Neutralizing the Adverse Industry Impacts of CO_2 Abatement Policies: What Does It Cost?

A. Lans Bovenberg and Lawrence H. Goulder

July 2000 • Discussion Paper 00–27

RESOURCES
FOR THE FUTURE

Resources for the Future
1616 P Street, NW
Washington, D.C. 20036
Telephone: 202–328–5000
Fax: 202–939–3460
Internet: http://www.rff.org

Neutralizing the Adverse Industry Impacts of CO_2 Abatement Policies: What Does It Cost?

A. Lans Bovenberg and Lawrence H. Goulder

Abstract

The most cost-effective policies for achieving CO_2 abatement (e.g., carbon taxes) are considered politically unacceptable because of distributional consequences. This paper explores policies designed to address distributional concerns. Using an intertemporal, numerical general equilibrium model of the United States, we examine how efficiency costs change when CO_2 abatement policies include elements that neutralize adverse impacts on energy industries.

We find that desirable distributional outcomes can be achieved at relatively low cost in terms of efficiency. Without substantial added cost to the overall economy, the government can implement carbon abatement policies that protect profits and equity values in fossil-fuel industries. The key to this conclusion is that CO_2 abatement policies have the potential to generate rents that are very large in relation to the potential loss of profit. By enabling firms to retain only a very small fraction of these potential rents, the government can protect firms' profits and equity values. Consequently, the government needs to grandfather only a small percentage of CO_2 emissions permits or, similarly, must exempt only a small fraction of emissions from the base of a carbon tax. Each of these government policies involves only a small sacrifice of potential government revenue. Such revenue has an efficiency value because it can be used to finance cuts in pre-existing distortionary taxes. Because these policies give up little of this potential revenue, they involve only a small sacrifice in terms of efficiency.

We also find that there is a very large difference between preserving firms' profits and preserving their tax payments. Allowing firms to enjoy a dollar-for-dollar offset to their payments of carbon taxes—for example, through industry-specific cuts in corporate tax rates—substantially overcompensates firms, raising profits and equity values significantly relative to the unregulated situation. This reflects the fact that producers can shift onto consumers most of the burden from a carbon tax. The efficiency costs of such policies are far greater than the costs of policies that do not overcompensate firms.

Key Words: climate policy, distributional impacts, general equilibrium

JEL Classification Numbers: H21, H22, L51, D58

Contents

Neutralizing the Adverse Industry Impacts of CO_2 Abatement Policies: What Does It Cost?

A. Lans Bovenberg and Lawrence H. Goulder*

1. Introduction

Most studies of U.S. CO_2 abatement policies have focused on the aggregate costs and benefits of these initiatives. Yet the desirability and political feasibility of these policies hinge critically on their distributional impacts. A full assessment of CO_2 abatement options therefore requires attention to distributional effects.

Some studies—including Poterba (1991), Bull, Hassett and Metcalf (1994), Schillo et al. (1996), and Metcalf (1998)—have focused on the distribution of impacts of CO_2 abatement policies across household income groups, with a carbon tax being the usual instrument for CO_2 abatement. This tax is generally found to produce a regressive impact, although this impact is fairly small, especially when one ranks households by measures of lifetime income (such as expenditure) rather than by annual income (which includes transitory shocks and lifetime variations making annual income a bad indicator of permanent income). Moreover, as indicated by Schillo et al. (1991) and Metcalf (1998), the government can reduce the regressive effect by lowering personal income tax rates at the bottom end of the income scale and by raising public transfers.

A second important distributional dimension is the variation in impacts across industries. CO_2 abatement policies, such as carbon taxes or carbon quotas, can reduce net output prices in the fossil-fuel (carbon-supplying) industries and raise costs in industries that intensively employ fossil fuels as inputs. These price and cost impacts have the potential to seriously harm profits, employment, and equity values. The distribution of impacts along these dimensions crucially influences political feasibility, since representatives of fossil-fuel producers carry significant weight in the political

---

* The authors are from Tilburg University; and Stanford University, Resources for the Future, and NBER, respectively.
This paper was prepared in connection with the FEEM-NBER Conference on Behavioral and Distributional Effects of Environmental Policy, June 10-11, 1999 in Milan, Italy. The authors are grateful to Gib Metcalf, Ruud de Mooij, Peter Orszag, Ian Parry, Jack Pezzey, Robert Stavins, and Roberton Williams III for helpful comments, and to Derek Gurney and Rudolf Schusteritsch for excellent research assistance.

process.[1] CO_2 abatement policies that pose serious burdens on these industries may stand little chance of political survival.[2]

This paper explores the distributional impacts of various U.S. CO_2 abatement policies in terms of their effect on profits and equity values for the industries supplying fossil fuels (coal, crude petroleum, and natural gas) and the industries that rely heavily on fossil fuels as intermediate inputs (e.g., petroleum refining and electric utilities.) We examine a range of abatement policies, including those designed to avoid adverse consequences for the regulated industries. As discussed below, some of the adverse consequences can be avoided through industry-specific corporate tax cuts, direct transfers, and the government's free provision (or grandfathering[3]) of emissions permits to firms. A main purpose of this paper is to assess the efficiency cost of avoiding adverse impacts through such policies.

To perform this investigation, we employ an intertemporal general equilibrium model of the United States.[4] The general equilibrium framework is especially useful for assessing the incidence of carbon policies. Nearly all of the studies of distributional impacts of carbon policies have employed a partial equilibrium framework that ignores behavioral responses to environmental taxes.[5] These studies impose exogenous incidence assumptions and cannot analyze how behavioral responses affect pollution, efficiency, and distribution. An applied general equilibrium analysis, in contrast, derives

---

[1]Indeed, the industry-distribution impacts may be more important politically than the household-distribution impacts, since the stakes for each firm from these policies are high, while the impacts of abatement policies on households, though important in the aggregate, are fairly small for each individual household. Under these circumstances, affected firms may be more willing to incur the costs of political mobilization than affected households are. This discussion invokes the notion of political mobilization bias, an idea originated by Olson (1965). For a discussion of this bias and other political transactions cost issues, see Williamson (1996, ch. 5). For an analysis of the implications of political mobilization bias for legislators' choice of environmental policy instruments, see Keohane, Revesz, and Stavins (1998).

[2]This will be the case irrespective of the efficiency properties of abatement policies. In the real world, winners often cannot compensate losers through costless, lump-sum transfers. Hence the most efficient policies—those with the largest net benefits in the aggregate—may not yield actual Pareto improvements: they may only be *potentially* Pareto-improving. In such a world, political feasibility may require designing policies that avoid serious negative impacts on key stakeholders. This may involve a sacrifice of some of the efficiency gains from the most efficient policy.

[3]Grandfathering is a special case of free provision. It is a legal rule whereby old entities (e.g., firms subject to previous environmental rules) are waived of new regulatory requirements and remain bound only to the earlier (and perhaps more lax) regulatory provisions. Under grandfathering, the free provision of permits is linked to current production factors. Newly entering firms are not eligible for a free provision, and investments in new capital are not rewarded.

[4]This is the same model as that in Goulder (1995a) and Bovenberg and Goulder (1996, 1997), with some extensions to allow for attention to the industry-specific revenue-recycling and tradeable permits provisions described below.

[5]An exception is Jorgenson, Slesnick, and Wilcoxen (1992).

tax incidence endogenously from model-generated behavioral responses. An important distributional consideration is the impact of CO_2 abatement policies on returns to labor and capital. A general equilibrium framework is appropriate for this purpose, since it captures important links between energy markets and factor markets. The model used here is especially useful in this regard because it incorporates forward-looking investment behavior and the adjustment costs associated with the installation or removal of physical capital. These features enable us to consider the capitalization effects of unanticipated policies.[6] Most other general equilibrium models treat capital as perfectly mobile, and thus cannot successfully examine impacts on profits or equity values. In such models, the impacts on industries are measured largely in terms of the effects on outputs. Our results show that output effects are unreliable indicators of distributional effects.

Earlier analyses of CO_2 abatement policies reveal a tension between promoting economic efficiency, on the one hand, and avoiding serious adverse distributional consequences to key industries, on the other. Goulder, Parry, and Burtraw (1997), Farrow (1999), Fullerton and Metcalf (1998), and Parry, Williams, and Goulder (1999) show that policies that raise revenues and use these revenues to finance cuts in pre-existing distortionary taxes have lower costs than policies that do not generate and recycle revenues in this way. The differences in the costs of the two types of policies can be large enough to determine whether the overall efficiency impact—environment-related benefits minus economy-wide costs of abatement—is positive or negative.[7] Yet the latter, less-efficient policies impose a smaller financial burden on regulated industries because they do not charge firms for every unit of their pollution.[8] These considerations suggest a conflict between efficiency and political feasibility: the efficient policy—the carbon tax—appears less politically acceptable because it puts too much of a burden on politically mobilized, fossil-fuel industries, while

---

[6]Our model does not incorporate adjustment costs for industry-specific labor; indeed, labor is perfectly mobile across industries. To the extent that labor faces adjustment costs, one should explore capitalization effects on labor along lines similar to this paper′s exploration of such effects on capital.

[7]Parry, Williams, and Goulder (1999) show that while a carbon tax with revenues recycled through cuts in marginal income tax rates produces efficiency gains, reducing CO_2 emissions through a system of freely provided (grandfathered) CO_2 permits may be an efficiency-reducing proposition: for any level of emissions reduction, the environmental benefits will fall short of society′s costs of abatement!

[8]Two revenue-raising policies are an emissions tax and a system of auctioned emissions permits, where the permits are initially auctioned. Under these policies, firms endure costs of emissions abatement and must either pay a tax or purchase permits, for whatever emissions they continue to produce.. In contrast, under a system of freely provided emissions permits requiring equivalent emissions reductions, firms endure the same costs of abatement but do not pay for remaining emissions. Hence the burden on polluting firms is smaller.

the politically more acceptable policy of grandfathered carbon (or CO_2) permits involves serious inefficiencies.

Our findings show that the choice between efficiency and insulating profits of key industrial stakeholders (to enhance political feasibility) may be less problematic than previously thought. We find that desirable distributional outcomes at the industry level can be achieved at relatively low cost in terms of efficiency. Without substantial added cost to the overall economy, the government can implement carbon abatement policies that protect profits and equity values in fossil-fuel industries. The key to this conclusion is that CO_2 abatement policies have the potential to generate rents that are very large in relation to the potential loss of profit. Under a standard carbon tax policy, these potential rents do not materialize: instead they become revenues collected by the government. In contrast, under a policy involving freely allocated emissions permits, or a policy in which some (inframarginal) emissions are exempted from a carbon tax, firms realize some of the potential rents.[9] Because the potential rents are very large in relation to potential lost profit, the government can protect firms' profits and equity values in fossil-fuel industries by enabling firms to retain only a very small fraction of the potential rents. Thus, the government needs to freely allocate (as opposed to auction) only a small percentage of CO_2 emissions permits or, similarly, must exempt only a small fraction of emissions from the base of a carbon tax.[10] Each of these government policies involves only a small sacrifice of potential government revenue. Such revenue has an efficiency value because

[9] Buchanan and Tullock (1975) pointed out that environmental policies can generate significant rents to firms to the extent that such policies cause output to be restricted. They showed that because of such rents, regulated firms can experience high profits than in the absence of regulation. The findings in the present paper are consistent with Buchanan and Tullock's analysis. Fullerton and Metcalf (1998) emphasize the importance of rents to the overall efficiency costs of policies to reduce pollution. They indicate that efficiency costs are substantially higher under policies that produce rents that are not taxed away, in comparison with policies that do not produce rents that are left in private hands. A parallel line of investigation was conducted by Goulder, Parry, and Burtraw (1997), who show that policies that fail to tax away rents are at a disadvantage in terms of efficiency because they fail to generate revenues that can be used to reduce pre-existing distortionary taxes. Such policies thus fail to exploit an efficiency-enhancing revenue-recycling effect. In the present study, we examine the extent to which policy-generated rents affect the impacts of CO_2 abatement policies on the profitability and equity values of regulated firms.

