levels of fuels used and levels of outputs produced in each industry, we generate the predicted levels of emissions of each pollutant from each industry. Changes in emissions stemming from a policy change reflect the policy-induced changes in fuel use and output levels.[32]

3.7 *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

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utilities industry was calculated by taking the ratio of observed 1990 TSP emissions from coal used in electric utilities to the quantity of coal used by electric utilities in 1990.

[30] We calculate the output-based emissions factors by taking the ratio of the residual emissions to the level of industry output. As with the fuel-based emissions factors, the ratio is calculated based on 1990 data on emissions from ELI and on industry outputs from the general equilibrium model's data set.

[31] We aggregated data on emissions from very specific sources to obtain total emissions for each pollutant from the following mobile-source categories: (1) passenger vehicles, (2) other highway vehicles, (3) farm equipment, (4) construction equipment, and (5) other mobile sources. Because the model does not measure vehicle use directly, we use proxies for vehicle use to determine mobile-source emissions. Gasoline consumption is the proxy for the quantity of passenger car and other highway vehicle use. Agriculture output, construction industry output, and services industry output are proxies for the level of use of farm equipment, construction equipment, and other mobile sources, respectively.

[32] This approach is not perfect. One loses potentially important information when detailed industrial processes are aggregated to the level in the model. Even though the model has considerable industry- and consumer-good disaggregation, it masks some important detail that is highly relevant to emissions levels. Many important contributions to emissions stem from industries or industrial processes that are more detailed than can be captured in this thirteen-industry, seventeen-consumer good model. In addition, we assume that emissions factors do not change over time; hence the model does not aptly capture industry-specific technological change that may alter these factors over time.

Moreover, this approach, which assumes that emissions are proportional to fuel uses and industry outputs, does not directly address ways that environmental regulations might affect emissions rates. We make one adjustment in this approach to confront this issue: we assume that aggregate emissions of sulphur dioxide from coal-fired electric power plants are constrained by the provisions of the 1990 Clean Air Act. Thus, tax policies cannot reduce this particular emission from this particular source. To the extent that taxes reduce demands for electricity from these plants, the reduced electricity output does not lead to a reduction in SO_2 emissions. The reduced output instead enables electric-power producers to meet the aggregate emissions constraint somewhat more easily.

requires that supply equal demand for labor inputs and for all produced goods,[33] that firms' demands for loanable funds equal the aggregate supply by households, and that the government's tax revenues equal its spending less the current deficit. These conditions are met through adjustments in output prices, in the market interest rate, and in lump-sum taxes or tax rates.[34]

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

3.8 Data and Parameters

Complete data documentation for the model is provided in Cruz and Goulder (1992). In the present subsection we indicate the sources for some important data and parameters.

The data stem from several sources. Industry input and output flows (used to establish production function share parameters) were obtained from 1986 input-output tables published in the February 1991 *Survey of Current Business*. These tables were also the source for consumption, investment, government spending, import and export values by industry. The initial period for the simulations of this paper is the year 1990. To obtain 1990 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 relative 1990 values correspond closely to relative values projected for 1988 by the OECD (see OECD/IEA, 1990).

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

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

34 When oil/gas imports are the marginal source of supply for the domestic economy, the *quantity* of these imports is an equilibrating variable, and the oil/gas price is exogenous. Once synfuels become the marginal source of supply (that is, once synfuels drive oil/gas imports to zero), the synfuels *price* becomes an equilibrating variable.

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

The Appendix to this paper indicates functional forms and lists parameter values for the production and household sectors.

4. SIMULATION EXPERIMENTS AND RESULTS

In this section we describe simulation experiments performed to compare effects of energy and other taxes. In addition, we report and interpret the simulation results.

4.1 Policies Considered

To assess the impacts of policy changes, we compare results under each simulation of a policy change with results from a baseline or reference-case simulation (which assumes no change in tax policy). In the baseline simulation, all tax rates remain constant through time.

We simulate the following four policies:

1. *A Btu tax.* This is a tax imposed on oil, natural gas, and coal in proportion to the Btu content of these fuels.[35] The same tax rates apply to imported fuels as to the domestically produced counterparts. Exports are exempt from the tax.[36]
2. *A gasoline tax.* This is a specific, or per-unit, tax on the purchases of gasoline by consumers. "Gasoline and other fuels" is one of the seventeen consumer goods distinguished in the model. The gasoline tax is applied to household purchases of this good.
3. *An increase in marginal rates of the personal income tax.* The model includes marginal tax rates on individual wage income, dividend income, interest income, and capital gains income. These are the average marginal rates that apply in the benchmark year, 1994. Under the policy of an increase in personal income taxes, each of these marginal rates is increased in the same proportion.
4. *An increase in the corporate income-tax rate.* This is an increase in the rate of tax on corporate profits.

[35] The model treats crude petroleum and natural gas together as a single industry. It was still possible, however, to capture the different tax rates applying to these fuels, because nearly all crude petroleum serves as an input into the petroleum refining industry. Thus the industry 3 (crude petroleum and natural gas industry) inputs into industries other than petroleum refining faced a tax equal to the tax rate on natural gas, in keeping with the fact that very little crude oil (except for some feedstocks) is used outside of the petroleum industry. In contrast, industry 3 inputs into the petroleum refining industry faced a tax reflecting the share of natural gas and crude oil as inputs into petroleum refining.

[36] This avoids putting U.S.-produced fuels at a cost disadvantage relative to imported fuels in the domestic market, and avoids putting exported U.S. fuels at a cost disadvantage relative to foreign-produced fuels in the international market.

TABLE 3.
Tax Rates under Energy and Income Tax Policies.

	Reference case	Btu tax	Gasoline tax increase	Personal income tax increase	Corporate tax increase
Tax rate per million Btu's of fuels	0	**.4500**	0	0	0
Tax rate per gallon of gasoline	.2875	.2875	**.6925**	.2875	.2875
Marginal rate on labor income	.2300	.2300	.2300	**.2388**	.2300
Marginal Rate on dividend and interest income	.2290	.2290	.2290	**.2328**	.2290
Marginal rate on capital gains income	.0572	.0572	.0572	**.0582**	.0572
Marginal rate on corporate profits	.3850	.3850	.3850	.3850	**.3946**

Note: Policies are scaled to imply the same gross revenue impact. Numbers that differ from reference case values are shown in bold face. Income tax rates represent nominal dollars collected per dollar of nominal income. Energy tax rates express real (1990) dollars collected per energy or physical unit (Btu's, gallons).

Table 3 indicates the tax rates employed under the baseline and policy-change scenarios. The rates shown for the policy changes are after the policy in question is fully phased in. All policies are phased in over a three-year period, beginning in 1994.

