NBER WORKING PAPER SERIES

WHEN CAN CARBON ABATEMENT POLICIES INCREASE WELFARE? THE FUNDAMENTAL ROLE OF DISTORTED FACTOR MARKETS

Ian W. H. Parry
Roberton C. Williams III
Lawrence H. Goulder

Working Paper 5967

NATIONAL BUREAU OF ECONOMIC RESEARCH
1050 Massachusetts Avenue
Cambridge, MA 02138
March 1997

The authors gratefully acknowledge the helpful comments and suggestions of Dallas Burtraw. We also thank the National Science Foundation (Grant SBR-9613458) for financial support. This paper is part of NBER's research program in Public Economics. Any opinions expressed are those of the authors and not those of the National Bureau of Economic Research.

When Can Carbon Abatement Policies Increase
Welfare? The Fundamental Role of Distorted
Factor Markets
Ian W. H. Parry, Roberton C. Williams III
and Lawrence H. Goulder
NBER Working Paper No. 5967
March 1997
JEL Nos. L51, H23, D52
Public Economics

ABSTRACT

This paper employs analytical and numerical general equilibrium models to assess the efficiency impacts of two policies to reduce U.S. carbon emissions -- a carbon tax and a carbon quota -- taking into account the interactions between these policies and pre-existing tax distortions in factor markets. We show that tax interactions significantly raise the costs of both policies relative to what they would be in a first-best setting. In addition, we show that these interactions put the carbon quota at a significant efficiency disadvantage relative to the carbon tax: the costs of reducing emissions by 10 percent are more than three times higher under the carbon quota than under the carbon tax. This disadvantage reflects the inability of the quota policy to generate revenue that can be used to reduce pre-existing distortionary taxes.

Indeed, second-best considerations severely limit the potential of a carbon quota to generate overall efficiency gains. Under our central estimates, a non-auctioned carbon quota (or set of grandfathered carbon emissions permits) cannot increase efficiency unless the marginal benefits from avoided future climate change are at least $25 per ton of carbon abatement. Most estimates of these marginal environmental benefits are well below $25 per ton. Thus, our analysis suggests that any carbon abatement by way of a non-auctioned quota will be efficiency-reducing. In contrast, a revenue-neutral carbon tax is found to be efficiency-improving so long as marginal environmental benefits are positive.

Ian W. H. Parry
Resources for the Future
1616 P Street, NW
Washington, DC 20036-1400

Roberton C. Williams III
Department of Economics
Stanford University
Stanford, CA 94305-6072

Lawrence H. Goulder
Department of Economics
Stanford University
Stanford, CA 94305-6072
and NBER
GOULDER@LELAND.STANFORD.EDU

When Can Carbon Abatement Policies Increase Welfare? The Fundamental Role of Distorted Factor Markets

I. Introduction

The prospect of global climate change from the continued atmospheric accumulation of carbon dioxide (CO_2) and other greenhouse gases has prompted analysts to consider a number of policy options for mitigating emissions of CO_2. This paper examines the efficiency implications of some potential U.S. policy options. The crucial point of departure from previous studies of CO_2 abatement policies[1] is the present paper's focus on connections between the efficiency impacts of CO_2 abatement policies and pre-existing tax distortions. The motivation for this focus stems from recent studies of environmental regulation in a second-best setting. These papers[2] have shown that the costs of environmental regulations

[1] See for example Nordhaus (1994), Manne and Richels (1992) and Jorgenson and Wilcoxen (1995).

are higher in a world with pre-existing factor market distortions than they would be in the absence of such distortions. The higher costs reflect two effects. First, by raising the costs of production in the affected industry, environmental regulations give rise to higher prices of output in that industry and thus a higher price of consumption goods in general. This, in turn, implies a lower real wage and a reduction in labor supply. If there are pre-existing taxes on labor, the reduction in labor supply has a first-order -- that is, non-incremental -- efficiency cost, which has been termed the *tax-interaction effect.*

Second, under some environmental policies, another effect can partially offset the tax-interaction effect. Pollution taxes and other environmental policies that raise revenue allow that revenue to be recycled through cuts in the marginal rates of pre-existing distortionary taxes. The lower marginal rates reduce the distortionary costs associated with these taxes, thus providing an efficiency gain. This is the *revenue-recycling effect.*