[10] Correspondingly, if the government were to freely allocate 100% of the emissions permits, or exempt 100% of inframarginal emissions from the base of a carbon tax, it would generate substantial windfalls to firms. The rents produced and enjoyed by producers would be many times larger than the income losses otherwise attributable to the policy. The government does not need to be nearly this generous in order to safeguard firms′ profits and equity values. Our focus on the use of inframarginal exemptions to accomplish distributional objectives is in the spirit of Farrow (1999), who employs a model with one factor of production (labor), along the lines of Bovenberg and de Mooij (1994). Our analysis differs from Farrow′s in its consideration of imperfectly mobile capital and its attention to the implications of pollution-abatement policies for firms′ profits and equity values.

it can be used to finance cuts in pre-existing distortionary taxes. Since these policies give up little of this potential revenue, they involve only a small sacrifice in terms of efficiency. In suggesting that the revenue sacrifice is small relative to potential revenues, our findings complement those obtained by Vollebergh, de Vries, and Koutstaal (1997), who employ a partial equilibrium model to compare the potential tax revenues and abatement costs that could stem from a carbon tax in the European Union.[11]

Because the potential rents are quite large, it is also possible to devise policies that, with relatively little loss of efficiency, protect not only the fossil-fuel industries but also certain industries (such as petroleum refining and electric utilities) that intensively use fossil fuels. These industries would suffer significant profit losses under a standard carbon tax.

We also find that there is a very large difference between preserving firms' profits and preserving their tax payments. Allowing firms to enjoy a dollar-for-dollar offset to their payments of carbon taxes (through industry-specific cuts in corporate tax rates, for example) substantially overcompensates firms, by raising profits and equity values significantly relative to the unregulated situation. This reflects the fact that producers can shift onto consumers most of the burden from a carbon tax. The efficiency costs of such policies are far greater than the costs of policies that do not overcompensate firms. To maintain firms' profits, the government needs to offer tax relief representing only a small fraction of carbon tax payments.[12]

The remainder of the paper is organized as follows. Section 2 provides a brief description of the numerical general equilibrium model employed to evaluate the various policy alternatives. Section 3 indicates the links in the model between the various policy alternatives and firms' profits and equity values. Section 4 briefly describes the model's data and parameters. Section 5 indicates the policies under consideration, and Section 6 conveys and discusses the results from numerical simulations. Section 7 offers conclusions.

---

[11]Vollebergh et al. calculate the tax revenues and abatement costs that would stem from a carbon tax sufficient to reduce CO_2 emissions by 13% in the European Union countries. Their results indicate that the revenues from this tax would be many times the policy-generated abatement costs. This (antecedent unclear-result?) suggests that exempting a small share of inframarginal emissions from the carbon tax (or grandfathering a small share of the permits under a permits policy) would be sufficient to compensate the fossil-fuel suppliers involved.

[12]Felder and Schleiniger (1999) consider the efficiency costs of meeting the constraint that there be no monetary transfers (that is, no change in overall tax payments) as a result of a carbon tax policy. Using a numerical general equilibrium model of Switzerland, they meet this constraint through industry-specific output subsidies or labor subsidies.

2. The Model

This section outlines the structure of the model employed in this study. The model is an intertemporal general equilibrium model of the U.S. economy with international trade. It generates paths of equilibrium prices, outputs, and incomes for the U.S. economy and the rest of the world under specified policy scenarios. All variables are calculated at yearly intervals beginning in the benchmark year 2000 and usually extending to the year 2075.

The model combines a fairly realistic treatment of the U.S. tax system and a detailed representation of energy production and demand. It incorporates specific tax instruments and addresses effects of taxation along a number of important dimensions. These include firms' investment incentives, equity values, and profits,[13] and household consumption, savings, and labor supply decisions. The specification of energy supply incorporates the nonrenewable nature of crude petroleum and natural gas and the transitions from conventional to synthetic fuels.

U.S. production divides into the 13 industries indicated in Table 1. The energy industries consist of coal mining, crude petroleum and natural gas extraction, petroleum refining, synthetic fuels, electric utilities, and gas utilities. The model also distinguishes the 17 consumer goods shown in the table.

Producer Behavior

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

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

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

$$E = E\,(\bar{x}_2\,,\ \bar{x}_3\ +\ \bar{x}_4\,,\ \bar{x}_5\,,\ \bar{x}_6\,,\ \bar{x}_7\,) \qquad (2)$$

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

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

Table 1. Industry and Consumer Goods

Industries

		*Gross Output, Year 2000**	
		Level	Percent
1.	Agriculture and Non-Coal Mining	993.6	6.2
2.	Coal Mining	50.5	0.3
3.	Crude Petroleum and Natural Gas	193.7	1.2
4.	Synthetic Fuels	0.0	0.0
5.	Petroleum Refining	324.6	2.0
6.	Electric Utilities	234.6	1.5
7.	Gas Utilities	211.5	1.3
8.	Construction	1508.8	9.5
9.	Metals and Machinery	799.1	5.0
10.	Motor Vehicles	541.2	3.4
11.	Miscellaneous Manufacturing	3365.2	21.3
12.	Services (except housing)	5183.6	32.8
13.	Housing Services	2420.8	15.3

where $\bar{x}_i$ is a composite of domestically produced and foreign-made input *i*.[14] Industry indices correspond to those in Table 1.

Managers of firms choose input quantities and investment levels to maximize the value of the firm. The investment decision takes account of the adjustment (or installation) costs represented by $\phi(I/K) \bullet I$ in equation (1). ϕ is a convex function of the rate of investment, *I/K*.[15]

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:

$$X = \gamma(Z) \bullet f\,[\,g(L,K),h(E,M)\,] - \phi(I/K) \bullet I \qquad (4)$$

where γ is a decreasing function of *Z*, the cumulative extraction of oil and gas up to the beginning of the current period. This captures the idea that as *Z* rises (or, equivalently, as reserves are depleted), it

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

[15]The function ϕ represents adjustment costs per unit of investment. This function expresses the notion that installing new capital necessitates a loss of current output, as existing inputs (*K*, *L*, *E* and *M*) are diverted to install new capital.

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). Each oil and gas producer perfectly recognizes the impact of its current production decisions on future extraction costs.[16] Increasing production costs ultimately induce oil and gas producers to remove their capital from this industry.

The model incorporates a synthetic fuel—shale oil—as a backstop resource, a perfect substitute for oil and gas.[17] The technology for producing synthetic fuels on a commercial scale is assumed to become known in 2020. Thus, capital formation in the synfuels industry cannot begin until that year.

All domestic prices in the model are endogenous, except for the domestic price of oil and gas. The path of oil and gas prices follows the assumptions of the Stanford Energy Modeling Forum.[18] The supply of imported oil and gas is taken to be perfectly elastic at the world price. So long as imports are the marginal source of supply to the domestic economy, domestic producers of oil and gas receive the world price (adjusted for tariffs or taxes) for their own output. However, rising oil and gas prices stimulate investment in synfuels. Eventually, synfuels production plus domestic oil and gas supply together satisfy all of domestic demand. Synfuels then become the marginal source of supply, so that the cost of synfuels production rather than the world oil price dictates the domestic price of fuels.[19]

Household Behavior

Consumption, labor supply, and savings result from the decisions of a representative household maximizing its intertemporal utility, defined as a function of leisure and overall consumption in each period. The utility function is homothetic and leisure and consumption are weakly separable (see Appendix). The household faces an intertemporal budget constraint requiring the present value of consumption not to exceed potential total wealth (nonhuman wealth plus the present value of labor and transfer income). In each period, overall consumption of goods and

---

[16]We assume representative oil and gas firms; specifically, initial resource stocks, profit-maximizing extraction levels, and resource-stock effects are identical across producers.

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

[18]The world price is $19 per barrel in 2000 and rises in real terms by $5.00 per decade. See Gaskins and Weyant (1996).

[19]For details, see Goulder (1994, 1995a).

services is allocated across the 17 specific categories of consumption goods or services shown in Table 1. Each of the 17 consumption goods or services is a composite of a domestically and foreign-produced consumption good (or service) of that type. Households substitute between domestic and foreign goods to minimize the cost of obtaining a given composite.

The Government Sector

The government collects taxes, distributes transfers, and purchases goods and services (outputs of the 13 industries listed in Table 1). The tax instruments include energy taxes, output taxes, corporate income taxes, property taxes, sales taxes, and taxes on individual labor and capital income. In the benchmark year, 2000, the government deficit amounts to approximately 2% of the gross domestic product (GDP). In the reference case (or status quo) simulation, the real deficit grows at the steady-state growth rate given by the growth of potential labor services. In the policy-change cases, we require that real government spending and the real deficit follow the same paths as in the reference case. To make the policy changes revenue-neutral, we accompany the tax rate increases that define the various policies with reductions in other taxes, either on a lump-sum basis (increased exogenous transfers) or through reductions in marginal tax rates.

Foreign Trade

Except for oil and gas imports, imported intermediate and consumer goods are imperfect substitutes for their domestic counterparts.[20] Import prices are exogenous in foreign currency, but the domestic-currency price changes with variations in the exchange rate. Export demands are modeled as functions of the foreign price of U.S. exports and the level of foreign income (in foreign currency). The exchange rate adjusts to balance trade in every period.

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. The requirements of the general equilibrium are that supply equal demand for labor inputs and for all produced goods; firms' demands for loanable funds match the aggregate supply by households; and the government's tax revenues equal its spending less the

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

current deficit. These conditions are met through adjustments in output prices, in the market interest rate, and in lump-sum taxes or marginal tax rates.[21]

Economic growth reflects the growth of capital stocks and of potential labor resources. The growth of capital stocks stems from endogenous saving and investment behavior. Potential labor resources are specified as increasing at an exogenous rate.

3. Relationships between Carbon-Abatement Policies, Profits, and Equity Values

An important component of this study is the impact of CO_2 abatement policies on the profitability of firms that supply fossil fuels. The first part of this section describes in fairly general terms the model's treatment of firms' profits and equity values, while the second part focuses on how abatement policies affect these elements. In all of this section we concentrate on the fossil-fuel industries, namely coal and oil&gas.

Profits, Dividends, and Equity Values

Let α denote the (fixed) ratio of carbon emissions to units of fuel (output) in the industry in question, and let τ_c denote the carbon tax rate per unit of emissions. Then the carbon tax τ_c requires a payment of $\tau_c\,\alpha$ per unit of output X. The equity 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:

$$\pi = (1-\tau_{\alpha})\left[(p-\tau_c\alpha)X - w(1+\tau_L)L - EMCOST - iDEBT - TPROP + LS\right] + \tau_a(DEPL + DEPR) \tag{5}$$

where τ_a is the corporate tax rate (or tax rate on profits), p is the output price, 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, *LS* is a lump-sum receipt (if applicable) by the firm, *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

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

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.[22]

The firm's sources and uses of revenues are linked through the cash-flow identity:

$$\pi + BN + VN = DIV + IEXP \quad (6)$$

The left-hand side represents the firm's sources 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 a source of revenue.

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

$$DIV_s = \alpha \left[\pi_s + (P_{K,s} - P_{K,s-1})K_s - \delta P_{K,s} K_s\right] \quad (7)$$

$$BN_s \equiv DEBT_{s+1} - DEBT_s = b(\ p_{K,s} K_{s+1} - p_{K,s-1} K_s\ ) \quad (8)$$

Investment expenditure is expressed by:

$$IEXP_s = (\ 1 - \tau_K\ )\ p_{K,s}\, I_s \quad (9)$$

where τ_K is the investment tax credit rate. Of the elements in equation (6), new share issues, *VN*, are the residual, making up the difference between $\pi + BN$ and $DIV + IEXP$.[23]

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

$$(1 - \tau_e)\, DIV_s + (1 - \tau_v\ )(V_{s+1} - V_s - VN_s\ ) = (\ 1 - \tau_b)\, i_s V_s \quad (10)$$

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

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

[23] This treatment is consistent with the so-called old view of dividend behavior. For an examination of this and alternative specifications, see Poterba and Summers (1985).