Each of these policies is introduced in a revenue-neutral fashion: the path of tax revenues under each policy is made identical to the revenue path in the baseline. In the absence of compensating tax reductions, new energy taxes or higher income tax rates generally would lead to higher overall government revenues. To assure revenue neutrality, we accompany the rate increases with compensating tax reductions either through lump-sum reductions in personal income taxes or by way of reductions in the marginal tax rates on individual income.

For comparability, the policies are scaled to imply the same *gross* revenue impact—the same revenue yield, abstracting from the revenue-preserving reductions in other taxes. The gross revenue impact of these policies, over the infinite time horizon, is $1,155 billion in present value. Over the first five years, these taxes yield gross revenues ranging from 61 to 76 billion 1990 dollars.

4.2 Simulation Results: "Traditional" Effects

4.2.1 Differences in Aggregate Economic Impacts Figures 2a–2c show the effects of the alternative policies on real GNP, consumption, and investment. These results are from experiments with lump-sum replacement of revenues. The figures indicate the percentage change in these variables relative to a reference case involving no policy change. The first year corresponds to 1994.

Figure 2a compares the GNP effects. Within the first twelve years following implementation, the Btu and gasoline taxes imply larger reductions in GNP than the income tax alternatives. For example, in the year 2000 (six years after implementation), the Btu and gas taxes imply GNP reductions (relative to baseline) of about 0.22 and 0.18 percent, as compared with 0.14 and 0.07 percent under the personal and corporate tax increases. The GNP costs of the Btu tax remain larger than those of the income tax alternatives. In contrast, the GNP cost of the gasoline tax eventually becomes smaller than that of the personal tax increase. The relatively benign long-term GNP impact of the gasoline tax reflects its more favorable impact on investment, as discussed below.

The impacts on consumption are compared in Figure 2b. As with the GNP losses, the losses in consumption are greatest for the energy tax policies. However, in contrast with the GNP results, the losses here are greater for the gasoline tax than for the Btu tax. While the Btu tax raises the costs of production for intermediate, capital, and consumer goods, the gasoline tax is targeted to consumption. Thus, in comparison with the Btu tax, under the gasoline tax the GNP reductions come in the form of reduced consumption rather than reduced investment.

Figure 2c contrasts the investment impacts. The investment losses of the gasoline tax are less severe than those of any of the other policies. Hence the path of the capital stock is higher under the gasoline tax than under the other policies. This helps explain why, over time, the GNP path under the gasoline tax improves relative to the paths under the other policies.

There are various ways to discern economic well-being from the preceding figures. One way is to apply the equivalent-variation measure, which translates changes in consumption from a given policy into a dollar equivalent.[37] The welfare costs of the different policies are given in

[37] The equivalent-variation measure used here is the amount that a dynastic or infinitely-lived household would require under the status quo to be made as well off as under the policy change. It is a single number that consolidates the welfare impacts from changes in current and future consumption. As applied here, this measure does not address equity issues as reflected in changes in the distribution of well-being across household income groups or between current and future generations.

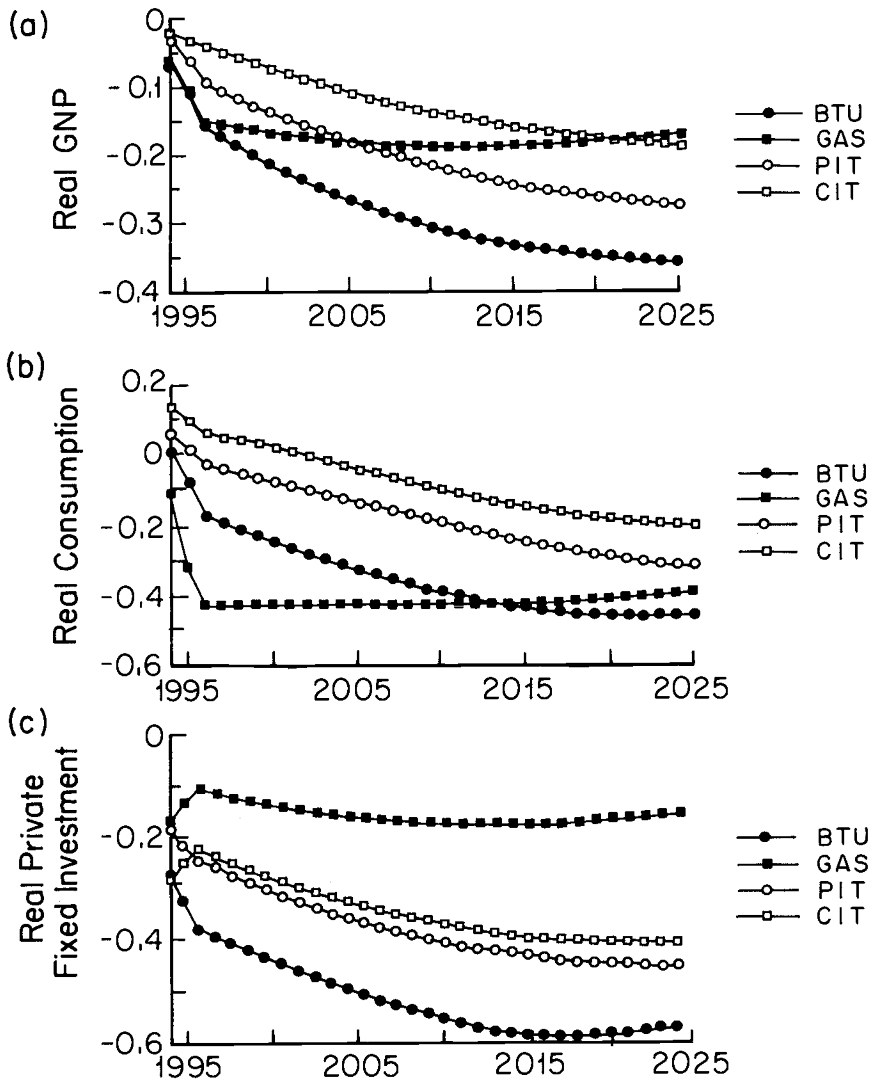

FIGURE 2. *Aggregate Effects of Energy and Income Tax Policies (Percentage Changes from Reference Cases).*

Table 4. To give a perspective on the magnitude of these numbers, the welfare cost of the Btu tax with lump-sum income tax replacement is shown as −0.394. This tax is roughly equivalent to a permanent reduction in consumption of about 0.39 percent.

TABLE 4.
Welfare Impacts.

Policy	Tax replacement method: *Lump-sum reduction in personal taxes*	Tax replacement method: *Reduction in marginal rates of personal income tax*
Btu tax	−.394	−.238
Gasoline tax increase	−.334	−.176
Raised personal income tax rates	−.161	—
Raised corporate tax rates	−.156	.006

Note: The welfare effect is expressed by the equivalent variation as a percentage of lifetime resources (present value of capital and labor income) under the status quo. These welfare assessments disregard welfare benefits from reduced environmental damages.