These considerations are highly relevant to the choice among alternative instruments for reducing emissions of CO_2. The most frequently cited instruments for dealing with CO_2 emissions are carbon taxes, carbon quotas, and marketable carbon emissions permits.[3] All of these policies generate a (costly) tax-interaction effect, but only some of them can exploit the offsetting revenue-recycling effect. Carbon taxes with revenues devoted to marginal tax rate cuts enjoy the revenue-recycling effect; in contrast, carbon quotas and grandfathered (non-auctioned) carbon permits raise no revenue and are therefore unable to take advantage of this effect. As shown later in this paper, the inability to make use of the revenue-recycling effect puts the latter policies at an efficiency disadvantage relative to the former policies.[4] Indeed, the absence of the revenue-recycling effect may make it impossible for the latter policies to generate efficiency gains, no matter what the level of CO_2 abatement![5]

---

[2] See for example Bovenberg and de Mooij (1994), Bovenberg and van der Ploeg (1994), Goulder (1995), Goulder *et al.* (1996), Parry (1995, 1996), and (in a somewhat different context) Browning (1996).

[3] See for example, Tietenberg (1991), Poterba (1993), Hoel (1991), Oates and Portney (1992).

[4] Some earlier analyses of carbon taxes have recognized the potential importance of the revenue-recycling effect. Repetto et al. (1992) and Nordhaus (1993a) indicate that the costs of a carbon tax are much lower when revenues are returned through cuts in marginal tax rates than when revenues are returned lump-sum. These studies make a valid point about the relative costs of policies that do or do not exploit the revenue-recycling effect. However, the absolute costs of carbon tax policies are not fully captured in these studies because they do not integrate pre-existing taxes in the analysis and thus they cannot account for the tax-interaction effect. The presence or absence of the revenue-recycling effect can be linked to whether policy-generated rents are captured by the government and returned to taxpayers (as in the case of a pollution tax) or instead left in producers' hands (as in the case of pollution quotas or freely offered pollution permits). On this see Fullerton and Metcalf (1996).

[5] The impossibility of efficiency gains was demonstrated through numerical simulations performed by Bovenberg and Goulder (1996a), who found that any carbon abatement through a carbon tax policy that recycles the revenues in lump-sum fashion (and thus does not exploit the revenue-recycling effect) will be efficiency-

In this paper we concentrate on two policies: a carbon tax with revenues devoted to cuts in marginal tax rates, and a non-auctioned carbon emissions quota. The crucial difference between these policies is the presence or absence of the revenue-recycling effect.[6] Using analytical and numerically-solved general equilibrium models, we assess the efficiency effects of these policies in a second-best setting with pre-existing taxes on labor. To our knowledge, this is the first study to compare these policies in a second-best setting.

In the analytical model of this paper, we derive formulas indicating that the efficiency costs associated with the tax-interaction effect can be quite large relative to the direct costs of carbon abatement considered in typical policy models. The numerical simulations in this paper show that the absence of the revenue-recycling effect makes the quota policy significantly more costly than the carbon tax. The marginal costs of emissions abatement begin at approximately $25 per ton under the quota, as compared with $0 per ton under the revenue-neutral carbon tax. The quota's minimal marginal cost of $25 per ton has some powerful implications for policy. Estimated marginal benefits from carbon abatement typically are below $25 per ton (see, for example, Nordhaus (1991a, 1994)). If marginal benefits are indeed below this value, then only the carbon tax can produce an efficiency improvement in our model; a carbon quota (or set of grandfathered tradable permits) necessarily reduces efficiency, and potentially by a large amount. Clearly, there is enormous uncertainty as to the potential gains from reducing carbon emissions; as discussed below, under more extreme scenarios for climate change, benefit estimates can exceed $25 per ton. Yet even in this case, there is still a very strong efficiency argument for preferring a carbon tax over a quota. Our numerical results indicate, for example, that a 5 percent reduction in carbon emissions is seven times more costly under a quota than a carbon tax; a 15 percent reduction is three times more costly.

These results are consistent with -- but perhaps more striking than -- the results obtained by Goulder *et. al* (1996) in a study of the sulfur dioxide (SO_2) permit program under the 1990 Clean Air Act Amendments. While the present study casts doubt on the possibility of efficiency gains through quotas or non-auctioned permits, the study by Goulder *et al.* estimates that, under central estimates for marginal environmental benefits from SO_2 reductions, the system of grandfathered (freely-allocated) SO_2 permits is

---

reducing, if the marginal environmental benefits from carbon abatement do not exceed a strictly positive threshold value. This restriction on environmental benefits does not apply to carbon tax policies involving recycling through cuts in marginal rates.