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*.

Recursively applying equation (10) subject to the usual transversality condition ruling out eternal speculative bubbles yields the following expression for the equity value of the firm:

$$V_t = \sum_{s=t}^{\infty} \left[\frac{1-\tau_e}{1-\tau_v} DIV_s - VN_s \right] \mu_t(s) \qquad (11)$$

where

$$\mu_t(s) \equiv \prod_{u=t}^{s} \left[1 + \frac{r_u}{1-\tau_v} \right]^{-1}$$

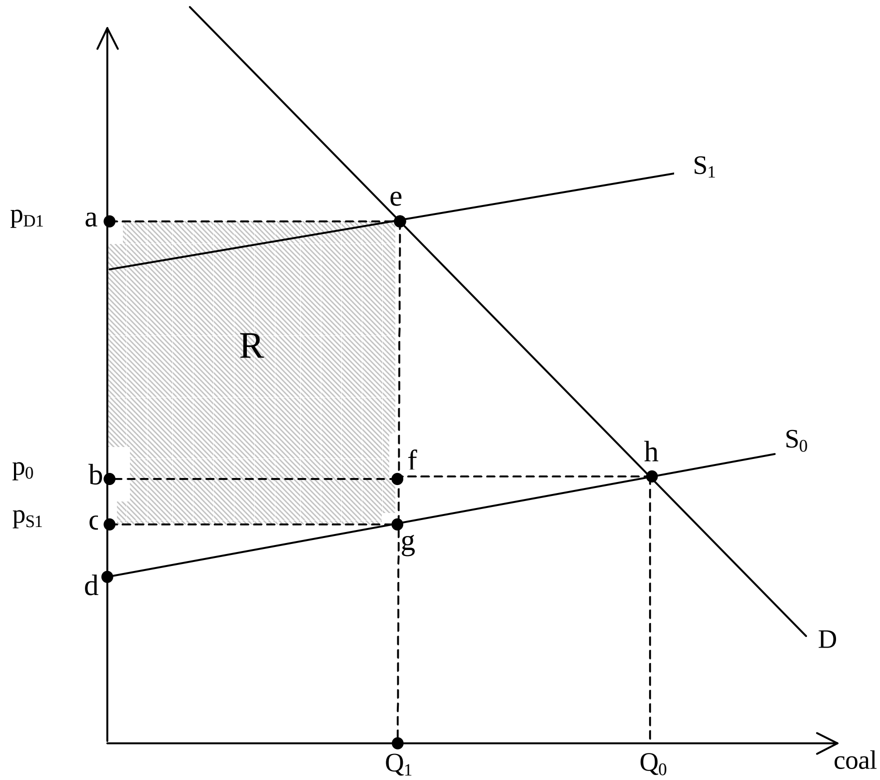
Equation (11) indicates that the equity value of the firm is the discounted sum of after-tax dividends net of new share issues.

Abatement Policies and Equity Values

Standard Carbon Tax. Abatement policies affect equity values by altering firms′ profits and the stream of dividends paid by firms. A carbon tax, in particular, will tend to lower the profits of firms in the industries on which the tax is imposed. Figure 1 heuristically indicates the carbon tax's implications for the coal industry.

The line labeled S_0 in Figure 1 is the supply curve for coal in the absence of a tax. This diagram accounts for the quasi-fixed nature of capital resulting from capital adjustment costs. The supply curve S_0 should be regarded as an average of an infinite number of supply curves, beginning with the curve depicting the marginal cost of changes in supply in the first instant, and culminating with the marginal cost of changing supply over the very long term, when all factors are mobile. This curve therefore indicates the average of the discounted marginal costs of expanding production, given the size of the initial capital stock. We draw the supply curve as upward sloping, in keeping with the

Figure 1: CO_2 Abatement and Profits



fact that in all time frames, except the very long run, capital is not fully mobile and production exhibits decreasing returns in the variable factors—labor and intermediate inputs.[24]

The supply curve represents the marginal costs associated with increments in the use of variable factors to increase supply. Capital is the fixed factor underlying the upward-sloping supply curve. The return to this factor is the producer surplus in the diagram. With an upward sloping supply curve, this producer surplus is positive. The existence of producer surplus does not necessarily imply supernormal profits. Indeed, in an initial long-run equilibrium, the producer surplus is just large enough to yield a normal return on the capital stock. To illustrate, at the initial equilibrium with a market price p_0 and aggregate quantity supplied Q_0, the producer surplus amounts to the triangular area *bhd.* On a balanced growth path, this producer surplus yields a normal (market) return on the

[24] In the long run, in contrast, capital is fully mobile, production exhibits constant returns to scale, and the supply curve is infinitely elastic.

initial capital stock so that the value of the initial capital stock equals the price of investment (and thus Tobin's *q* is unity).

Now consider the impact of an unanticipated carbon (coal) tax. The introduction of this tax shifts the supply curve upward to S_1. As a direct consequence, the output price paid by coal consumers increases from p_0 to p_{D1}. However, since supply is not infinitely elastic, the suppliers of coal are not able to shift the entire burden of the tax onto demanders. Indeed, the producer price of coal declines to $p_{S1.}$ This causes producer surplus to shrink to the area *cgd*. Since this triangle is smaller than the initial producer surplus, the return on the initial capital stock (valued at the price of investment goods) falls short of the market rate of return. Hence, to satisfy the arbitrage condition, Tobin's *q* falls below unity and the owners of the capital stock suffer a capital loss.

This analysis is complicated by the fact that the carbon tax can finance reductions in other taxes, which may imply reductions in costs to firms. This cost-reduction will tend to offset the carbon-tax-induced losses in profits and the associated reductions in equity values. To the extent that the carbon-tax revenues finance general (economy-wide) reductions in personal or corporate income taxes, the reductions in tax rates will be small and thus will exert only a small impact on costs to the fossil- fuel industries. If the revenues are recycled through tax cuts targeted for the fossil-fuel industries, however, the changes in marginal rates can be significant and the beneficial offsetting impact on profits and equity values may be more pronounced.

Effects of Rent-generating Policies. In the diagram, the shaded rectangle *R* (with area *aegc*) represents the firms' payments of the carbon tax. If the government forgoes some of the carbon tax revenue, and allows producers to retain this potential revenue as a rent, the impact on profits, dividends, and equity values can be fundamentally different. Consider for example, the case in which the government restricts CO_2 emissions through a system of carbon permits. Because such emissions are proportional to coal combustion, the government can accomplish a given percentage reduction in emissions from coal by restricting coal output by that same percentage through the sale of a limited number of coal-supply permits. For comparability, suppose that the number of permits restricts supply to the level Q_1 in the figure. If the permits are auctioned competitively, then the government (ideally) collects the revenue *R* from sale of the permits and the effects on firms are the same as under the carbon tax. In contrast, if the permits are given out free (or "grandfathered"), then the area *R* represents a rent to firms. The government-mandated restriction in output causes prices to rise, but there is no increase in costs of production (indeed, marginal production costs are lower).

As suggested by the figure, this rent can be quite large and, indeed, can imply substantial increases in profits and equity values to the regulated industries. In the figure, the post-regulation profits enjoyed by the firm are given by the sum of areas *R* and area *cgd*. Here post-regulation profits are many times higher than the profit prior to regulation (*bhd*). Owners of industry-specific capital enjoy a capital gain as Tobin's *q* jumps above unity. Intuitively, by restricting output, government policy allows producers as a group to exploit their market power and reap part of the original consumer surplus.

Using comparable diagrams, it is easy to verify that the magnitude of the profit increase under a system of grandfathered emissions permits depends on:

The extent of abatement (or number of permits issued relative to business-as-usual emissions). The regulation-induced increase in profit is represented by the difference between the areas of the rectangular area *aefb* and the triangle *fhg*. For incremental restrictions in supply, the former will be larger than the latter (if demand is less than infinitely elastic); thus producers must gain. However, this is not necessarily the case as the magnitude of the required reduction in supply gets larger. If the demand curve has a choke price (a price above which demand is strictly zero), then the potential rent will shrink to zero as the extent of abatement approaches 100%.

The elasticity of supply. The potential to enjoy significant additional profits from restrictions on output is larger, the higher the elasticity of supply. In this case, most of the burden associated with reductions in output is borne by consumers, and a large share of the rent rectangle *R* represents an increase in producer surplus—that is, most of *R* will lie above p_0. In contrast, if supply is inelastic (as in the case where adjustment costs are substantial), very little of the rent rectangle *R* represents an increase in producer surplus because much of it extends below the initial output price p_0. In this case, restrictions in output do not enable producers to expropriate much of the consumer surplus. Thus, the rectangle *aefb* will be smaller than the triangle *fhg*, and profits will fall.

A small income share of the fixed factor (capital in our model) contributes to a large supply elasticity. A large supply elasticity (or flat supply curve) implies that the producer surplus *bhd* (i.e., the income to the fixed factor) is small while most of the area *R* will lie above p_0. Hence the additional profits will be large compared to the initial producer surplus.

The elasticity of demand. If demand is highly elastic, the policy-induced reduction in output gives firms relatively little market power—only a small part of *R* will lie above p_0. In contrast, if demand is inelastic, the abatement policy enables firms to exercise substantial market power. In this case, much of *R* will lie above p_0, and firms will be able to expropriate a considerable amount of the consumer surplus. The aggregate elasticity of demand for a given fossil fuel will reflect the elasticities of substitution inherent in the production functions of domestic users of coal. In addition, the response of demand will reflect the degree to which the government insulates domestic fossil fuel producers from foreign competition. In particular, the elasticity of demand will be smaller, and the potential to enjoy large rents larger, to the extent that the government accompanies taxes on domestic production with levies on imports of fossil fuels and subsidies to exports of such fuels. Carbon taxes or auctioned emissions permits applicable to imported fuels cause the imported fuel prices to rise in tandem with the prices of domestic fuels, thus preventing domestic consumers from shifting demands to imported fuels. Export subsidies ensure that the prices of exported fuels do not rise relative to foreign fuel prices, and thus they help to sustain foreign demand for domestically produced fuels.

Under rent-generating policies, the rectangle *R* corresponds in a dynamic context to:

$$\sum_{s=t}^{\infty}(1-v)(1-\tau_{\alpha})(P_{D1,t}-p_{S1,t})Q_{1,t}\mu_t(s) \tag{12}$$

The factors $1-v$ and $1-\tau_a$ respectively address the fact that the rents are subject to personal and corporate income taxes. Here $Q_{1,t}$ represents gross output (under the policy change) at time *t*.

A system of grandfathered permits is not the only form of regulation that would enable firms to capture much of *R*. Firms could capture some of *R* under a carbon tax policy in which inframarginal emissions (emissions below some trigger level) are exempt from the tax, while all emissions beyond that level face the tax.[25]

In sum, the impact on firms′ profits and equity values can be fundamentally different, depending on how much of the area *R* is retained by firms, rather than collected by the government. It also depends on how much of the area *R* lies above the initial equilibrium price. This, in turn, will

[25] Farrow (1999) describes and evaluates a policy of this sort. See also Pezzey (1992).

depend on the extent of abatement and on elasticities of supply and demand. We will return to these issues in the discussion of policy results in Section 6.

4. Data and Parameters

Our data are documented in Cruz and Goulder (1992), which is available on request. Industry input and output flows (used to establish share parameters for production functions) were obtained from the 1988 input-output table developed by the Bureau of Economic Analysis of the U.S. Department of Commerce. This table is also the source for consumption, investment, government spending, import, and export values by industry. Data on industry capital stocks derive from Bureau of Economic Analysis (1991). Employment by industry was obtained from the October 1990 *Survey of Current Business*. To form the benchmark data set, these data are projected to the year 2000 based on the average growth of real GDP from the relevant historical period to 1998. Data on the carbon content of fossil fuels were obtained from the 1998 U.S. Department of Energy *Annual Energy Outlook*.