The numbers in Table 4 indicate that the energy taxes have larger welfare costs than the income tax alternatives. The Btu tax implies the largest welfare cost. The rankings of welfare costs correspond to the differences in consumption paths from Figure 2b.[38] It should be kept in mind that these welfare measures abstract from the possible welfare benefits associated with policy-induced improvements in the environment (or avoided environmental damages).

4.2.2 Explaining the Differences in Aggregate Impacts The above results indicate that the Btu and gasoline taxes tend to impose larger costs in terms of consumption, welfare, and GNP than the two income-tax alternatives. It is important to ascertain how these cost differences arise. Here we harken back to the issues raised in section 2. How significant is it that energy taxes apply to a relatively narrow set of industries? How important is the fact that, in contrast with income taxes, a Btu tax applies to intermediate inputs? And how much difference does it make whether an energy tax applies to consumer goods as opposed to all final goods?

It is possible to address these questions by performing some additional simulations designed to isolate the different dimensions along which energy and other taxes differ.

[38] Welfare depends on the household's enjoyment of both consumer goods *and leisure*. To the extent that leisure changes are imperfectly correlated with the changes in consumption from Figure 2b, the values in the figure will not be perfect indicators of welfare changes.

TABLE 5.
Significance of Alternative Tax Bases.

Policy	% Change GNP 2000 (year 7)	2020 (year 27)	Welfare change*
Btu tax	−0.215	−0.351	−0.394
Broad output tax	−0.200	−0.314	−0.247
Gasoline tax increase	−0.177	−0.194	−0.334
Broad consumption tax	−0.138	−0.177	−0.084
Personal income tax increase	−0.138	−0.265	−0.161

* The measure of welfare change is the equivalent variation as a percentage of lifetime income.

Significance of the breadth of the tax base One important feature of energy taxes, in comparison with income taxes, is that their tax bases are relatively narrow. The Btu tax applies only to a few industrial outputs—the outputs of the oil, natural gas, coal, and synthetic fuels industries. These industries account for less than 3 percent of the value of the nation's gross output. Similarly, consumer purchases of gasoline account for a very small share of household expenditure on goods and services.

To consider the importance of the breadth of base, we perform two new simulations. First, we simulate a uniform, broad-based tax on gross output with the same gross revenue impact as the taxes already considered. Since the Btu tax is also a tax on gross output (of oil, natural gas, and coal), the main structural difference between the broad-based tax and the Btu tax is the breadth of the base. Second, we simulate a uniform general consumption tax—applying to all consumer goods, not just consumer purchases of gasoline. This isolates the significance of the breadth of the tax base at the level of household consumption.

Table 5 compares the GNP and welfare impacts of these new policies with those under the policies already considered. The excess cost of the Btu tax over the personal tax increase is 0.233; in contrast, the excess cost of the broad output tax over the personal tax increase is 0.086. Thus, about two thirds ([0.233 − 0.086] / 0.233) of the Btu tax's excess cost can be attributed to its relatively narrow industrial base.[39] For the consumer-

[39] The broad-based output tax is imposed as a specific, or per-unit tax, where units are defined as that quantity of output worth $1 in 1990. A subtle difference between the broad-based output tax and the Btu tax is that the latter tax is not uniform with respect to quantity units (or 1990 dollars' worth of output); instead, it is specified as uniform with respect to energy content. In further simulation experiments, we compare the effects of the Btu tax already considered with those of a "strictly uniform" Btu tax—a tax with the same rates per

level gasoline tax, the breadth of base is important as well, as is clear from a comparison of rows 3 and 4 of Table 5. Whereas the gasoline tax leads to a welfare cost about twice as large as that under the income tax, the general consumption tax produces a smaller welfare loss than under the income tax increase—the "excess cost" is negative. This fact suggests that financing a general consumption tax with cuts in the personal income tax would yield a net welfare gain.[40]

Significance of taxing gross, rather than net, output The overall difference between a Btu tax and the personal income tax can be decomposed into (1) the difference between a tax on particular industry outputs (fuels) and a tax on all industry gross outputs, and (2) the difference between a tax on all gross outputs and a tax on all final goods (the income tax). The welfare importance of the first of these differences was seen by comparing the results in rows 1 and 2 of Table 5, as discussed in the previous paragraph. The significance of the second of these differences is indicated from a comparison of the results in rows 2 and 5 of the table, which indicate that about a third (0.086 / 0.233) of the difference in GNP and welfare costs between the Btu and personal income tax is attributable to this second dimension.

Significance of taxing consumption goods rather than all final goods Table 5 affords another useful comparison. The overall difference between a gasoline tax and the personal income tax can be decomposed into (1) the difference between a tax on a particular consumer good (gasoline) and a tax on all consumer goods, and (2) the difference between a tax on all consumer goods and a tax on all final goods (the income tax). The first of these differences was already observed by comparing rows 3 and 4 of Table 5. It is clear that the first difference has a negative impact relative to the personal income tax. The second of these differences is seen by comparing rows 4 and 5. The table shows that the narrow consumption base of the gasoline tax exerts a strong negative welfare impact. In fact, the narrowness of the base is important enough to undo the positive

unit of output. The differences in welfare effects are small. The strictly uniform Btu tax generated a welfare loss of 0.375, as opposed to 0.394 under the original Btu tax, and 0.246 under the broad-based gross output tax. With this information, a small fraction of the excess cost now attributed to the narrowness of the base can be attributed to the lack of strict uniformity. Recall that the excess cost of the ordinary Btu tax is 0.233. The results from the strictly uniform Btu tax imply that the lack of strict uniformity accounts for about 8 percent ([0.394–0.375]/0.233) of the excess cost, and that the narrowness of the base accounts for about 55 percent ([0.375–0.246]/0.233) of this cost.

[40] Subsequent simulation experiments confirm this suggestion.

TABLE 6.
The "Excess" Costs of Energy Taxes: A Decomposition.

	Excess cost	Contribution to overall excess cost (%)
1. Btu tax	−0.233	
a. Intermediate goods base rather than final goods base	−0.086	37
b. Narrow rather than broad intermediate goods base	−0.147	63
2. Gasoline tax increase	−0.173	
a. consumption goods base rather than final goods base	+0.077	−44
b. narrow rather than broad consumption goods base	−0.250	144

Note: The overall excess cost (lines 1 and 2) is the difference in the welfare impact of the energy tax in question and a personal tax increase of equal revenue yield. The decomposition of overall excess cost is based on the following comparisons:
Line 1a: Difference in welfare cost of broad-based output tax and the income tax increase.
Line 1b: Difference between excess costs of line 1 and line 1a.
Line 2a: Difference in welfare cost of broad-based consumption tax and the income tax increase.
Line 2b: Difference between excess costs of line 2 and line 2a.

welfare impact (relative to an income tax) of taxing consumption in general.