[6] Our analysis abstracts from some other issues that could introduce other differences in efficiency impacts across the two policies. We do not consider, for example, heterogeneity in the abatement costs among producers within a given industry. If regulators have imperfect information about these costs, in general they will be unable to achieve production efficiency in the allocation of quotas: marginal costs of abatement are likely to differ across producers. Under these circumstances a carbon tax has an advantage over non-tradeable quotas.

efficiency-improving. Quotas or non-auctioned permits have a greater chance at yielding efficiency gains in the SO_2 case because the central estimates for marginal environmental benefits are relatively high (compared with marginal production costs) in this case. In contrast, central estimates for marginal environmental benefits from CO_2 reductions are fairly low relative to marginal production cost.

The rest of the paper is organized as follows. Section II develops and applies our analytical model. This model is fairly simple, containing two final goods, a clean and dirty intermediate input, and one primary factor -- labor. In Section III, we describe an extended version of the original model that distinguishes different fossil fuels and identifies different non-fuel intermediate goods. Section IV applies the extended model, which is solved numerically. The numerical solution method enables us to consider large (non-incremental) policy changes, and this turns out to be relevant to the relative costs of the different policies. Section V discusses the sensitivity of the results to alternative values for important parameters. Section VI concludes and discusses some limitations of the analysis.

II. The Analytical Model

Here we present an analytically tractable model that reveals the efficiency impacts of carbon taxes and non-auctioned carbon quotas in a second-best setting. This model shares some features of analytical models developed by Parry (1995, 1996) and Goulder *et al.* (1996). However, the present model is distinct from Parry's in deriving results explicitly from utility maximization. It differs from the model in Goulder *et al.* in incorporating a more flexible relationship between the levels of pollution emissions and the level of output produced by the regulated industry.

A. Model Assumptions

A representative household allocates its time endowment ($\overline{L}$) between labor supply (L) and leisure, or non-market time ($l = \overline{L} - L$). It also purchases two consumption goods, C_F and C_N. C_F represents an aggregate of final output from industries that use fossil fuels (F) intensively, and C_N is an aggregate of all other consumption goods. We ignore capital accumulation in the economy, which means that just focus on behavior in one period, rather than solving a dynamic problem. The household utility function is given by:

(II.1) $u(C_F, C_N, l) - \phi(F)$

where $u(.)$, utility from non-environmental goods, is continuous and quasi-concave. ϕ is disutility from current, man-made additions to the stock of CO_2 in the atmosphere, caused by (combustion of) fossil fuels. These damages represent the present discounted value of the expected utility losses due to induced changes in future global climate.[7] The separability in (II.1) implies that future climatic change does not affect the current tradeoffs between consumption goods and leisure.

C_F and C_N are produced under constant returns to scale. The production functions are given by:

(II.2) $$C_F = C_F(L_F, F_F, N_F); \quad C_N = C_N(L_N, F_N, N_N);$$

where N is a "clean" (non-polluting) intermediate good. Labor is the only input used to produce F and N, and the marginal product of labor in each of these intermediate goods industries is taken to be constant. We assume that production in all four industries is competitive. The use of fossil fuels in the C_F and C_N industries leads to a proportional amount of carbon emissions. This is a standard assumption in energy models: unlike the case of SO_2, there are no economically viable scrubber technologies to reduce CO_2 emissions per unit of fuel input. Aggregate fossil fuel use is:

(II.3) $$F = F_F + F_N$$

We choose units to imply one ton of carbon per unit of F.[8]

Finally, we assume that the government has an exogenous spending requirement of G, which is returned to households as a lump sum transfer. The government also levies a proportional tax of t_L on labor income, and regulates carbon emissions using either a tax or a non-auctioned quota. The government budget is assumed to balance, and therefore any revenue consequences from regulation are neutralized by adjusting the rate of t_L.

Denoting the demand prices of C_F and C_N by p_F and p_N, and normalizing the gross wage to unity, the household budget constraint is given by:

(II.4) $$p_F C_F + p_N C_N = (1 - t_L)L + G$$

Households choose C_F, C_N and L to maximize utility (II.1) subject to (II.4) and the time endowment. From the resulting first-order conditions and the household budget constraint, we obtain the (implicit) uncompensated demand and labor supply functions:

(II.5) $$C_F(p_F, p_N, t_L); \quad C_N(p_F, p_N, t_L); \quad L(p_F, p_N, t_L)$$

---

[7] Although we focus on the costs to the U.S. of carbon abatement policies, we use environmental benefit estimates for the world economy. Therefore, our analysis is from the perspective of a "world government," choosing carbon abatement policies for the U.S.

[8] We assume there is no internalization of the carbon externality by Coasian bargaining, altruism, etc.