Elasticities of substitution determine the industry and household price elasticities of demand. We derive the production function elasticities by transforming parameters of translog production functions estimated by Dale Jorgenson and Peter Wilcoxen. The capital adjustment cost parameters are based on Summers (1981).

Other important parameters apply to the household side of the model. The elasticity of substitution in consumption between goods and leisure, υ, is set to yield a compensated elasticity of labor supply of 0.4.[26] The intertemporal elasticity of substitution in consumption, σ, equals .5.[27] The intensity parameter α_C is set to generate a ratio of labor time to the total time endowment equal to .44. These parameters imply a value of 0.19 for the interest elasticity of savings between the current period and the next.

5. Abatement Policies Investigated

In nearly all simulations, the tool for abatement is the carbon tax (although we also consider CO_2 quotas or tradeable permits, as discussed below). All policies are unanticipated and phased in

[26] This lies midway in the range of estimates displayed in the recent survey by Russek (1996).

[27] This value falls between the lower estimates from time-series analyses (e.g., Hall, 1988) and the higher ones from cross-sectional studies (e.g., Lawrance, 1991).

smoothly (with equal increments to the carbon tax) over a three-year period beginning in the base year, 2000. The carbon tax is levied upstream; that is, the tax is imposed on suppliers of fossil fuels: producers of coal and of oil&gas. To prevent an adverse impact on the international competitive position of fossil-fuel producing industries, exports of fossil fuels are exempted from the carbon tax while imports of these fuels are subject to the carbon tax. Nearly all proposals for a U.S. carbon tax include export and import elements of this type.

The policies differ in two main ways: how the gross revenues from the carbon tax are recycled to the private sector, and the extent to which the policies create and leave rents for the regulated firms. We normalize the carbon tax so that discounted carbon emissions are the same across the policies.[28] We do not allow for public debt policy. Hence, all gross revenues from the carbon tax are immediately returned to the private sector.

Starting Point: Policies without Distributional Adjustments

The first set of policies involves broad-based revenue recycling and thus does not attend to distributional concerns. These policies involve three alternative ways to recycle the revenues: higher lump-sum transfers to households, lower personal income tax rates, and lower corporate income tax rates. We implement these recycling options by using the recycling instrument to endogenously balance the government budget.

The other policies involve additional elements to address important distributional considerations. Thus these policies involve not only environmental neutrality (the reductions in emissions are normalized across policies) and revenue neutrality (all gross revenues are recycled) but also some form of distributional neutrality. The attention to distributional neutrality is motivated by concerns about equity and political feasibility.

[28] In the simulations, we have approximated environmental neutrality by scaling the results of a uniform carbon tax of $25 per ton of carbon by discounted emission reductions. We find that efficiency outcomes from the model are close to linear within the small range of variation in emissions reductions, so that this type of scaling does not significantly affect the interpretation of results.

Imposing the Requirement of Equity-value Neutrality

The first group of policies to attend to distributional neutrality adds the constraint that the real value[29] of equity of the principally affected industries must not be changed (that is, reduced) at the time the abatement policy is announced and implemented. We call this the requirement of equity-value neutrality. The most vulnerable industries are the fossil-fuel supplying industries (coal and oil&gas), the petroleum refining industry, and the electric utility industry.[30] The constraint on the value of equity can be interpreted as the requirement that industry-specific production factors not be hurt by the carbon tax. In the model, labor is perfectly mobile across industries while capital is subject to adjustment costs. Since capital is the only industry-specific production factor, the effect on the value of capital represents the impact of the carbon tax on industry-specific production factors. Unanticipated policies yield instantaneous changes in the value of industry-specific wealth, as measured by changes in the equity values of different industries.

We consider several mechanisms for achieving equity-value neutrality: industry-specific cuts in corporate tax rates, lump-sum transfers to capital employed in particular industries, and inframarginal exemptions to the carbon tax. Our model abstracts both from uncertainty and from heterogeneity across firms within a given industry. In such a model, a policy involving emissions permits— in which a certain fraction of the permits is given out free (rather than auctioned)—is equivalent to a carbon tax policy in which the same fraction of (inframarginal) emissions is exempt from the carbon tax.[31] Thus, the policy with inframarginal exemptions to the carbon tax policy can be interpreted as one where the government controls emissions through emissions permits, and freely allocates or grandfathers some of these permits. We simulate this policy by imposing a $25 per ton carbon tax and rebating to the firm a share of its tax payment, with the share corresponding to the percentage of emissions that are exempt from the tax. The rebate is lump-sum from the firm's point of view. Under this simulation, output and emissions from the coal and oil&gas industries rise

[29] To express the equity values in real terms, we adopt the ideal price index that is associated with the utility function of the representative household.

[30] Thus we focus on four of the six energy industries identified in the model. We give less attention to the natural gas delivery industry, which experiences considerably smaller impacts from the abatement policies, and the synfuels industry, which does not emerge significantly until 2025.

[31] They are equivalent under appropriate scaling of the two policies: the limit on emissions under the permits program must be the same as the level of emissions that occurs under the carbon tax.

through time. Hence, this corresponds to an emissions permit policy in which the number of permits in circulation increases through time.

In our simulations, the policies with inframarginal exemptions have the potential to produce dramatic impacts on profits and equity values. For this reason, we perform additional policy experiments involving inframarginal exemptions of various magnitudes. In these experiments, we do not aim to achieve equity-value neutrality, but instead focus on how profits, equity values, and other important variables are affected by the magnitude of the exemptions. The policies introduced under this heading are an emissions permit system where 100% of the permits are grandfathered, and a carbon tax with inframarginal exemptions equal to 50% or 90% of first-period emissions under the unregulated status quo. The rents generated by each of these policies face the same taxes as other producer income, and thus are subject to the corporate income tax.

These policies involve three instruments to achieve three targets. The carbon tax rate assures environmental neutrality (the same emissions reductions); the adjustment to the personal income tax rate yields revenue-neutrality (all additional revenues from the carbon tax must be recycled); and the industry-specific corporate income tax cuts, lump-sum payments, or inframarginal exemptions bring about equity-value neutrality.

Imposing the Requirement of Tax-payment Neutrality

In the political arena, a popular indicator of the distributional impact focuses on an industry's tax payments. [32] We can define an alternative notion of distributional neutrality in these terms. "Tax payment neutrality" results when a given industry's overall tax payments from carbon taxes, corporate taxes, property taxes, and indirect labor taxes remain constant. As instruments for this type of neutrality, we consider industry-specific corporate tax cuts and explicit lump-sum transfers to sector-specific capital. As with the simulations involving equity-value neutrality, the tax-payment neutrality simulations involve policy packages in which the three instruments achieve three targets.

[32] Indeed, in several countries such as Denmark and the Netherlands, additional environmental taxes raised from energy-intensive industries are earmarked for technology subsidies to this sector.

6. Simulation Results

Policies without Distributional Adjustments

Lump-Sum Recycling

We begin by examining the effects of the $25 per ton carbon tax with lump-sum recycling. Results are displayed in the first numbered column of Table 2. The table shows the impacts on prices, output, and after-tax profits for years 2002 (two years after implementation) and 2025.

The coal industry experiences the largest impact on prices and output. In this industry, prices rise by about 54% by the time the policy is fully implemented (year 2002), and the price increase is sustained at slightly above that level. The price increase implies a reduction in output of about 24% in the long run. The other major impacts on prices and output are in the oil&gas, petroleum refining, and electric utility industries. Although the carbon tax is imposed on the oil&gas industry, the resulting price increase is considerably smaller than in the coal industry, reflecting the lower carbon content (per dollar of fuel) of oil and gas as compared with coal. There are significant increases in prices and reductions in output in the petroleum refining and electric utility industries as well, in keeping with the significant use of fossil fuels in these industries. The reductions in output are accompanied by reductions in annual after-tax profits. Associated with these output reductions is a reduction in CO_2 emissions of about 18%.[33]

The reductions in after-tax profits are associated with reductions in equity values. As shown in Table 3, the largest equity-value impacts are in the coal industry, where such values fall by about 28%. The reductions in equity values in the oil&gas, petroleum refining, and electric utility industries are also substantial, in the range of 4.8 to 6.3%. As indicated in the table, the impacts on equity values of other industries are relatively small.

[33]This is the reduction in emissions associated with domestic consumption of fossil fuels. It accounts for the carbon content of imported fossil fuels, and excludes the carbon content of exported fossil fuels. These figures do not adjust for changes in the carbon content of imported or exported refined products. The percent change in emissions is the percentage change, between the reference case and policy-change case, in the present value of emissions, where the emissions stream is discounted using the after-tax interest rate. If marginal environmental damages from emissions are constant, the percentage changes in discounted emissions will be equivalent to percentage changes in damages.

Table 2: Industry Impacts of CO2 Abatement Policies

(percentage changes from reference case)

	No Distributional Adjustments -- Revenue-Recycling via ...			**Equity-Value Neutrality Imposed**			**Inframarginal Exemptions Offered**			**Tax-Payment Neutrality Imposed**	
	Lump-Sum Transfer (1)	PIT Rate Reduction (2)	CIT Rate Reduction (3)	via Industry-Specific CIT Rate Cut (4)	via Industry-Specific Lump-sum Payment (5)	via (Partial) Grandfather-ing of Emissons Permits (6)	Exempt 100% of Actual Emissions (100% Grandfather-ing of Emissions Permits) (7)	Exempt 50% of BAU Emissions (8)	Exempt 90% of BAU Emissions (9)	via Industry-Specific CIT Rate Cut (10)	via Industry-Specific Lump-Sum Payment (11)
Gross of Tax Output Price (2002, 2025)											
Coal Mining	54.5, 57.0	54.5, 57.0	54.5, 57.1	54.3, 55.9	54.5, 57.0	54.5, 57.0	54.5, 57.0	54.5, 57.0	54.5, 57.0	54.3, 56.0	54.5, 57.0
Oil &Gas	13.2, 8.3	13.2, 8.3	13.2, 8.3	13.2, 8.3	13.2, 8.3	13.2, 8.3	13.2, 8.3	13.2, 8.3	13.2, 8.3	13.2, 3.0	13.2, 8.3
Petroleum Refining	6.4, 5.1	6.4, 5.1	6.4, 5.1	6.3, 4.7	6.4, 5.1	6.4, 5.1	6.4, 5.1	6.4, 5.1	6.4, 5.1	6.4, 2.0	6.4, 5.1
Electric Utilities	2.5, 5.6	2.5, 5.5	2.5, 5.7	2.5, 5.1	2.5, 5.5	2.5, 5.5	2.4, 5.5	2.5, 5.5	2.5, 5.6	2.5, 5.6	2.5, 5.6
Average for Other Industries	-0.6, -0.6	-0.6, -0.7	-0.6, -0.7	-0.6, -0.6	-0.6, -0.7	-0.6, -0.7	-0.6, -0.6	-0.6, -0.7	-0.6, -0.6	-0.6, -0.4	-0.6, -0.6
Output (2002, 2025)											
Coal Mining	-19.2, -23.6	-19.1, -23.3	-19.2, -23.5	-18.9, -21.9	-19.1, -23.3	-19.1, -23.3	-19.0, -23.3	-19.1, -23.4	-19.1, -23.4	-19.4, -23.3	-19.1, -23.5
Oil &Gas	-2.0, -3.9	-2.1, -4.4	-1.3, -2.5	1.5, -0.4	-2.1, -4.4	-2.1, -4.3	-2.0, -4.2	-2.1, -4.3	-2.1, -3.5	7.5, 23.9	-2.0, -4.1
Petroleum Refining	-7.9, -5.6	-7.8, -5.3	-7.9, -5.3	-7.8, -5.0	-7.8, -5.3	-7.8, -5.3	-7.8, -5.4	-7.8, -5.4	-7.8, -5.4	-8.0, -2.8	-7.9, -5.5
Electric Utilities	-3.0, -5.7	-3.0, -5.4	-3.0, -5.5	-2.9, -5.0	-3.0, -5.4	-3.0, -5.4	-3.0, -5.5	-3.0, -5.4	-3.0, -5.5	-3.0, -5.0	-3.0, -5.6
Average for Other Industries	-0.2, -0.3	-0.1, 0.1	-0.1, 0.1	-0.1, 0.1	-0.1, 0.1	-0.1, 0.1	-0.1, -0.1	-0.1, 0.0	-0.1, -0.1	-0.2, -0.2	-0.2, -0.2
After-Tax Profits (2002, 2025)											
Coal Mining	-32.5, -25.8	-32.3, -25.5	-32.0, -25.1	-19.9, -12.0	-32.3, -25.5	-16.6, -10.4	542.7, 526.9	555.9, 351.5	957.2, 653.0	-19.9, -12.8	-32.4, -25.7
Oil &Gas	-2.3, -3.5	-2.3, -3.9	-0.3, -0.4	-6.6, -9.1	-2.3, -3.8	1.3, -1.8	21.4, 9.4	18.0, 5.5	34.3, 13.7	25.7, 45.7	-2.3, -3.6
Petroleum Refining	-9.2, -3.9	-9.1, -3.6	-8.1, -2.7	-5.5, -0.9	-9.1, -3.6	-9.1, -3.6	-9.1, -3.8	-9.1, -3.7	-9.2, -3.8	-10.5, -2.6	-9.2, -3.8
Electric Utilities	-7.7, -5.2	-7.4, -4.8	-7.1, -4.2	-5.2, -2.7	-7.4, -4.8	-7.4, -4.8	-7.5, -5.0	-7.4, -4.9	-7.5, -5.0	-8.6, -4.7	-7.6, -5.1
Average for Other Industries	-0.9, -1.1	-0.7, -0.7	0.2, 0.2	-0.7, -0.7	-0.7, -0.7	-0.7, -0.8	-0.7, -0.9	-0.7, -0.8	-0.8, -0.9	-1.0, -1.0	-0.9, -1.0