Table 6 consolidates these findings. It shows the contributions of each of the above dimensions to the differences in overall welfare impacts between the energy taxes and the personal income tax. The relatively narrow base of both the Btu tax and gasoline tax accounts for the greatest share of their excess cost over a personal income tax increase. The other key feature of the gasoline tax, its focus on consumption goods, narrows the excess cost of this policy; in contrast, the other key feature of the Btu tax, its focus on intermediate goods rather than final goods, enlarges its excess cost over an income tax. This general pattern of results is sustained through further simulation experiments.[41] These results are quali-

[41] For example, we find that this pattern is the same regardless of the scale of the tax policies. We have performed experiments in which the scale (or gross-revenue yield) of the policies is 0.5, 2, and 4 times that considered in the main experiments. The rankings of the policies, as well as the relative significance of the various structural features, remain the same as in the original experiments.

In addition, we have examined the effects of a tax imposed on *industrial* users of gasoline. This latter tax represents a narrowly based gross output tax. This tax (scaled to imply the same gross-revenue yield as the consumer-level tax) produces a welfare change of tatively similar to those obtained by Rotemberg and Woodford (1993) in a more aggregated model that addresses issues of imperfect competition. These authors find that the costs of energy taxes are considerably lower when the taxes are applied at the household level only, as compared with when the taxes are applied on all energy use.

Two important qualifications are in order. First, it is important to keep in mind that these results ignore environmental effects; we consider such effects later in this section. In addition, these results, strictly speaking, only indicate the relative impacts of marginal reforms—tax changes that are superimposed on the existing tax structure; they do not directly compare the effects of pure tax systems in which the tax base takes just one form (energy, gasoline use, or income).

4.2.3 ***Further Sensitivity Analysis*** Table 7 shows the sensitivity of results to key parameters. We concentrate on parameters that govern the relative significance of the various margins discussed in the theoretical section of the paper.

The intertemporal elasticity of substitution in consumption regulates the responsiveness of household savings to changes in interest rates. The higher the value of this elasticity, the greater is the potential for efficiency or welfare losses under policies that distort the capital market, or intertemporal allocation of resources. Higher values for this elasticity imply larger welfare costs per dollar for the energy tax policies and for the personal income tax increase. As this elasticity increases, welfare costs rise less for the consumer-level gasoline tax than for the income tax; hence the excess cost declines with an increase in this elasticity. This outcome is in keeping with the fact that the income tax is inferior to this gasoline tax on the intertemporal margin, and the higher elasticity raises the significance of this margin. A higher intertemporal elasticity increases somewhat the excess costs of the Btu tax, although the effect is not so strong.

A higher elasticity of labor supply raises the potential magnitude of efficiency losses along the labor-leisure margin. Higher values for this elasticity raise the welfare costs per dollar of all three taxes shown here. The excess costs of both energy taxes decline with increases in this elasticity, indicating that income taxes tend to distort the labor-leisure margin more than the energy taxes do.

Higher energy demand elasticities imply a greater potential for effi-

−0.442, which is consistent with the results from tables 5 and 6. As under the Btu tax, the welfare cost is larger than the cost of a broad-based gross-output tax of equal revenue yield.

TABLE 7.
Sensitivity Analysis.

	Welfare cost per dollar of revenue			Excess cost per dollar of revenue	
	Btu tax	*Consumer-level gasoline tax*	*Personal income tax increase*	*Btu tax*	*Consumer-level gasoline tax*
Central case	0.457	0.395	0.185	0.272	0.210
Intertemporal elasticity of substitution in consumption					
low (0.5 × central case value)	0.412	0.382	0.167	0.245	0.215
high (1.5 × central case value)	0.479	0.403	0.204	0.275	0.199
Labor-leisure substitution elasticity					
low (0.66 × central case value)	0.454	0.385	0.162	0.292	0.223
high (1.33 × central case value)	0.475	0.428	0.231	0.244	0.197
Energy demand elasticities					
low (0.75 × central case values)	0.375	0.383	0.181	0.194	0.202
high (1.5 × central case values)	0.497	0.408	0.191	0.306	0.217

Notes: Figures in columns 1–3 are the equivalent variation divided by the present value of gross tax revenues from the policy change. Figures in the last two columns are the difference in results for the energy tax in question (from column 1 or 2) and the personal income tax increase (column 3). Central case values for intertemporal elasticity of substitution and labor-leisure substitution elasticity are 0.5 and 0.69, respectively. The value of 0.69 for the labor-leisure substitution parameter implies a compensated elasticity of labor supply of 0.5 at initial baseline prices.

ciency losses along the margin of producer choice between energy inputs and the margin of consumer choice between energy products (such as gasoline) and other consumer goods. Because energy taxes distort this margin more than income taxes (subject to the qualifications of section 2), it is no surprise that the excess cost of the energy taxes rise with increases in energy demand elasticities.

Interestingly, although certain parameter values reduced the excess costs of the energy taxes significantly, in no cases were the excess costs eliminated. Apparently, the narrowness of the economic base of these taxes (and, in the case of the Btu tax, the focus on intermediate production) is enough to generate excess costs along a wide range of parameter values.[42]

4.2.4 Effects on Particular Industries The focus of this paper is on economy-wide impacts. However, as is evident in the following discussion, there are significant differences in the pollution impacts of the policy alternatives, and such differences are explained by different patterns of industry impacts. Thus, in Table 8 we present the effects of the energy and income taxes on the gross outputs of each industry. These results stem from the experiments in which revenue neutrality is accomplished through lump-sum reductions in personal taxes.

The distribution of impacts across industries is quite different across policies. As one might expect, the effects on gross output under the two energy taxes are much more concentrated. Under the gasoline tax, the industrial effects are the most concentrated, with the petroleum refining industry (whose activities include the processing of gasoline) experiencing the greatest impact by far. Under the Btu tax, effects are concentrated among the fossil-fuels industries, petroleum-refining industry, and the electric- and gas-utilities industries. In contrast, under the two income-tax policies the effects are much more evenly dispersed.

4.3 Emissions Impacts

4.3.1 Comparison of Results across Policies An ideal comparison of efficiency effects of energy and income taxes would incorporate value measures of the economic benefits from reduced pollution. The traditional efficiency costs from a given policy would be subtracted from the value of the environmental benefits, producing the net efficiency gain or loss. However, the values of the environmental benefits are largely un-

[42] Further sensitivity analysis is performed in Bovenberg and Goulder (1993) for quite similar policies. That analysis examines the sensitivity of excess costs to the rates of preexisting taxes on labor and capital. Under the range of tax rates considered, energy taxes remain more costly than income taxes.

TABLE 8.

Effects on Industry Output* (Percentage Changes from Reference Case).