Substituting these into (II.6) gives the indirect utility function:

(II.6) $V = v(p_F, p_N, t_L) - \phi(F)$

From Roy's Identity:

(II.7) $$\frac{\partial v}{\partial p_F} = -\lambda C_F; \quad \frac{\partial v}{\partial p_N} = -\lambda C_N; \quad \frac{\partial v}{\partial t_L} = -\lambda L$$

where the Lagrange multiplier λ is the marginal utility of income.

Consider a policy -- either a carbon tax or quota -- that creates a wedge of τ_F per unit between the demand and supply price of fossil fuels. Under constant returns to scale and competition, the general equilibrium increase in final product prices[9] that results from an incremental increase in τ_F is (see Appendix A):

(II.8) $$\frac{dp_F}{d\tau_F} = \frac{F_F}{C_F}; \quad \frac{dp_N}{d\tau_F} = \frac{F_N}{C_N}$$

that is, the ratio of fossil fuel input to final output. Finally, the equilibrium quantity of fossil fuels can be expressed as a function of the policy variables (see Appendix A):

(II.9) $F(\tau_F, t_L) = F_F(\tau_F, t_L) + F_N(\tau_F, t_L)$

where $dF/d\tau_F < 0$. These functions summarize the effect of changes in τ_F on fossil fuel use through: (a) the substitution effect, that is, the replacement of labor and N for fossil fuels in production of C_F and C_N; (b) the output effect, that is, the change in derived demand for fossil fuels from changes in the quantities of C_F and C_N caused by the effect of τ_F on final product prices. Changes in t_L affect fossil fuels through their effect on the quantity of final consumption goods, in response to a change in the relative price of leisure.

B. Carbon Tax

Suppose τ_F^t represents a tax per unit paid by firms purchasing fossil fuels. Given the fixed proportions between fuel use and emissions, this is equivalent to a tax of τ_F^t per ton on carbon emissions. In this case, the government budget constraint is:

(II.10) $\tau_F^t F + t_L L = G$

---

[9] That is, the increase that applies when all prices and quantities are treated as variable.

that is, the sum of carbon tax revenues and labor tax revenues equals government spending. Consider a balanced-budget policy change involving an incremental change in τ'_F and t_L. Totally differentiating (II.10) holding G constant and using (II.5) and (II.9),[10] we can express the resulting change in t_L as:

$$\text{(II.11)}\quad \frac{dt_L}{d\tau'_F} = -\frac{F + \tau'_F \dfrac{dF}{d\tau'_F} + t_L \dfrac{\partial L}{\partial \tau'_F}}{L + t_L \dfrac{\partial L}{\partial t_L}}$$

We define:

$$\text{(II.12)}\quad Z = \frac{-t_L \dfrac{\partial L}{\partial t_L}}{L + t_L \dfrac{\partial L}{\partial t_L}}$$

This is the partial equilibrium efficiency cost from raising an additional dollar of labor tax revenue, or marginal welfare cost of taxation. The numerator is the welfare loss from an incremental increase in t_L; it is the wedge between the gross wage (equal to the value marginal product of labor) and net wage (equal to the marginal social cost of labor in terms of foregone leisure), multiplied by the reduction in labor supply. The denominator is marginal labor tax revenue (from differentiating $t_L L$).

The welfare effect of the policy change is obtained by differentiating the utility function (II.6) with respect to τ'_F, allowing t_L to vary. This gives:

$$\frac{dV}{d\tau'_F} = \frac{\partial v}{\partial p_F}\frac{dp_F}{d\tau'_F} + \frac{\partial v}{\partial p_N}\frac{dp_N}{d\tau'_F} + \frac{\partial v}{\partial t_L}\frac{dt_L}{d\tau'_F} - \phi'(F)\frac{dF}{d\tau'_F}$$

Substituting (II.3), (II.7), (II.8), (II.11) and (II.12) gives:

$$\text{(II.13)}\quad \frac{1}{\lambda}\frac{dV}{d\tau'_F} = \underbrace{\left(\frac{\phi'}{\lambda} - \tau'_F\right)\left(-\frac{dF}{d\tau'_F}\right)}_{dW^P} + \underbrace{Z\left\{F + \tau'_F \frac{dF}{d\tau'_F}\right\}}_{\partial W^R} - \underbrace{(1+Z)t_L\left(-\frac{\partial L}{\partial \tau'_F}\right)}_{\partial W^I}$$

---

[10] This gives

$$\left\{F + \tau'_F \frac{\partial F}{\partial \tau'_F} + t_L \frac{\partial L}{\partial \tau'_F}\right\} d\tau'_F + \left\{\tau'_F \frac{\partial F}{\partial t_L} + t_L \frac{\partial L}{\partial t_L} + L\right\} dt_L = 0$$

Substituting

$$\frac{dF}{d\tau'_F} = \frac{\partial F}{\partial \tau'_F} + \frac{\partial F}{\partial t_L}\frac{dt_L}{d\tau'_F}$$

gives (II.11).