Table 3: Equity Values and Efficiency Impacts

	No Distributional Adjustments -- Revenue-Recycling via ...			Equity-Value Neutrality Imposed			Inframarginal Exemptions Offered			Tax-Payment Neutrality Imposed	
	Lump-Sum Transfer (1)	PIT Rate Reduction (2)	CIT Rate Reduction (3)	via Indusry-Specific CIT Rate Cut (4)	via Industry-Specific Lump-sum Payment (5)	via (Partial) Grandfather-ing of Emissons Permits (6)	Exempt 100% of Actual Emissions (100% Grandfather-ing of Emissions Permits) (7)	Exempt 50% of BAU Emissions (8)	Exempt 90% of BAU Emissions (9)	via Industry-Specific CIT Rate Cut (10)	via Industry-Specific Lump-Sum Payment (11)
Equity Values of Firms (year 2000) (percentage changes from reference case)											
Agriculture and Non-Coal Mining	-0.7	0.2	1.4	0.1	0.1	0.1	0.0	0.0	-0.1	-0.2	-0.4
Coal Mining	-28.4	-27.8	-27.2	0.0	0.0	0.0 (0.043)	1005.4	709.1	1284.0	1283.3	4283.7
Oil&Gas	-4.8	-5.0	-0.7	0.0	0.0	0.0 (0.150)	29.2	22.3	43.1	43.2	117.2
Petroleum Refining	-5.2	-4.5	-3.3	0.0	0.0	-4.5	-4.7	-4.7	-4.8	-4.8	-12.1
Electric Utilities	-6.3	-5.4	-4.4	0.0	0.0	-5.4	-5.7	-5.6	-5.7	-5.8	-12.9
Natural Gas Utilities	-1.4	-0.4	0.6	-0.3	-0.4	-0.4	-0.8	-0.6	-0.8	-0.9	-1.1
Construction	-0.3	1.5	2.1	1.8	1.5	1.5	1.0	1.1	0.8	0.7	0.2
Metals and Machinery	-1.2	-0.4	1.0	-0.6	-0.4	-0.4	-0.5	-0.6	-0.7	-0.7	-0.9
Motor Vehicles	-0.6	0.2	1.6	0.2	0.2	0.2	0.1	0.0	-0.1	-0.2	-0.4
Miscellaneous Manufacturing	-0.8	-0.1	1.4	-0.2	-0.1	-0.1	-0.2	-0.3	-0.4	-0.4	-0.6
Services (except housing)	-0.8	0.2	1.2	0.2	0.1	0.1	-0.1	-0.1	-0.2	-0.3	-0.5
Housing Services	0.0	0.4	0.1	0.4	0.4	0.4	0.1	0.3	0.3	0.2	0.1
Total	-0.8	-0.1	0.9	0.1	0.1	0.0	1.1	0.7	1.3	1.2	4.5
Efficiency Cost											
Absolute (billions of year-2000 dollars)	-817	-471	-374	-345	-482	-506	-751	-549	-611	-355	-713
Per Ton of CO2 Reduction	102.6	60.0	47.7	46.9	61.4	64.4	95.1	69.7	77.4	61.1	89.9
Per Dollar of Carbon Tax Revenue	.73	.42	.34	.30	.43	.50	-	.79	1.64	.32	.64

Note: Numbers in parentheses are proportion of emissions permits required to achieve equity-value neutrality.

Table 3 also indicates efficiency impacts. We employ the equivalent variation to measure these impacts; this is a gross measure because our model does not account for the benefits associated with the environmental improvement from reduced emissions. As indicated in the table, the policy implies a gross efficiency loss of approximately $103 per ton of emissions reduced, or 73 cents per dollar of discounted gross revenue from the carbon tax.

Personal Income Tax Recycling

Policy 2 recycles the revenues through personal income tax cuts rather than lump-sum payments. As shown in the second numbered column of Table 2, such recycling does not significantly alter the impacts of the carbon tax on prices and output. Furthermore, such recycling only slightly attenuates the impacts on profits and equity values in the most affected industries. However, as indicated in Table 3, this form of recycling reduces the economy-wide efficiency costs by over 40%. The equivalent variation is about $60 per ton of emissions reduced, and 42 cents per dollar of discounted carbon-tax revenues.

The reason for the smaller efficiency losses with personal-income-tax recycling is that, by lowering the marginal rates of the personal income tax, this recycling helps lower the distortionary costs of the personal income tax. This efficiency consequence has been termed the revenue-recycling effect. Despite the lower distortionary taxes, the carbon tax package still imposes gross efficiency costs because it tends to raise output prices and thereby reduce real returns to labor and capital. This tax-interaction effect tends to dominate the revenue-recycling effect. Hence the carbon tax still involves an overall economic cost (abstracting from the environmental benefits), even when the revenues are devoted to cuts in the personal income tax.[34]

[34] This exemplifies the now-familiar result that, abstracting from the value of the environmental improvements they generate, green taxes tend to be more costly than the ordinary taxes they replace. Although this is the central result, the opposite outcome can arise when the pre-existing tax system is suboptimal along non-environmental dimensions (for example, when it involves overtaxation of capital relative to labor) and the introduction of the environmental reform helps alleviate the non-environmental inefficiency. For analysis and discussion of this issue, see Bovenberg and de Mooij (1994), Parry (1995), Goulder (1995b), Bovenberg and Goulder (1997, 2000), and Parry and Bento (2000).

Corporate Income Tax Recycling

The carbon tax revenue can be used instead to reduce the corporate income tax (Policy 3). This type of recycling further reduces the gross efficiency costs of emission reductions to 34% of discounted carbon tax revenues. Thus, corporate tax recycling appears to be more efficient than personal tax recycling. This indicates that, in the model, the corporate tax is more distortionary than the personal income tax in the initial equilibrium. Although there is considerable disagreement as to the distortionary impacts of the corporate income tax, these results are consistent with the prevailing results from other applied general equilibrium analyses.[35] In the U.S. economy, taxes on capital investment, such as the corporate income tax, appear to be more distortionary than labor income taxes or the personal income tax (a tax on both capital and labor income).

A cut in the corporate tax rate benefits the owners of capital because it reduces the tax burden on earnings from the installed capital stock. As a result, equity values in the most affected industries (coal, oil&gas, petroleum refining, and electric utilities) fall less than they do in the cases of lump-sum recycling or personal-income-tax recycling. Indeed, the value of equity in the oil&gas sector is almost unaffected by this policy package. While corporate-income-tax recycling significantly changes the impact on equity values, it makes relatively little difference to output patterns. This indicates that changes in industry output are an unreliable measure of the impact of environmental policy on the real earnings of industry-specific production factors.

Policies Achieving Equity-value Neutrality

We now consider policies that introduce an additional instrument to alter the distributional impacts. We start with results from policies that impose the requirement of equity-value neutrality.

Industry-specific Cuts in the Corporate Income Tax

Policy 4 achieves equity-value neutrality through industry-specific adjustments to corporate tax rates, with the remainder of the revenues recycled via cuts in the personal income tax. This policy appears to offer an efficient way to attain such neutrality. In fact, as indicated in

[35] See, for example, Jorgenson and Yun (1991), and Goulder and Thalmann (1989).

Table 3, the gross efficiency losses are smaller than in the case where this constraint is not imposed (Policy 2), suggesting that there is no trade-off between efficiency and distributional neutrality in this case. Two factors help explain this result. First, in our model the corporate income tax is more distortionary than the personal income tax, as indicated by the difference in efficiency costs of Policies 2 and 3. Under Policy 4, the efficiency benefit from cutting the corporate tax rate is offset by the need to finance these cuts through the personal income tax—that is, the personal tax cannot be lowered as much under this policy as under Policy 2, which involves no corporate income tax cuts. Since the corporate tax is more distortionary than the personal tax, there is an overall efficiency benefit from this tax-swap.

A second reason for the relatively low efficiency cost relates to tax distortions in the fossil-fuel industries. The carbon tax significantly raises the overall taxation of energy industries relative to other industries. On non-environmental grounds, these industries are over-taxed relative to other industries. Targeted corporate tax cuts undo some of the non-environmental distortions attributable to the carbon tax. We have verified this effect by performing an additional simulation experiment, which (like Policy 3) recycles some carbon tax revenues through reductions in the overall corporate tax rate, but also (like Policy 4) recycles sufficient revenues in the form of additional corporate tax cuts for the energy industries to preserve equity-values in those industries. This policy involves an efficiency cost of $40.9 per ton, significantly lower than the efficiency cost per ton under Policy 3. The difference between this policy and Policy 3 is that this policy includes the additional, targeted corporate income tax cuts. Thus there is a (gross) efficiency benefit from reducing the excess taxation of energy industries under the carbon tax.[36] This is a second reason why Policy 4's efficiency cost is lower than that of Policy 2.

Industry-specific Lump-sum Transfers

Policy 5 produces equity-value neutrality through industry-specific lump-sum transfers. This appears to be an inexpensive way to ensure distributional neutrality: relatively small lump-sum transfers ensure that the real value of equity is not affected by the carbon tax. These small transfers absorb relatively little revenue, allowing personal income tax rates to be cut almost as much as under Policy 2. The cost of emissions abatement (relative to Policy 2) is raised by only a small amount: from $60.0 to $61.4 per ton.

[36] We are grateful to Ruud de Mooij for suggesting this diagnostic experiment.

Grandfathered Emissions Permits

As discussed in Section 2, emissions quotas or permits, by forcing firms to restrict output, can create rents for regulated industries. At the same time, there are costs to these industries connected with the reduction in output and the associated need to remove capital or retire capital prematurely.[37] The question arises as to whether the policy-induced rents might be sufficient to compensate firms for the other costs associated with abatement.[38]

We consider this issue with Policy 6; here we introduce a carbon tax but grant firms exemptions to this tax for a certain percentage of their actual emissions. It is important to recognize that the value of the exemption, although tied to actual emissions in the industry (in the aggregate), is exogenous from the firm's point of view. As discussed in Section 5, this experiment can also be interpreted as a policy where the government introduces a tradable permits program, but grandfathers a percentage of the permits. The special case (to be considered later) where the firm enjoys a 100% (inframarginal) exemption from the carbon tax corresponds to the case of fully grandfathered emissions permits.[39]

Perhaps surprisingly, only a very small percentage of emissions permits need to be grandfathered in order to achieve equity-value neutrality. Only 15% need to be grandfathered in the oil&gas industry, and an even smaller percentage—4.3%—must be grandfathered in the coal industry! As a result, the goal of distributional neutrality can be achieved at a small cost in terms of efficiency. As mentioned in the introduction, earlier research has made clear that there is a trade-off between efficiency and political feasibility associated with the implementation of an

[37] There are other transition costs, such as the unemployment costs that may result from reduced output. These are not captured in our analysis.