Industry	Btu tax		Gasoline tax increase		Personal tax increase		Corporate tax increase	
	2000	*2020*	*2000*	*2020*	*2000*	*2020*	*2000*	*2020*
1. Agriculture	−0.09	−0.26	−0.05	−0.12	−0.12	−0.41	−0.18	−0.63
2. Coal mining	−10.21	−11.49	−0.33	−0.30	−0.16	−0.17	−0.03	0.06
3. Crude petroleum and natural gas	−3.22	−3.98	−0.11	−0.99	0.20	−1.55	−0.35	−2.20
5. Petroleum refining	−8.25	−6.09	−6.15	−6.76	−0.14	−0.25	−0.07	−0.15
6. Electric utilities	−2.47	−3.31	0.08	0.03	−0.10	−0.29	−0.02	−0.11
7. Gas utilities	−2.65	−2.71	0.02	−0.06	−0.11	−0.33	−0.01	−0.14
8. Construction	−0.37	−0.41	−0.08	−0.09	−0.33	−0.42	−0.32	−0.38
9. Metals and machinery	−0.38	−0.48	−0.25	−0.31	−0.19	−0.25	−0.13	−0.17
10. Motor vehicles	−0.09	−0.30	0.06	−0.01	−0.18	−0.27	−0.07	−0.13
11. Miscellaneous manufacturing	−0.32	−0.43	−0.05	−0.08	−0.15	−0.28	−0.11	−0.25
12. Services (except housing)	−0.32	−0.43	−0.24	−0.28	−0.15	−0.27	−0.04	−0.12
13. Housing services	0.04	0.00	0.09	0.37	0.00	−0.07	0.03	0.06
Total	−0.56	−0.62	−0.24	−0.26	−0.15	−0.30	−0.10	−0.22

* The synfuels industry is not included here because synfuels production is not significant prior to 2020.

known. Although valuing the environmental impacts is a worthwhile pursuit, at present it seems more sensible to take a first step toward that goal, namely, assessing the different emissions impacts of the different policies. To our knowledge, no other general equilibrium study has linked the economy-wide impacts of these or other tax reforms to the emissions impacts.[43]

The different distributions of output effects shown in Table 8 translate into differences in emissions impacts to the extent that industries vary in their "pollution intensities," that is, in pollution emissions per unit of output.[44] Table 9 provides information on pollution intensities. It shows the relative emissions contributions from the different industries of the model in the baseline or reference case. These intensities are not exogenous inputs to the model; rather, they are functions of the underlying emissions factors, input choices, and output levels for each industry and household activity. Results in the table are for the year 2000 in the baseline. For SOX, NOX, and CO_2, energy industries account for the lion's share of emissions. For this reason one might expect the energy taxes—which have significant impacts on these industries—to induce much larger emissions reductions than income taxes of equal revenue yield.

This expectation is borne out by the policy impacts shown in tables 10a and 10b, which show the emissions reductions stemming from the four policies in the years 2000 (Table 10a) and 2020 (Table 10b). The differences in emissions impacts between the energy-tax and income-tax policies are striking. For every pollutant, the emissions reduction under the Btu or gasoline tax is at least nine times larger than under either of the income-tax policies. Under the energy taxes, the reductions in emissions are much larger in percentage terms than the reductions in overall economic output (GNP) and reflect substitutions of cleaner activities and fuels for those involving more pollution.

In percentage terms, the emissions reductions from the Btu tax are largest for CO_2 and NOX compounds. Whereas the Btu tax induces significant reductions from both stationary and mobile sources, the gasoline tax (as expected) promotes reductions mainly from mobile sources.

[43] Argonne National Laboratories is currently developing a model that explores the economy-wide emissions impacts of alternative energy policies. The model has considerable detail on energy technologies, but it does not have a general equilibrium structure, although it attends to some important market interactions.

[44] To gauge the emissions impacts of different policies, it does not suffice to observe the changes in industrial output and the status quo pollution intensities. This is the case because pollution intensities also change in response to policy initiatives. As discussed in Section 3, the simulation model attempts to account for such changes.

TABLE 9.
Industry Contributions to Baseline Emissions (Results for Year 2000 in the Reference Case).

	TSP	SOX	NOX	VOC	CO	Pb	PM_{10}	CO_2
Total emissions from all sources[a]	8851.4	25247.3	22327.4	21564.7	68495.2	7731.2	10475.2	1671.7
Percentage contributions from industrial and commercial stationary sources[b]								
1. Agriculture	18.23	0.03	0.02	0.94	0.00	2.72	15.08	0.07
2. Coal mining	4.48	0.08	0.04	0.00	0.00	0.00	3.77	0.09
3. Crude petroleum and natural gas	0.05	0.17	0.82	2.83	0.04	0.01	0.02	3.72
5. Petroleum refining	0.72	4.65	9.80	3.73	0.99	0.08	0.41	39.46
6. Electric utilities	5.65	67.75	37.93	0.28	0.60	0.91	1.78	29.17
7. Gas utilities	0.15	0.53	2.60	0.06	0.11	0.02	0.07	11.77
8. Construction	0.01	0.04	0.12	4.26	0.07	0.00	0.00	0.53
9. Metals and machinery	4.49	5.58	0.83	0.37	2.75	28.15	3.08	0.97
10. Motor vehicles	0.02	0.10	0.07	1.02	0.00	0.00	0.00	0.19
11. Miscellaneous manufacturing	10.93	9.11	3.09	28.45	4.74	3.38	8.84	4.37
12. Services	1.07	5.91	2.86	2.76	0.14	0.20	0.21	5.89
13. Housing services	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.02
All industries	45.79	93.94	58.19	44.71	9.43	35.48	33.27	100.00[c]
Percentage contributions from other sources (residential, mobile)	54.21	6.06	41.81	55.29	90.57	64.52	66.73	0.00

Key: TSP = total suspended particles; SOX = sulphur oxides; NOX = nitrous oxides; VOC = volatile organic compounds; CO = carbon monoxide; Pb = lead; PM_{10} = particle matter; CO_2 = carbon dioxide

[a] Units are metric tons for lead, millions of metric tons for carbon dioxide, and thousands of metric tons for other pollutants.

[b] The synfuels industry is not shown because synfuels production does not begin until 2015.

[c] CO_2 emissions were allocated based on the emissions content of fossil-fuel inputs. Hence, no emissions are attributed to residential and transportation uses of derivative (refined) fuels.

TABLE 10a.

Emissions Effects of Energy and Income Tax Policies—Year 2000 (Percentage Changes from Baseline).