Thus, the welfare effect (in dollars) can be separated into three terms. The first, dW^P, is the effect within the fossil fuel market, or *primary welfare gain*. This is the overall incremental reduction in fossil fuel multiplied by the gap between the marginal social cost ($q_F + \phi'/\lambda$), and marginal social benefit or demand price ($q_F + \tau^{\prime}_F$) of fossil fuel (where q_F is the supply price of F). The second, ∂W^R, is the (marginal) *revenue-recycling effect*, or efficiency gain from using additional carbon tax revenues to reduce the labor tax. This equals marginal carbon tax revenue multiplied by the marginal welfare cost of taxation. The third, ∂W^I, is the (marginal) *tax-interaction effect*. This consists of: (i) $t_L(-\partial L/\partial \tau^{\prime}_F)$, the welfare loss from the reduction in labor supply, caused by the effect of $\tau^{\prime}_F$ on increasing final goods prices and thereby reducing the real household wage; plus (ii) $Zt_L(-\partial L/\partial \tau^{\prime}_F)$, the resulting reduction in labor tax revenue multiplied by the marginal welfare cost of taxation.

The tax-interaction effect can be expressed as (see Appendix A):

$$\text{(II.14)} \quad \partial W^I = \mu Z F; \qquad \mu = \frac{h_F \eta^c_{FI} + h_N \eta^c_{NI} - \eta_{LI}}{s_F \eta^c_{FI} + s_N \eta^c_{NI} - \eta_{LI}}$$

where η^c_{FI} and η^c_{NI} are the compensated elasticity of demand for C_F and C_N with respect to the price of leisure; η_{LI} is the income elasticity of labor supply; h_F and h_N are the shares of fossil fuels in the C_F and C_N sectors (h_F + h_N = 1); and s_F and s_N are the shares of C_F and C_N in the value of total output ($s_F + s_N = 1$). μ is a measure of the degree of substitution between fossil-fuel-intensive consumption and leisure, relative to that between aggregate consumption and leisure. In general, both η^c_{FI} and η^c_{NI} are positive, because from the household budget constraint (II.4), aggregate consumption and leisure are inversely related. If C_F and C_N are equal substitutes for leisure (that is, $\eta^c_{FI} = \eta^c_{NI}$) then $\mu = 1$. In this case (comparing ∂W^I -- that is, μZF -- with ∂W^R), the tax-interaction effect equals the revenue-recycling effect when $\tau^{\prime}_F = 0$, but exceeds it when $\tau^{\prime}_F > 0$ (since $dF/d\tau^{\prime}_F < 0$). Therefore, taking into account the pre-existing labor tax raises the slope, but does not affect the intercept (equal to zero), of the marginal cost of carbon emissions reduction.[11] Since C_F is carbon-intensive, the share of fossil fuels used

[11] This is the same qualitative result as that for a revenue-neutral pollution tax on a final good (Goulder *et al.* (1996)). Note that, despite substitution of labor for fossil fuels in production of final goods, the aggregate effect on labor supply is still negative. This is because, given our assumptions of constant returns to scale and that labor is the only primary factor input, the aggregate demand for labor is perfectly elastic and the quantity of labor is determined purely by the real household wage (that is, the non-substitution theorem is satisfied (Varian (1992), pp. 354). Any policy which causes final goods prices to increase, and hence the real wage to fall, will therefore reduce labor supply.

in the C_F sector exceeds the share of C_F in total production ($h_F > s_F$). Therefore, if C_F were a stronger (weaker) substitute for leisure than Y (that is η^c_{Fl} is greater (less) than η^c_{Ml}), then μ would be greater (less) than 1, and the marginal cost of emissions reduction would have a positive (negative) intercept.

C. Carbon Quota

Suppose instead that carbon emissions are reduced by a quota (or non-auctioned permits). We define this quota by τ^q_F, the wedge it creates between the demand and supply price of fossil fuels (τ^q_F can also be regarded as a "virtual tax"). τ^q_F produces quota rents of $\pi = \tau^q_F F$ (since the price exceeds marginal private cost by τ^q_F for each unit of F), which accrue to households, who own firms (in their role as shareholders). We assume that this rent income is taxed at the same rate as labor income (see below). Therefore the government budget constraint is now:

(II.10′) $t_L(\pi + L) = G$

If instead, rent income were taxed at 100%, or the quotas were sold by the government at a price of τ^q_F, then the carbon quota would be equivalent to the carbon tax in this model.