[38] This policy imposes equity-value neutrality only for the coal and oil&gas industries, since the carbon tax (and its exemptions) or emissions permits apply only to these industries. The government would need to invoke additional instruments to achieve equity-value neutrality in other industries.

[39] Three modeling assumptions underlying this correspondence may be noted. First, the equivalence between a carbon tax policy and a carbon-emissions permits policy would not hold in a more general model in which regulators faced uncertainty. In the presence of uncertainty, taxes and permit policies intended to lead to a given level of emissions will generally yield different aggregate emissions *ex post*. Second, we assume that a cost-effective allocation of emissions responsibilities is achieved under the permit policy. This implicitly assumes that any differences in abatement costs (associated with heterogeneity in firms' production methods) are ironed out through permit trading. Third, our model does not distinguish new and old firms (although it does distinguish installed and newly acquired capital). The model's treatment of grandfathering is most consistent with a situation in which only established firms enjoy the freely offered emissions permits, where these permits are linked to the (exogenous) initial (or old) capital stock.

emissions permit program: efficiency requires auctioning of permits (no grandfathering), whereas political feasibility calls for grandfathering. These results indicate that the trade-off may be relatively benign: it only takes a small amount of grandfathering, and a small sacrifice in efficiency, to preserve equity values in the industries that otherwise would suffer most from CO_2 abatement regulations.[40]

Why does a small amount of grandfathering go a long way? As suggested by the discussion in Section 3, the gain offered to regulated firms by exemptions to a carbon tax or by the free allocation of emission permits is enhanced to the extent that elasticities of supply are large and elasticities of demand are low. In this model, the elasticity of supply is determined by the share of cash flow (payments to owners of the quasi-fixed factor, capital) in overall production cost, along with the specification of adjustment costs. We find that for the coal and oil&gas industries, cash flow in the unregulated situation is quite small relative to production cost, which contributes to a larger supply elasticity. Although adjustment costs restrict the supply elasticity in the short run, the average elasticity (taking into account the medium and long run) is fairly large under our central values for parameters. Indeed, the long run elasticity in the coal industry is infinite because of the assumption of constant returns to scale.[41] These conditions imply that most of the cost from abatement policies is shifted onto demand.

Table 4 bears this out. It displays the impact of a revenue-neutral carbon tax policy (Policy 2) on gross and net output prices at different points in time. In the coal industry, the net-of-tax coal price falls a bit (relative to the reference-case price) in the short run, but the carbon tax is fully shifted in the long run. Even in the short run, over 90% of the tax is shifted onto coal

[40]Table 3 reveals that it is more costly to achieve equity-value neutrality through partial grandfathering of emissions permits (Policy 6) than through lump-sum payments to firms (Policy 5). The difference can be attributed to differences in the treatment of importers of fossil fuels under the two policies. Both policies can be interpreted as a carbon tax plus an inframarginal lump-sum rebate. Under Policy 5, the rebate or lump-sum payment is offered only to domestic fossil-fuel producers. In contrast, under Policy 6, the rebate (via grandfathering) is offered both to domestic fossil-fuel producers and to importers of fossil fuels. Under Policy 6, the government is somewhat more generous and forgoes more tax revenue; hence the added efficiency cost. Another difference between the policies is that the petroleum refining and electric utility industries receive direct compensation under Policy 5, but enjoy no protection under Policy 6. This would tend to raise the costs of Policy 5 relative to Policy 6. However, this cost-impact is more than offset by the differences just described in the treatment of importers.

[41]In the oil&gas industry, the presence of a fixed factor implies decreasing returns even in the long run.

Table 4: Price Responses under Carbon Tax*

Ratio of Price under Policy Change to Reference-Case Price

	2000	2001	2002	2004	2010	2025	2050
Coal Industry							
Output price gross of carbon tax	1.1769	1.360	1.546	1.551	1.560	1.570	1.570
Output price net of carbon tax	0.986	0.978	0.973	0.978	0.995	0.995	0.998
Crude Petroleum and Natural Gas Industry							
Output price gross of carbon tax	1.046	1.090	1.132	1.125	1.109	1.083	1.059
Output price net of carbon tax	1.000	1.000	1.000	1.000	1.000	1.000	1.000

* Results are for Policy 2, a $25 per ton carbon tax with revenues recycled through reductions in personal income tax rates. Coal and oil&gas price responses are very similar under the other carbon tax policies.

consumers. In the oil&gas industry, the tax is entirely forward-shifted at all points in time, reflecting the fact that the United States is regarded as a price-taker with respect to oil&gas.[42]

In terms of the analysis of Section 3, the ability to shift forward the costs of regulation means that most of the *R* rectangle lies above the initial price. When the initial producer surplus or cash flow is small in relation to production cost, owners of the quasi-fixed factor (capital) can be fully compensated for the costs of regulation if they are given just a small piece of the *R* rectangle through grandfathering.

[42]The real net-of-tax price of oil&gas is the only exogenous price in the model. This price is assumed to increase at a rate of $5.00 per decade (in keeping with baseline assumptions employed by the Energy Modeling Forum at Stanford University). Hence the ratio of the (constant) real carbon tax rate to the (rising) net-of-tax price declines through time; this explains why, in Table 4, the percentage increase in the gross-of-tax price of oil&gas declines after 2004.

This is confirmed in Table 5. The table shows the dynamic equivalent of the *R* rectangle under Policy 2 (carbon tax with recycling through personal income tax cuts) and Policy 6. To enhance comparisons between Policies 2 and 6, we will interpret each policy as involving

Table 5: Carbon Payments and Equity Values*

	Industry Equity Value		Present Value of Potential Carbon Payments	α – fraction of Tax Payments Exempted or Permits Grandfathered	Present Value of Actual Carbon Payments	Present Value of Inframarginal Exemption or Grandfathered Permits
	Level	Difference from Reference Case			*[(1-α) (3)]*	*[α (3)]*
	(1)	(2)	(3)	(4)	(5)	(6)
Coal Industry						
Reference Case	17.6	-	-	-	-	-
Standard Carbon Tax (Policy 2)	12.7	-4.9	119.5	-	119.5	-
Carbon Tax with Inframarginal Exemption (Carbon Permits with Partial Grandfathering) (Policy 6)	17.6	-	119.6	.043	114.5	5.1
Oil&Gas Industry						
Reference Case	187.5	-	-	-	-	-
Standard Carbon Tax (Policy 2)	178.0	-9.5	65.8	-	65.8	-
Carbon Tax with Inframarginal Exemption (Carbon Permits with Partial Grandfathering) (Policy 6)	187.5	-	66.0	.150	56.1	9.9

*Values in billions of year-2000 dollars. Values in last three columns are net of deductions to corporate and personal income taxes (as indicated in equation (12) of text).

emissions permits: Policy 2 is the case of emissions permits with no grandfathering, while Policy 6 involves partial grandfathering to yield equity-value neutrality. (As mentioned, one could also interpret these as carbon tax policies, where Policy 2 includes no inframarginal exemption, and Policy 6 involves sufficient exemptions to preserve equity-value neutrality.) The second column of Table 5 shows that Policy 2 causes equity values to fall by $4.9 billion in the coal industry. This policy requires the firm to purchase $119 billion in carbon emissions permits. Potential carbon payments is the analog to the *R* rectangle: it is the permit price times the number of permits employed in the coal industry. For the coal industry, this value is $119 billion. Under Policy 2, all of the permits are in fact auctioned, and thus the actual carbon payments are the same as the potential payments. Note that this number is very large in relation to the reduction in equity values—$4.9 billion—suffered by the industry. If firms could retain only a small fraction of the $119 billion, they would be compensated for the $4.9 billion loss. Under Policy 6, firms can in fact retain a fraction of *R*. Enabling firms to retain just 4.3% of the potential carbon payments is worth an amount comparable to the $4.9 billion, and prevents any reduction in equity values.

Thus, in the coal industry, a very small amount of grandfathering preserves equity values. This reflects the fact that the potential tax payment (the *R* rectangle) is large relative to the loss in equity value in the absence of grandfathering. This, in turn, reflects the small share of cash flow in production cost and the large elasticity of supply, as discussed above. The result is similar in the oil&gas industry. However, in this industry, the potential carbon payments are not as large in relation to the loss of equity value. Hence the firm must be relieved of a somewhat larger fraction (15%) of these payments to suffer no loss of equity value.

While Policy 6 preserves profits in the fossil-fuel industries, it does not insulate all industries from negative impacts on profits. The petroleum refining and electric utility industries—which utilize fossil fuels (carbon) most intensively—also endure noticeable losses of profit and equity values, as indicated by Table 3. Protecting these industries would require expanded policies involving additional instruments.[43]

[43] One possible extension is to employ input subsidies for selected downstream industries. Such a subsidy could insulate downstream users from higher fuel prices. We are grateful to Ruud de Mooij for suggesting this option to us. Another possibility would be to give downstream users some of the carbon (fossil-fuel) permits. This effectively is a lump-sum transfer to downstream users: such users could sell the permits to fossil-fuel suppliers and earn revenues that compensate them for the higher costs of fossil fuels.

Other Policies Involving Inframarginal Exemptions

The grandfathered emissions permit policy just analyzed is one of many potential policies that offer inframarginal exemptions to the regulated firms. Before investigating policies that impose tax-payment neutrality, it seems worthwhile to examine some related policies that grant inframarginal exemptions from carbon taxation. Under Policy 7, we consider the limiting case where 100% of actual emissions are (inframarginally) exempt from the carbon tax or, equivalently, where all emissions permits are grandfathered. The results are shown in Tables 2 and 3. Full grandfathering leads to very large increases in equity values in the regulated industries, especially the coal industry. These large increases are consistent with the predicted magnitudes of the rents these policies generate and the associated increases in the discounted value of after-tax cash flow.

We also consider some policies that offer exemptions based on business-as-usual (BAU) emissions. In particular, we examine the case where firms receive exemptions from emissions corresponding to 50 or 90% of their first-period emissions in the unregulated situation. These simulations differ in two ways from the earlier experiments involving exemptions. First, the exemptions are tied to BAU emissions rather than to the actual emissions occurring under the new policy. Second, the exemptions are constant through time. (In the earlier experiments, actual emissions tended to grow with time, which meant that the number of permits in circulation grew as well.) Since we model a growing economy in which outputs of all industries tend to increase through time (even under a carbon tax), the exemption represents a diminishing percentage of actual output.

These policies (numbers 8 and 9) are less generous to firms than Policy 7, which involves 100% grandfathering, but more generous than Policy 6, which grandfathers just enough permits to assure equity-value neutrality. As shown in Table 3, offering a permanent exemption equal to 50% of first-year BAU emissions is enough to increase equity values of firms relative to the unregulated situation: equity values rise by a factor of seven in the coal industry, and by about 22% in the oil&gas industry. A permanent exemption equal to 90% of first-year BAU emissions raises equity values by more than a factor of 12 in the coal industry and about 43% in the oil&gas industry. The government forgoes more revenues under Policies 8 and 9 than under Policy 6; accordingly, the efficiency costs of these policies are somewhat higher than under Policy 6.