	TSP	SOX	NOX	VOC	CO	Pb	PM_{10}	CO_2
Btu tax								
Stationary sources	−2.08	−2.52	−11.64	−1.41	−.67	−.44	−1.38	−8.77
Mobile sources	−3.56	−2.72	−3.17	−3.43	−3.44	−4.06	−1.51	.00
Total	−2.37	−2.53	−8.49	−2.10	−2.42	−1.55	−1.44	−8.77
Gasoline tax increase								
Stationary sources	−.18	−.34	−1.35	−3.08	−.34	−.17	−.15	−2.62
Mobile sources	−17.80	−13.26	−15.71	−17.11	−17.19	−20.47	−6.68	.00
Total	−3.65	−.90	−6.69	−7.85	−10.93	−6.37	−3.02	−2.62
Personal income tax increase								
Stationary sources	−.09	−.05	−.12	−.11	−.04	−.10	−.10	−.13
Mobile sources	−.11	−.12	−.12	−.11	−.11	−.09	−.14	.00
Total	−.10	−.05	−.12	−.11	−.08	−.10	−.12	−.13
Corporate income tax increase								
Stationary sources	−.09	−.03	−.05	−.10	−.03	−.08	−.10	−.07
Mobile sources	−.02	−.04	−.04	−.02	−.02	.00	−.04	.00
Total	−.08	−.03	−.05	−.08	−.03	−.05	−.07	−.07

Key: TSP = total suspended particles; SOX = sulphur oxides; NOX = nitrous oxides; VOC = volatile organic compounds; CO = carbon monoxide; Pb = lead; PM_{10} = particulate matter; CO_2 = carbon dioxide

TABLE 10b.

Emissions Effects of Energy and Income Tax Policies—Year 2020 (Percentage Changes from Baseline).

	TSP	SOX	NOX	VOC	CO	Pb	PM_{10}	CO_2
Btu tax								
Stationary sources	−2.40	−2.26	−12.05	−1.26	−.66	−.50	−1.62	−8.08
Mobile sources	−3.40	−2.56	−3.00	−3.27	−3.28	−3.93	−1.44	.00
Total	−2.59	−2.27	−8.79	−1.92	−2.33	−1.45	−1.54	−8.08
Gasoline tax increase								
Stationary sources	−.19	−.32	−1.15	−2.65	−.33	−.18	−.17	−2.38
Mobile sources	−15.65	−11.29	−13.60	−14.97	−15.05	−18.38	−5.47	.00
Total	−3.10	−.76	−5.64	−6.71	−9.69	−5.25	−2.52	−2.38
Personal income tax increase								
Stationary sources	−.20	−.08	−.30	−.30	−.08	−.14	−.21	−.33
Mobile sources	−.33	−.32	−.33	−.32	−.33	−.32	−.30	.00
Total	−.23	−.09	−.31	−.31	−.24	−.19	−.25	−.33
Corporate income tax increase								
Stationary sources	−.23	−.06	−.18	−.29	−.07	−.12	−.25	−.24
Mobile sources	−.25	−.23	−.27	−.23	−.25	−.23	−.17	.00
Total	−.23	−.07	−.21	−.27	−.18	−.15	−.21	−.24

Key: TSP = total suspended particles; SOX = sulphur oxides; NOX = nitrous oxides; VOC = volatile organic compounds; CO = carbon monoxide; Pb = lead; PM_{10} = particulate matter; CO_2 = carbon dioxide

The gasoline tax leads to substantial reductions in mobile-source emissions of all pollutants except particulate matter (PM_{10}) and carbon dioxide (CO_2).

Overall, these results offer evidence that Btu and gasoline taxes afford significant environmental benefits relative to increases in income taxes, which complicates the ranking of energy and income taxes in terms of overall efficiency. As yet, we do not have the information to determine whether the larger emissions reductions from energy taxes are important enough to offset the disadvantages of these taxes on narrower efficiency grounds.

4.3.2. A Partial Benefit-Cost Analysis Despite the information limitations, some useful comparisons are possible. Table 11 offers partial benefit-cost information. The first row shows the average annual emissions reductions from the two energy tax policies.[45] To give an idea of the levels (tons) of emissions reductions implied by these percentages, we apply the average reductions to projected 1994 (baseline) emissions and present the implied reductions in the second row of the table. As in previous tables, the units in row 2 are thousands of metric tons for all pollutants except lead (which is in metric tons) and CO_2 (which is in millions of metric tons of carbon).

In the second portion of this table, we make suggestive benefit-cost comparisons. Row 3 presents the annualized excess cost of the two energy-tax policies. This cost index translates the overall excess cost (a stock concept) into an annual cost flow that grows at the long-run growth rate of the economy.[46]

In row 4, we make a tentative foray into the benefits dimension. Several caveats are in order here. First, we only consider CO_2-related benefits. Obviously this limitation understates the overall environmental benefits. Our purpose is simply to consider what portion of the GNP costs might be offset by CO_2-related benefits and to allow readers to

[45] More precisely, these are averages of the excess reductions in CO_2 emissions over and above the (negligible) reductions that would occur from a personal income-tax increase. The averages are computed by taking the present value of the changes in emissions over an infinite horizon, using the long-run after-tax interest rate (4.8 percent) as the discount rate. An alternative approach is simply to treat the percentage reduction in cumulative emissions (at some future point in time) as the average emissions reduction. In an economy where output and emissions tend to increase with time, this latter approach tends to assign more weight to future emissions reductions than does the approach we have taken.

[46] The annualized excess cost is equal to $EV * (r + g)/(1 + r)$, where EV is the excess cost of the policy change (as measured by the equivalent variation), r is the long-run or steady-state, after-tax interest rate, and g is the long-run growth rate of the economy. The values for r and g in the model are 4.8 percent and 2.0 percent, respectively.

TABLE 11a.
Overall Emissions Changes.

	TSP	SOX	NOX	VOC	CO	Pb	PM_{10}	CO_2
1. Average Percentage reductions in emissions								
Btu tax	−1.44	−5.91	−7.52	−0.78	−1.18	−0.30	−0.39	−7.36
Gasoline tax	−2.90	−0.55	−5.38	−6.47	−9.47	−5.04	−2.30	−2.25
2. 1994 Emissions reductions implied by (1)								
Btu tax	115.0	1328.8	1540.8	153.9	232.8	21.0	37.1	116.5
Gasoline tax	235.0	123.7	1102.3	1276.7	1868.7	353.0	218.5	35.6

* See text for explanation of figures.

TABLE 11b.
Comparsions of Costs and (Some) Benefits.

	Btu Tax		Gasoline Tax	
	Low CO_2 Damages	*High CO_2 Damages*	*Low CO_2 Damages*	*High CO_2 Damages*
3. Annualized excess cost				
% of trend GNP	0.211	0.211	0.179	0.179
Value in 1994 ($ billion)	12.89	12.89	10.92	10.92
4. Annualized benefit from CO_2 reduction				
% of trend GNP	0.004	0.158	0.001	0.041
Value in 1994 ($ billion)	0.24	8.74	0.07	2.52
5. "Residual" GNP loss [(4) − (3)]				
% of trend GNP	0.207	0.053	0.178	0.138
Value in 1994 ($ billion)	12.65	4.15	10.85	8.40

* See text for explanation of figures.

ponder whether the remaining GNP costs might be offset by the reductions in other pollutants.