Following the analogous procedure to before, we can express the welfare change from a marginal tightening of the quota (that is an increase in τ^q_F) as (see Appendix):

$$\text{(II.13′)}\quad \frac{1}{\lambda}\frac{dV}{d\tau^q_F} = \underbrace{\left(\frac{\phi'}{\lambda} - \tau^q_F\right)\left(-\frac{dF}{d\tau^q_F}\right)}_{dW^P} + \underbrace{t_L Z'\left\{F + \tau^q_F \frac{dF}{d\tau^q_F}\right\}}_{\partial W^R} - \underbrace{(1+Z')t_L\left(-\frac{\partial L}{\partial \tau^q_F}\right)}_{\partial W^I}$$

where

$$\text{(II.12′)}\quad Z' = \frac{-t_L \dfrac{\partial L}{\partial t_L}}{L + t_L \dfrac{\partial L}{\partial t_L} + \pi}$$

Comparing (II.13′) with (II.13), one will observe that the quota causes the same primary welfare effect as the tax. It also induces the analogous tax-interaction effect, since it increases the price of consumption goods in the same way as the carbon tax. The key difference is that it only produces an indirect revenue-recycling effect, through the taxation of quota rents, and this is equal to fraction t_L of the revenue-recycling effect under the carbon tax. Therefore when C_F and C_N are equal substitutes for leisure, the revenue-recycling effect will only partially offset the tax-interaction effect for the first unit reduction in carbon; hence the marginal cost of emissions reduction will now have a positive intercept. If the environmental benefits from carbon abatement are below this intercept, then a carbon quota cannot increase welfare.[12]

The formula for this threshold benefit level ($\overline{B}$), when C_F and C_N are equal substitutes for leisure, can be expressed (see the Appendix):

$$\text{(II.15)} \quad \overline{B} = Z''(1-t_L)\frac{d\tau_F^q}{dF}F^0$$

where

$$\text{(II.12'')} \quad Z'' = \frac{\frac{t_L}{1-t_L}\varepsilon^c}{1-\frac{t_L}{1-t_L}\varepsilon^u}$$

and ε^c and ε^u are the compensated and uncompensated labor supply elasticity respectively. Z'' is an alternative, empirically useful expression for the marginal welfare cost of labor taxation, that takes into account general equilibrium income effects.[13] In the numerical model below, the benchmark parameter values we use for t_L, ε^c, ε^u are 0.4, 0.5, and 0.15, implying $Z'' = 0.37$. In addition, $d\tau_F^q / dF$ = \$0.085 per million tons, and initial emissions are 1749 million tons. Substituting these values in (II.12''), *the analytical model predicts that the quota cannot increase welfare unless environmental benefits exceed \$33 per ton.*

III. The Numerical Model

The simplicity of the model in Section II lends to transparency of results, but it also limits the model's ability to gauge the empirical importance of the second-best issues of interest. In this section we introduce some extensions to the original analysis to gain a better sense of the significance of these issues. We extend the analysis in two main ways. First, we consider the effects of "large" policy changes,

---

[12] The marginal welfare cost of taxation in (II.12') is slightly different than in (II.12), because increasing t_L now affects tax revenues from rent as well as labor income.

[13] That is, when the dollar of revenue raised is returned to households as a lump sum transfer. (The formulas in (II.12) and II.(12') are partial equilibrium and do not take into account this income effect, and therefore depend only on uncompensated coefficients). For a comprehensive discussion of the formula in (II.12'') see Browning (1987).

that is, policy changes that produce greater than incremental reductions in emissions. As will be shown below, the relative (as well as absolute) costs of carbon taxes and quotas depend on the extent of carbon abatement achieved through these policies. In order to consider large changes, we must specify functional forms for the utility and production functions and solve the model numerically. [14] The second extension is to disaggregate further the intermediate goods in production. We disaggregate fossil fuels into oil, coal, and natural gas in order to allow for emissions reductions not only through substitution between fossil fuels (collectively) and other goods, but also through substitution between high-carbon fossil fuels such as coal and low-carbon fossil fuels such as natural gas. Non-fuel intermediate goods are also disaggregated, recognizing that the production of certain goods such as transportation is very energy-intensive, and thus that carbon abatement policies will have varying effects on different non-fuel industries. This disaggregation allows us to perform a rich sensitivity analysis, which is not possible in the analytical model.

Subsection A describes the behavioral assumptions for households, firms, and the government, and the equilibrium conditions of the extended model. The complete set of equations for the model is presented in Appendix B. Subsection B describes the calibration of the model.