Policies Achieving Tax-Payment Neutrality

Industry-specific Cuts in the Corporate Income Tax

Policies 10 and 11 invoke additional instruments (relative to Policy 2) to yield tax-payment neutrality for the coal, oil&gas, petroleum refining, and electric utility industries. In Policy 10, we introduce industry-specific corporate tax cuts to achieve such neutrality, with a constraint that the corporate cuts cannot bring the industry's tax rate below zero. It turns out that this constraint is binding for the coal industry: under this policy, the corporate tax rate for this industry reaches zero before tax-payment neutrality is achieved. This result reflects the fact that this industry's carbon tax payments are very large relative to corporate tax payments under the status quo. In the oil&gas industry, tax-payment neutrality is achieved when the corporate rate is lowered to .17 from its initial value of .42.

The corporate tax reductions that move toward tax-payment neutrality (in the coal industry) or achieve such neutrality (in the oil&gas industry) are much larger than the reduction necessary to achieve equity-value neutrality (Policy 4), and they imply extremely large increases in equity values relative to the unregulated situation. As mentioned earlier, the average of short-, medium-, and long-run elasticities of supply in the model is fairly high. Thus, overall, firms are able to shift onto demanders a large fraction of the carbon tax. Because producers bear only a small share of the tax burden, only a small corporate tax cut is needed to undo the potential impact of a carbon tax on profits and equity values. In contrast, a corporate tax cut that achieves tax-payment neutrality vastly overcompensates firms in terms of the real burden of the carbon tax to producers—most of the tax was shifted onto consumers.

Industry-specific Lump-sum Transfers

When we maintain tax-payment neutrality through lump-sum recycling, the efficiency costs are fairly high. As in the case with industry-specific corporate tax cuts, lump-sum recycling substantially overcompensates firms in terms of profits and equity values. Again the reason is that most of the carbon tax's burden falls on demanders rather than suppliers. But the case with lump-sum recycling is considerably more costly than the prior case because lump-sum recycling lacks the beneficial influence on efficiency associated with the cut in marginal corporate tax rates.

The efficiency costs, however, do not become as large as with full lump-sum recycling to households (Policy 1). The reason is that part of the lump-sum transfers to firms are taxed away by the personal tax on dividend income when firms pay out these lump-sum transfers as dividends. Since the personal income tax rate endogenously balances the government budget, the additional tax revenue associated with the higher dividend income is returned to households in the form of a lower personal income tax rate. In contrast, under full lump-sum recycling to households (Policy 1), the personal income tax rate stays constant.

It may be noted that ensuring tax neutrality through lump-sum transfers does not have much consequence for industry-specific output, employment, and investment. Lump-sum transfers decouple interindustry allocation from interindustry distribution.

These experiments indicate that imposing tax-payment neutrality substantially overcompensates firms. While equity concerns might justify compensating firms for lost profits or equity values, they seem to offer little justification for tax-payment neutrality. Real-world backing for tax-payment neutrality may stem from the misperception that it is necessary to leave firms' tax revenues unchanged in order to neutralize the real burden from regulation.

Sensitivity Analysis

Table 6 indicates how key parameters affect results under Policies 1, 2, 6, and 7. Panel A of the table illustrates the implications of the size of the carbon tax (or extent of abatement). Here we consider carbon tax rates of $12.50 and $50.00 per ton, as well as the previously considered central-case value of $25.00 per ton. Impacts on equity values increase with the size of the carbon tax, but somewhat less than linearly. The results for the 100% exemption case indicate that considerable rents are generated even when the carbon tax is $12.50 B in this situation, equity values in the coal mining industry rise by almost a factor of six. Under all three policies, efficiency costs per ton—or average abatement costs B increase as the carbon tax rises from $12.50 to $50.00 per ton, attesting to rising marginal costs of abatement. The efficiency rankings of the three policies do not change as the carbon tax rate changes.

Panel B of Table 6 reveals the significance of alternative values for elasticity of demand for energy. The high-elasticity case involves a doubling, in each industry, of the elasticities of substitution between the energy composite *E* and the materials composite *M*, as well as the elasticity of substitution between the specific forms of energy. The low-elasticity case halves each of these elasticities in each industry. For the coal industry, the high, central, and low elasticity of substitution cases yield general equilibrium elasticities of demand of .26, .41, and .64, respectively, under Policy 2. Under every policy, the efficiency costs per ton of abatement are lower, the larger is the elasticity of demand. The efficiency rankings of policies remain

Table 6: Sensitivity Analysis

A. Sensitivity to Carbon Tax Rate

	Carbon Tax with Recycling via Lump-Sum Transfer (1)			Carbon Tax with Recycling via PIT Rate Reduction (2)			Carbon Tax with (Partial) Grandfathering of Emissons Permits for Equity Neutrality (6)			Carbon Tax with 100% Inframarginal Exemption (Emissions Permits with 100% Grandfathering) (7)		
Tax Rate	$12.50	$25.00	$50.00	$12.50	$25.00	$50.00	$12.50	$25.00	$50.00	$12.50	$25.00	$50.00
Pct. Change in Equity Value of Firms (year 2000)												
Coal Mining	-17.0	-28.4	-42.8	-16.6	-27.8	-41.9	0.0 (.037)	0.0 (.043)	0.0 (.053)	554.9	1005.4	1749.6
Oil&Gas	-2.6	-4.8	-9.3	-2.8	-5.0	-9.4	0.0 (.151)	0.0 (.150)	0.0 (.141)	14.7	29.2	56.7
Petroleum Refining	-2.7	-5.2	-9.6	-2.3	-4.5	-8.4	-2.4	-4.5	-8.4	-2.5	-4.7	-8.9
Electric Utilities	-3.4	-6.3	-11.2	-2.8	-5.4	-9.5	-2.9	-5.4	-9.6	-3.1	-5.7	-10.3
Efficiency Cost per Ton of CO_2 Reduction	93.1	102.6	126.0	51.7	60.0	77.9	60.2	64.4	83.0	82.5	95.1	109.4

Note: Numbers in parentheses are proportion of emissions permits required to achieve equity-value neutrality.

Table 6, continued

B. Sensitivity to Elasticity of Demand

	Carbon Tax with Recycling via Lump-Sum Transfer (1)			Carbon Tax with Recycling via PIT Rate Reduction (2)			Carbon Tax with (Partial) Grandfathering of Emissons Permits for Equity Neutrality (6)			Carbon Tax with 100% Inframarginal Exemption (Emissions Permits with 100% Grandfathering) (7)		
Demand Elasticity	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High
Pct. Change in Equity Value of Firms (year 2000)												
Coal Mining	-19.0	-28.4	-43.2	-18.2	-27.8	-42.9	0.0 (.032)	0.0 (.043)	0.0 (.058)	1104.9	1005.4	840.5
Oil&Gas	-5.1	-4.8	-4.5	-5.3	-5.0	-4.5	0.0 (.151)	0.0 (.150)	0.0 (.154)	28.7	29.2	28.9
Petroleum Refining	-4.6	-5.2	-5.8	-3.8	-4.5	-5.3	-3.8	-4.5	-5.3	-4.2	-4.7	-5.5
Electric Utilities	-4.4	-6.3	-8.3	-3.3	-5.4	-7.6	-3.3	-5.4	-7.6	-3.7	-5.7	-7.9
Efficiency Cost per Ton of CO_2 Reduction	151.9	102.6	60.7	86.6	60.0	38.3	94.5	64.4	38.8	140.0	95.1	48.8

Table 6, continued

C. Sensitivity to Adjustment Costs (Inversely Related to Elasticity of Supply)

	Carbon Tax with Recycling via Lump-Sum Transfer (1)			Carbon Tax with Recycling via PIT Rate Reduction (2)			Carbon Tax with (Partial) Grandfathering of Emissons Permits for Equity Neutrality (6)			Carbon Tax with 100% Inframarginal Exemption (Emissions Permits with 100% Grandfathering) (7)		
Adjustment Costs	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High
Pct. Change in Equity Value of Firms (year 2000)												
Coal Mining	-26.2	-28.4	-31.1	-25.5	-27.8	-30.5	0.0 (.040)	0.0 (.043)	0.0 (.067)	1065.4	1005.4	901.3
Oil&Gas	-4.8	-4.8	-5.7	-5.0	-5.0	-5.9	0.0 (.136)	0.0 (.150)	0.0 (.158)	30.3	29.2	26.2
Petroleum Refining	-5.0	-5.2	-5.4	-4.3	-4.5	-4.7	-4.3	-4.5	-4.7	-4.6	-4.7	-5.0
Electric Utilities	-6.1	-6.3	-6.5	-5.2	-5.4	-5.4	-5.2	-5.4	-5.5	-5.6	-5.7	-5.9
Efficiency Cost per Ton of CO_2 Reduction	101.6	102.6	102.1	57.9	60.0	59.8	62.0	64.4	65.5	90.2	95.1	89.5

invariant across the different demand-elasticity scenarios. The numbers in parentheses in the columns associated with Policy 6 are the proportion of emissions permits required to achieve equity-value neutrality. In keeping with the analysis of Section II, this proportion tends to rise with the elasticity of demand.

Panel C of Table 6 examines the implications of alternative assumptions for the elasticity of supply. We regulate this elasticity by altering the parameter ξ in the adjustment cost function for each industry (see equation (A-2) in appendix). This parameter determines the marginal adjustment cost, which is inversely related to the elasticity of supply. The low adjustment cost (high elasticity of supply) case reduces this parameter by 25% in all industries; the high adjustment cost (low elasticity of supply) case doubles it everywhere.[44] Efficiency costs per ton do not vary substantially with this parameter. As predicted by the analysis in Section 2, the proportion of emissions permits required to achieve equity-value neutrality rises with adjustment costs (or falls with the elasticity of supply).

7. Conclusions

We have examined how carbon abatement policies can be designed to protect profits in key industries, and we show that such protections need not involve significant revenue costs or sacrifices of economic efficiency. In the coal and oil&gas industries, firms are able to shift a significant portion of the regulatory burden onto downstream consumers. This ability implies that only a very small fraction of the potential rents associated with CO_2 policies need to be earmarked for the fossil-fuel industries to preserve profits and equity values. Equity values can be safeguarded through policies that depart only slightly from the most efficient carbon tax (or auctioned carbon permits) policies. In particular, the government has to grandfather only a small fraction of tradable emission permits, or exempt a small fraction of inframarginal emissions from a carbon tax, to protect the value of capital in these industries. Since these policies involve fairly small sacrifices of potential government revenue, the efficiency sacrifice is small as well.

The simplest programs involving freely allocated emissions permits or inframarginal exemptions to the carbon tax protect only the fossil-fuel supplying industries—downstream industries are not protected. In our model, the downstream industries that suffer the largest

[44] We were unable to obtain a solution for the model when adjustment cost parameters were reduced by more than 25%.

proportionate reductions in equity values are the electric utility and petroleum refining industries. To protect these industries, other policy instruments would need to be invoked. We find that the potential carbon revenues are very large in relation to the revenue that would be required to protect profits, even when the protected industries include not only fossil fuels but electric utilities and petroleum refining as well. As a result, in our simulations the profits of this broader group of energy industries can be protected at relatively small efficiency cost.

Some caveats are in order. First, our model's aggregation may mask significant losses in some industries (such as aluminum manufacturing) that are not explicitly identified. To protect these industries, additional compensation methods would be required.

Second, our model assumes pure competition. If, in contrast, industries producing fossil fuels already exercise considerable market power before the carbon tax is introduced, they may have already enjoyed much or all of the potential rents. In this case, CO_2 abatement policies may be unable to generate significant additional rents, and thus the opportunities for achieving equity-value neutrality at low cost may be considerably more limited.

Third, in our model, capital is the only factor that is not perfectly mobile. To the extent that labor also is imperfectly mobile, there can be serious transition losses from policy changes, and such losses may have significant political consequences. Overcoming barriers to political feasibility requires attention to these losses.

Finally, it is worth emphasizing that the forces underlying the political feasibility of CO_2 abatement policies are complex. Protecting the profits of key energy industries may not be sufficient to bring about political feasibility.

Notwithstanding these qualifications, the present analysis offers significant hope that some major distributional concerns related to CO_2 abatement policies can be eliminated at low cost. The price tag on removing key political obstacles to domestic CO_2 abatement policies may be lower than previously thought.