The benefit-cost numbers are limited in another sense. The true benefits from reductions of CO_2 (or other pollutants) are the result of complex links from benefits to concentrations to ultimate health and welfare impacts. Given this complexity, it is likely that the benefits per unit of emission reduction for each pollutant will vary geographically and temporally. We disregard these important complications and instead assume, in the case of CO_2, fixed ratios of benefits per unit of emission reduction. Hopefully, despite this limitation, the figures in Table 11 are still illuminating.

First steps toward assessing CO_2-related benefits were taken by Nordhaus (1991), who postulated marginal environmental benefits from CO_2 emissions reduction as ranging from approximately $1.80 to $66 per ton. Row 4 of the table shows the annualized benefits from the CO_2 reductions under two cases for each policy.[47] The "low CO_2 damages" scenario imputes the $1.80 / ton value; the "high CO_2 damages" case imputes the $66.00 / ton value.[48]

The results in the table indicate that the residual GNP losses—annualized excess costs minus annualized CO_2-related benefits—are highly sensitive to assumptions about the CO_2 damages. In the case with high CO_2 damages, the CO_2-related environmental benefits from a Btu tax offset over 75 percent of the excess cost; in the case with low CO_2 damages, about 3 percent of the excess cost is offset. The residual GNP losses are smaller for the gasoline tax than for the Btu tax; the reverse is true in the high CO_2 damage scenario. This reflects the significant differences in the induced CO_2 reductions of the two policies.[49]

[47] We annualize the environmental benefits in the same way we annualize excess costs. The annualized benefit equal to $EB * (r - g) / (1 + r)$, where EB is the present value of the environmental benefits, r is the long-run, real after-tax interest rate, and g is the long-run, real growth rate.

[48] These figures are based on assessments of the potential global-warming-related damages from CO_2. Because they do not take into account direct health effects of CO_2, they may understate overall benefits from CO_2 reductions. On the other hand, it should be noted that the Nordhaus estimates concern *worldwide* damages from CO_2 emissions (or worldwide benefits from CO_2 emissions reductions). Benefits to the United States from CO_2 reductions would be only a fraction of the worldwide benefits.

[49] It may seem surprising that when CO_2 damages of $66 are assumed, the Btu tax still fails to create positive net benefits (or a negative residual GNP loss). Basic Pigovian tax principles indicate that, so long as an environmental tax rate is below (or not far above) the value of marginal environmental damages, then the tax is efficiency-improving. Under the Btu tax, the implied rate of tax per ton of carbon is $12.80 on coal, $17.90 on natural gas, and $32.50 on crude oil. The fact that these rates are less than the assumed marginal damages

Table 11 does not answer the question whether either of the energy taxes is efficiency-improving overall. Answering this question requires more information about the environmental benefits associated with reductions in the other pollutants (as well as reduced uncertainty about CO_2-related benefits). Perhaps economics and environmental science will be able to provide this information some day.

5. CONCLUSIONS

This paper has employed a dynamic simulation model of the United States to assess "traditional" (nonenvironmental) efficiency consequences and environmental effects of two U.S. energy tax policies: a tax on fossil and synthetic fuels based on Btu (or energy) content and a tax on consumer purchases of gasoline. The model uniquely combines attention to details of the U.S. tax system with a consolidated treatment of U.S. energy use and pollution emissions.

On traditional efficiency grounds, each of the energy taxes emerges as more costly to the economy than equal-revenue increases in personal or corporate income taxes: the time profiles of GNP and consumption are significantly lower under the energy taxes than under the alternatives. Likewise, the welfare costs of the energy taxes are more than twice as large (Table 4) as the costs of equal-revenue increments to personal or corporate income taxes. This result that energy taxes involve higher gross costs is sustained over a fairly wide range of values for key behavioral parameters.

An important structural difference between the Btu tax and the consumer-level gasoline tax is that the former applies to a gross output and the latter to a particular, final-consumption good. This difference underlies the contrasting investment and consumption profiles of the two energy tax options.

We perform a number of simulation experiments designed to identify which features of these taxes account for their "excess costs"—the nonenvironmental welfare cost over and above that of an equal-revenue increase in the personal income tax. For both energy taxes, the relative *narrowness* of the tax base accounts for most of the excess cost. For the

from carbon emissions suggests that the Btu tax should be efficiency-improving. The positive residual GNP loss thus seems to defy the Pigovian prediction.

The Pigovian prediction fails because it does not account for pre-existing taxes. In particular, it neglects the ways that energy taxes compound the gross distortions that other taxes generate in other markets. When other taxes are present, the welfare (and GNP) costs of "small" environmental taxes can be quite large. The fact that tax rates are below the marginal environmental damages does not assure a welfare improvement. This issue is analyzed in detail in Bovenberg and Goulder (1993).

Btu tax, the *type* of tax base—its focus on gross output (as opposed to net output under the personal income tax)—also contributes to a significant share of the excess cost. For the consumer-level gasoline tax, the fact that this tax applies to consumption rather than income has a mitigating effect, serving to reduce the excess cost.

On the environmental side, we find that for each of the eight major air pollutants considered, the energy taxes induce emissions reductions that are at least nine times larger than the reductions under the income-tax alternatives. The differences in emissions impacts reflect the close connections between energy use and pollution generation. For the Btu tax, the largest emissions reductions (in terms of percentage) are for CO_2 and NOX compounds. For the gasoline tax, the emissions reductions are spread fairly evenly across six of the eight pollutants considered.

Overall, this study indicates that the Btu and gasoline taxes considered are inferior to the alternatives on narrow efficiency grounds but superior on environmental grounds. It remains an open question whether the environmental attractions of these taxes are large enough to offset their relatively high nonenvironmental costs. To settle this issue, analysts need to be able to quantify more accurately the links from emission reductions to environment-related improvements in human welfare. Further research along these lines will help important environmental considerations gain a firm footing within the general domain of tax-policy analysis.

APPENDIX 1: MODEL STRUCTURE[50]

A.1 Production

A.1.1 Technology

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:

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

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

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

[50] A more comprehensive description of the structure of the model is in Goulder (1992b).

TABLE A-1.
Nested Production Structure.