A. Model Structure

The extended model has the following structure. There are six intermediate goods. Fossil fuels are divided into three goods: natural gas (F_N); coal (F_C); and petroleum (F_P). Non-fuel intermediates divide into three goods: an aggregate of fuel-intensive intermediate goods (I); electricity (E); and a general non-energy-intensive good (N) representing all other intermediate goods in the economy. As in the analytical model, there are two consumption goods purchased by households. C_N represents final output from industries that use N intensively, and C_I represents final output from industries which use the other five intermediate goods (notably energy) intensively. Labor time is the sole primary factor of production, and is allocated between leisure and labor time. All of the intermediate goods and labor are used as inputs in production of intermediate goods. Final goods are produced using only intermediate goods as inputs.

As in the analytical model, labor is taxed at a proportional rate of t_L. The tax revenue is used to provide a fixed level of lump-sum transfers to households. Carbon emissions[15] are proportional to the use

[14] Taking a Taylor series expansion of the utility function and ignoring higher order terms would provide a tractable second order welfare approximation for a non-incremental policy in the analytical model. However, the approximation might not be accurate when the reduction in emissions is substantial.

[15] This study measures emissions in terms of carbon content. One ton of carbon emissions is equivalent to 3.67 tons of carbon dioxide.

of each of the three fossil fuels, with a different carbon content for each. Again, we consider two instruments: a tax and a quota on carbon emissions.

i. Firm Behavior

We assume competitive producers that take input and output prices as given. Production functions in all industries have the following constant-elasticity-of-substitution (CES) form:

(III.1) $X_j = \left(\sum_i \alpha_{i,j} X_{i,j}^{\rho_j}\right)^{\frac{1}{\rho_j}}$; $i = \{F_N, F_C, F_P, E, I, N, L\}$; $j = F_N, F_C, F_P, E, I, N, C_I, C_N$

where ρ and the $\alpha_{i,j}$'s are parameters; $\rho = (\sigma - 1)/\sigma$ and σ is the elasticity of substitution between factors in production. Because this production function possesses constant returns to scale, supply curves in all industries are perfectly elastic for given input prices.

Producers choose input quantities in order to maximize profits. In the case of the carbon quota, this is subject to the constraint on emissions. Profits equal the value of output minus expenditures on labor and intermediate goods used in production, less any charges per unit of carbon emissions (τ_c).[16] Thus, profit for industry j (π_j) is given by:

(III.2) $\pi_j = (p_j - \beta_j \tau_C) X_j - \sum_I p_i X_{i,j}$

where p_i and p_j are the prices of inputs and outputs, respectively, and β_j represents the carbon emissions per unit of good j. β_j is zero for all goods except F_N, F_C, and F_P. Note that because this production function exhibits constant returns to scale, profits will equal zero under the carbon tax, but will equal the quota rents under the emissions quota. Total carbon emissions are:

(III.3) $e = \beta_{FN} X_{FN} + \beta_{FC} X_{FC} + \beta_{FP} X_{FP}$

ii. Household Behavior

We assume the following nested CES utility function:

(III.4) $U = U(l, C_I, C_N, e) = \left(\alpha_l l^{\rho_*} + \alpha_F C^{\rho_*}\right)^{\frac{1}{\rho_*}} + \phi(e)$

where

[16] We assume here that carbon taxes are levied on the producers of fossil fuels imposed at source, in keeping with most carbon tax proposals.

(III.5) $C=\left(\alpha_{C_I}C_I^{\rho_C}+\alpha_{C_N}C_N^{\rho_C}\right)^{\frac{1}{\rho_C}}$

l is leisure time and the α's and ρ's are parameters. ρ_U and ρ_C are related to the elasticities of substitution between aggregate consumption and leisure and between the two consumption goods, respectively, in the same manner as in the production function. e denotes carbon emissions.[17]

The household maximizes utility subject to the budget constraint:

(III.6) $p_{C_I}C_I+p_{C_N}C_N=p_L L(1-t_L)+\pi(1-t_R)+p_C G$

where t_L is the tax rate on labor income, t_R is the tax rate on rent income, $L=\overline{L}-l$ is labor supply, π is the total rent generated by a quota policy, G is real government spending in the form of transfers to households, and p_C is the composite price of consumption. This constraint requires that expenditure on consumption equal after-tax income in the form of wages, rents, and government transfers. Except in the sensitivity analysis in Section V, we assume that the tax rates on labor income and rent income are the same: $t_R=t_L$.[18]

iii. Government Policy

The numerical model considers the same two types of emissions regulation considered in the analytical model: a tax of τ_t on carbon emissions, and an emissions quota yielding a virtual tax of τ_q. As shown in Appendix B and in the analytical model, firms behave identically under the carbon tax as under the quota for a given level of abatement. The crucial difference between the two policies is that the tax directly raises revenue for the government.