References

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

Bovenberg, A. Lans, and Ruud A. de Mooij, 1994. Environmental Levies and Distortionary Taxation. *American Economic Review* 84(4):1085-9.

Bovenberg, A. Lans, and Lawrence H. Goulder, 1996. Optimal Environmental Taxation in the Presence of Other Taxes: General Equilibrium Analyses. *American Economic Review* 86(4):985-1000.

———, 1997. Costs of Environmentally Motivated Taxes in the Presence of Other Taxes: General Equilibrium Analyses, *National Tax Journal*.

———, 2000. Environmental Taxation and Regulation in a Second-Best Setting, In *Handbook of Public Economics,* A. Auerbach and M. Feldstein, eds., second edition, Amsterdam: North-Holland, forthcoming.

Buchanan, James M. and Gordon Tullock, 1975. Polluters Profits and Political Response: Direct Controls versus Taxes. *American Economic Review* 65:139-147.

Bull, N., K. Hassett, and G. Metcalf, 1994. Who Pays Broad-Based Energy Taxes? Computing Lifetime and Regional Incidence. *The Energy Journal* 15:145-164.

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

Farrow, Scott, 1999. The Duality of Taxes and Tradeable Permits: A Survey with Applications in Central and Eastern Europe. *Environmental and Development Economics* 4:519-535.

Felder, Stefan, and Reto Schleiniger, 1999. Environmental Tax Reform: Efficiency and Political Feasibility. Working paper, Faculty of Economics, Institute for Social Medicine, Otto-Von-Guericke-Universität Magdeburg, January.

Fullerton, Don and Gilbert Metcalf, 1998. Environmental Controls, Scarcity Rents, and Pre-Existing Distortions, Working paper, University of Texas at Austin.

Gaskins, Darius, and John Weyant, eds., 1996. *Reducing Global Carbon Dioxide Emissions: Costs and Policy Options*. Energy Modeling Forum, Stanford University, Stanford, Calif.

Goulder, Lawrence H., 1994. Energy Taxes: Traditional Efficiency Effects and Environmental Implications. In *Tax Policy and the Economy 8*, James M. Poterba, ed. Cambridge MA: MIT Press.

———, 1995a. Effects of Carbon Taxes in an Economy with Prior Tax Distortions: An Intertemporal General Equilibrium Analysis. *Journal of Environmental Economics and Management*.

———, 1995b. Environmental Taxation and the 'Double Dividend:' A Reader's Guide. *International Tax and Public Finance* 2(2):157-183.

Goulder, Lawrence H., Ian W. H. Parry, and Dallas Burtraw, 1997. Revenue-Raising vs. Other Approaches to Environmental Protection: The Critical Significance of Pre-Existing Tax Distortions. *RAND Journal of Economics*, Winter.

Goulder, Lawrence H., and Philippe Thalmann, 1993. Approaches to Efficient Capital Taxation: Leveling the Playing Field vs. Living by the Golden Rule. *Journal of Public Economics* 169-186.

Hall, Robert, 1988. Intertemporal Substitution in Consumption. *Journal of Political Economy* 96(2):339-357.

Jorgenson, Dale W., Daniel T. Slesnick and Peter J. Wilcoxen, 1992. Carbon Taxes and Economic Welfare, *Brookings Papers on Economic Activity: Microeconomics 1992.*

Jorgenson, Dale W. and Peter J. Wilcoxen, 1996. Reducing U.S. Carbon Emissions: An Econometric General Equilibrium Assessment. In *Reducing Global Carbon Dioxide Emissions: Costs and Policy Options*, Darius Gaskins and John Weyant, eds. Energy Modeling Forum, Stanford University, Stanford, Calif.

Jorgenson, Dale W., and K. Y. Yun, 1991. *Tax Reform and the Cost of Capital*. Oxford: Oxford University Press.

Keohane, Revesz, and Stavins, 1998. The Choice of Regulatory Instruments in Environmental Policy. *The Harvard Environmental Law Review* 22(2):313-367.

Lawrance, Emily, 1991. Poverty and the Rate of Time Preference: Evidence from Panel Data. *Journal of Political Economy* 99(1):54-77.

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

Metcalf, Gilbert E., 1998. A Distributional Analysis of an Environmental Tax Shift, NBER Working Paper No. 6546, Cambridge, Mass., May.

Olson, Mancur, 1965. *The Logic of Collective Action.* Cambridge, Mass.: Harvard University Press.

Parry, Ian W. H., 1995. Pollution Taxes and Revenue Recycling. *Journal of Environmental Economics and Management* 29:S64-S77.

———, 1997. Environmental Taxes and Quotas in the Presence of Distorting Taxes in Factor Markets. *Resource and Energy Economics* 19:203-220.

Parry, Ian W. H., and A. Bento, 2000. Tax Deductions, Environmental Policy, and the Double Dividend Hypothesis. *Journal of Environmental Economics and Management* 39(1):67-96.

Parry, Ian W. H., Roberton C. Williams III, and Lawrence H. Goulder, 1999. When Can CO_2 Abatement Policies Increase Welfare? The Fundamental Role of Pre-Existing Factor Market Distortions. *Journal of Environmental Economics and Management* 37:52-84, January.

Pezzey, John, 1992. The Symmetry between Controlling Pollution by Price and Controlling It by Quantity. *Canadian Journal of Economics* 25(4):983-91.

Poterba, James M., 1991. Tax Policy toward Global Warming: On Designing a Carbon Tax. In *Economic Policy Responses to Global Warming*, R. Dornbusch and J. Poterba, eds. Cambridge, Mass.: MIT Press.

Poterba, James M., and Lawrence H. Summers, 1985. The Economic Effects of Dividend Taxation. In *Recent Advances in Corporate Finance*, E. Altman and M. Subramanyam, eds. Homewood, Ill: Irwin.

Russek, Frank S., 1996. Labor Supply and Taxes. Working paper, Macroeconomic Analysis Division, Congressional Budget Office, Washington, D.C., January.

Schillo, Bruce, Linda Giannarelli, David Kelly, Steve Swanson, and Peter Wilcoxen, 1996. The Distributional Impacts of a Carbon Tax. In *Reducing Global Carbon Dioxide Emissions: Costs and Policy Options*, D. Gaskins and J. Weyant, eds. Energy Modeling Forum, Stanford University, Stanford, Calif.

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

Vollebergh, Herman R. J., Jan L. de Vries and Paul R. Koutstaal, 1997. Hybrid Carbon Incentive Mechanisms and Political Acceptability. *Environmental and Resource Economics* 9:43-63.

Williamson, Oliver E., 1996. The Politics and Economics of Redistribution and Efficiency. In *The Mechanisms of Governance.* Oxford, U.K.: Oxford University Press.

Appendix: Structure and Parameter Values of the Numerical Model

I. Structure

A. Production

1. Technology

General Features

Equations (1)-(3) of the main text indicated the nested production structure. The second term in equation (1) represents the loss of output associated with installing new capital (or dismantling existing capital). Per-unit adjustment costs, N, are given by:

$$\phi(I/K) = \frac{(\xi/2)(I/K-\delta)^2}{I/K} \qquad \text{(A-1)}$$

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 production function for the oil & gas industry (equation (4)) contains the additional element γ_g, which is a decreasing function of cumulative oil & gas extraction:

$$\gamma_{g,t} = \varepsilon_1\left[1-(Z_1/\bar{Z})^{\varepsilon_2}\right] \qquad \text{(A-2)}$$

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

The following equation of motion specifies the evolution of Z_t:

$$Z_{t+1} = Z_t + X_t \qquad \text{(A-3)}$$

Equation (A-2) implies that the production function for oil and gas shifts downward as cumulative oil & gas extraction increases. This addresses the fact that as reserves are depleted, remaining reserves become more difficult to extract and require more inputs per unit of extraction.

2. Behavior of Firms

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

The equation of motion for the firm=s capital stock is:

$$K_{s+1} = (1-\delta)K_s + I_s \tag{A-4}$$

B. Household Behavior

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

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

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

$$C_s = \left[\tilde{C}_s^{\frac{\upsilon-1}{\upsilon}} + \alpha_c^{\frac{1}{\upsilon}}\ \ell_s^{\frac{\upsilon-1}{\upsilon}}\right]^{\frac{\upsilon}{\upsilon-1}} \tag{A-6}$$

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

The variable $\tilde{C}$ in (A-6) is a Cobb-Douglas aggregate of 17 composite consumer goods:

$$\tilde{C}_s = \prod_{i=1}^{17}\overline{C}_{i,s}^{\alpha_{\tilde{C},i}} \tag{A-7}$$

where the $\alpha_{\tilde{C},i}\ (i=1,...17)$ are parameters. The 17 types of consumer goods were shown in Table 1 of the main text.

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

$$\overline{C} = \gamma_{\overline{C}} \left[\alpha_{\overline{C}} CD^{\rho_{\overline{C}}} + (1-\alpha_{\overline{C}}) CF^{\rho_{\overline{C}}} \right]^{1/\rho_{\overline{C}}} \tag{A-8}$$

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*:

$$WK_{t+1} - WK_t = \bar{r}_t WK_t + YL_t + GT_t - \tilde{p}_t \tilde{C}_t \tag{A-9}$$

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

C. Government Behavior

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

1. Components of Government Expenditure

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

$$G_t = GP_t + GI_t + GT_t \tag{A-10}$$

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

$$GP_t^P / P_{GP,t}^P = GP_t^R / P_{GP,t}^R \tag{A-11a}$$

$$GI_t^P / P_{GI,t}^P = GI_t^R / P_{GI,t}^R \tag{A-11b}$$

$$GT_t^P \;/\; P_{GT,t}^{\;\;P} = GT_t^R \;/\; P_{GT,t}^{\;\;R} \qquad \text{(A-11c)}$$

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

2. Allocation of Government Purchases

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

$$\alpha_{G,i} GP = GPX_i\, p_i \qquad i = 1,...,13 \qquad \text{(A-12)}$$

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:

$$P_{GP} = \prod_{i=1}^{13} p_i^{\alpha_{G,i}} \qquad \text{(A-13)}$$

II. Parameter Values

A. Elasticities of Substitution in Production

Parameter:	σ_f	σ_{g1}	σ_{g2}	σ_E	σ_M	σ_x
Substitution margin:	g_1-g_2	L-K	E-M	E components	M components	dom-foreign inputs
<u>Producing Industry:</u>						
1. Agric. & Non-coal Mining	0.7	0.68	0.7	1.45	0.6	2.31
2. Coal Mining	0.7	0.80	0.7	1.08	0.6	1.14
3. Oil & Gas Extraction	0.7	0.82	0.7	1.04	0.6	(infinite)
4. Synthetic Fuels	0.7	0.82	0.7	1.04	0.6	(not traded)

5. Petroleum Refining	0.7	0.74	0.7	1.04	0.6	2.21
6. Electric Utilities	0.7	0.81	0.7	0.97	0.6	1.0
7. Gas Utilities	0.7	0.96	0.7	1.04	0.6	1.0
8. Construction	0.7	0.95	0.7	1.04	0.6	1.0
9. Metals & Machinery	0.7	0.91	0.7	1.21	0.6	2.74
10. Motor Vehicles	0.7	0.80	0.7	1.04	0.6	1.14
11. Misc. Manufacturing	0.7	0.94	0.7	1.08	0.6	2.74
12. Services (except housing)	0.7	0.98	0.7	1.07	0.6	1.0
13. Housing Services	0.7	0.80	0.7	1.81	0.6	(not traded)

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

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

Note: This function is parameterized so that γ_f approaches 0 as Z approaches $\bar{Z}$ (see equation (8)). The value of $\bar{Z}$ is 450 billion barrels (about 100 times the 1990 production of oil and gas, where gas is measured in barrel-equivalents.) $\bar{Z}$ is based on estimates from Masters *et al*. (1987). Investment in new oil and gas capital ceases to be profitable before reserves are depleted: the values of ε_1 and ε_2 imply that, in the baseline scenario, oil and gas investment becomes zero in the year 2050.

C. Utility Function Parameters

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