X	$=$	$f(g_1, g_2) - \phi(I/K)I$
g_1	$=$	$g_1(L, K)$
g_2	$=$	$g_2(E, M)$
$\bar{E}$	$=$	$\bar{E}(E_1, \ldots, E_5)$
M	$=$	$M(M_1, \ldots, M_7)$
E_i	$=$	$E_i(ED_i, EF_i)$[a]
M_i	$=$	$M_i(MD_i, MF_i)$[b]

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

[a]i = 1, . . . , 5

[b]i = 1, . . . , 7

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

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

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,

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

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

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 and gas extraction and synthetic fuels
3	Petroleum refining
4	Electricity
5	Processed natural gas

Oil and 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.[51]

Similarly, the materials composite ($\bar{M}_i$) in equation (1) is a *CES* function of the specific materials products of the seven nonenergy industries:

$$\bar{M} = \bar{M}(M_1, M_2, \ldots, M_7) \tag{A-5a}$$

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

where $\sum_{j=1}^{7} \alpha_{\bar{M}j} = 1$. The subscripts to M in equations (5a) and (5b) correspond to materials (nonenergy) 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 $E_j (j = 1, \ldots, 5)$ and $M_j (j = 1, \ldots, 7)$ in the $\bar{E}$ and $\bar{M}$ functions are themselves *CES* composites of domestically produced and foreign made inputs:

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

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

[51] E_2 denotes the total quantity (in energy-equivalent units) of oil and 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.

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

$$\gamma_{f,t} = \epsilon_1 \left[1 - (Z_t/\bar{Z})^{\epsilon_2}\right], \tag{A-8}$$

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 and gas (as estimated from the benchmark year). The following equation of motion specifies the evolution of Z_t:

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

Equation (8) implies that the production function for oil and gas shifts downward as cumulative oil and 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.

A.1.2 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

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

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.[52]

In equation (10), $EMCOST$ is given by

$$EMCOST = \sum_{j=1}^{5} (1 + \tau_{Ej})(p_{ED,j}ED_j + p_{EF,j}EF_j)$$

$$+ \sum_{j=1}^{7}(1 + \tau_{mj})(p_{MD,j}MD_j + p_{MF,j}MF_j), \qquad \text{(A-11)}$$

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 $p_{ED,j}$ and $p_{EF,j}$ ($p_{MD,j}$ and $p_{MF,j}$) are the pretax prices of domestic and foreign energy (materials) inputs of type j.[53]

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

$$\pi + BN + VN = DIV + IEXP. \qquad \text{(A-12)}$$

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,

$$DIV_s = a\,[\pi_s + (p_{K,s} - p_{K,s-1})K_s - \delta p_{K,s}K_s] \qquad \text{(A-13)}$$

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

53 To simplify the exposition, we have not included in equations (A-10) and (A-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 (A-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 and 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.

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

Investment expenditure is expressed by

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

where τ_K is the investment tax-credit rate. Of the elements in equation (12), new share issues VN are the residual, making up the difference between $\pi + BN$ and $DIV + IEXP$.[54]

Arbitrage possibilities compel the firm to offer its stockholders a rate of return comparable to the rate of interest on alternative assets.[55]

$$(1 - \tau_e)\, DIV_s + (1 - \tau_v)(V_{s+1} - V_s - VN_s) = (1 - \tau_b)\, i_s\, V_s. \tag{A-16}$$

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,

$$K_{s+1} = (1 - \delta)K_s + I_s. \tag{A-17}$$

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

A.2 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

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

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

[55] This abstracts from uncertainty and, therefore, risk. It is possible to modify the arbitrage equation to account for risk differentials across assets. See Goulder (1989).

TABLE A-2.
Nested Utility Structure.

Function	Functional form
$U_t(C_t, C_{t+1}, \ldots, C_8, \ldots)$	Constant intertemporal elasticity of substitution
$C_s(\bar{C}_s, \ell_s)$	*CES*
$\bar{C}_s(\bar{C}_{i,s}, \ldots, \bar{C}_{i,s}, \ldots, \bar{C}_{17,s})$	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
$\bar{C}_s$ = 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 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:

$$C_s = \left[\bar{C}_s^{\frac{v-1}{v}} + \alpha_C^{\frac{1}{v}} \ell_s^{\frac{v-1}{v}} \right]^{\frac{v}{v-1}}. \tag{A-19}$$

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

The variable $\bar{C}$ in (20) is a Cobb-Douglas aggregate of seventeen composite consumer goods:

$$\bar{C}_s = \prod_{i=1}^{17} \bar{C}_{i,s}^{\alpha_{\bar{C},i}}, \tag{A-20}$$

where the $\alpha_{\bar{C},i}(i = 1, \ldots, 17)$ are parameters. The seventeen types of consumer goods identified in the model are shown in Table 2 of the main text.

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

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

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:

$$WK_{t+1} - WK_t = \bar{r}_t WK_t + YL_t + GT_t - \bar{p}_t \bar{C}_t. \tag{A-22}$$

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 $\bar{p}$ is the price index representing the cost to the household of a unit of the consumption composite, $\bar{C}$.

A.3 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 nondurable and durable), transferring incomes, and raising revenue through taxes or bond issue.

A.3.1 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):

$$G_t = GP_t + GI_t + GT_t \tag{A-23}$$

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, investments, 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

$$GP_t^P / p_{GP,t}^P = GP_t^R / p_{GP,t}^R \tag{A-24a}$$

$$GI_t^P / p_{GI,t}^P = GI_t^R / p_{GI,t}^R \tag{A-24b}$$

$$GT_t^P / p_{GT,t}^P = GT_t^R / p_{GT,t}^R \tag{A-24c}$$

The superscripts P and R denote policy-change and reference-case magnitudes, and 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 in equation (A-26).

A.3.2 Allocation of Government Purchases *GP* divides into purchases of particular outputs of the thirteen domestic industries according to fixed expenditure shares:

$$\alpha_{G,i}GP = GPX_i p_i, \qquad i = 1, \ldots, 13. \tag{A-25}$$

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

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

APPENDIX 2: PARAMETER VALUES*

TABLE A-3.
Elasticities of Substitution in Production.

	Parameter					
	σ_f	σ_{g1}	σ_{g2}	σ_E Substitution margin	σ_M	σ_x
Producing Industry	g_1-g_2	*L-K*	*E-M*	*E components*	*M components*	*domestic-foreign inputs*
1. Agriculture and 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 and 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 and 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. Miscellaneous 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)

* Complete data documentation is provided in Cruz and Goulder (1992).

TABLE A-4.
Parameters of Stock Effect Function in Oil and Gas Industry.

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

Note: This function is parameterized so that γ_f approaches 0 as Z approaches $\tilde{Z}$ (see equation (A-8)). The value of $\tilde{Z}$ is 450 billion barrels (about 100 times the 1990 production of oil and gas, where gas is measured in barrel-equivalents.) $\tilde{Z}$ 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.

TABLE A-5.
Utility Function Parameters.

	Parameter			
	ω	σ	ν	η
Value:	0.007	0.5	0.69	0.84

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