Again, any revenue consequences of carbon regulation are neutralized by adjusting the tax rate in order to hold real transfers to households fixed. The government's budget constraint is given by:

(III.7) $p_C G=t_L L+t_R\pi+\tau_t e$

Under a carbon tax, π is equal to zero, while under a carbon quota, τ_t equals zero.

---

[17] As in the analytical model, the damages from climate change are assumed to be separable in utility from goods and leisure. Weak separability between goods and leisure and homothetic preferences over consumption goods together imply that C_I and C_N are equal substitutes for leisure (see Deaton (1983)). Since there is no obvious reason or empirical evidence to suggest that energy-intensive goods are relatively strong or relatively weak substitutes for leisure, we think this is a reasonable assumption.

[18] The effective tax on labor earnings (primarily personal income and payroll taxes) and non-labor earnings (personal and corporate income taxes) are roughly the same. For example, Lucas (1990) estimates them to be 40 per cent and 36 per cent respectively.

iv. Equilibrium Conditions

The requirements of general equilibrium are that the demand for labor and for each good equal supply, that the government's revenue requirement be satisfied, and that carbon emissions equal a specified target (if applicable). We can reduce the set of equilibrium conditions to three equations: aggregate labor demand equals aggregate supply, government revenue equals expenditures, and carbon emissions equal the target level.[19] The model is solved by adjusting the primary prices: the pre-tax wage (p_L); the tax rate on labor income (t_L); and the tax rate on carbon emissions (τ_t), or virtual tax rate (τ_q), such that these three conditions hold.

B. Calibration of the Model

The benchmark data set, summarized in Table 1, is intended to approximate the United States economy in the year 2000. We develop this data set by scaling observed 1990 data on input uses, output levels, and consumption patterns to the year 2000, assuming a real growth rate of 2.6% for all flows.[20] We choose the year 2000 to coincide with the starting date of proposed carbon-emissions-control policies (see below).

The effect on labor supply from changes in the after-tax wage in the model represent changes in the participation rate, average hours worked, and effort per hour, that occur in the real world. Based on the existing literature, we set $\sigma_U = 0.86$, which, along with an initial quantity of non-sleep leisure time equal to 0.9 times hours worked, implies an uncompensated and compensated labor supply elasticity of 0.15 and 0.5 respectively.[21] The baseline labor tax rate is taken to be 40%, which is meant to account for taxes at both

---

[19] Because all production functions possess constant returns to scale, supply of each good will always equal demand. The computational algorithm used to solve the model only uses the government budget and carbon emissions conditions. By Walras's law, if these two conditions are satisfied, then the aggregate excess demand for labor must also equal zero. As a check on the computation, we verify that the third equilibrium condition holds, and also that the result is consistent with the appropriate homogeneity conditions in prices and quantities.

[20] This is the average real growth rate for the U.S. over the period 1985-1994, as reported in Table 699 of the 1985 *Statistical Abstract of the U.S.* As shown in Section V, our results are largely insensitive to the assumption that all sectors of the economy grow at the same rate.

[21] Estimates of labor supply elasticities need to be interpreted carefully. Some studies just focus on average hours worked, others on the participation rate of either males or females, which differ substantially, and none on changes in effort (see the survey in Russek (1996)). Feldstein (1995) obtained a much higher (indirect) estimate than in the existing labor economics literature, by estimating the effect of changes in the net wage on labor tax revenues. Using his estimate in the above model would significantly strengthen the tax-interaction and revenue-recycling effects.

the Federal and state levels.[22] These assumptions imply the marginal welfare cost of labor taxation is 0.37, which is broadly consistent with other studies (see for example Ballard *et al.* (1985), Browning (1987)).

The elasticities of substitution in production of intermediate and final goods and in the sub-utility function for consumption goods are assumed to be the same. These elasticities are calibrated such that if the model is run using 1990 data and there is no tax on labor, the marginal cost of carbon emissions reduction closely matches the curve derived by Nordhaus (1991b) from a survey of existing studies, yielding an elasticity of approximately 0.52. For example, the marginal cost of abatement at a 20% reduction in carbon emissions is $43.4 per ton.

The carbon content for each of the three fossil fuel intermediate goods (β) is calculated by dividing the 1990 emissions of carbon from the burning of each fuel, as reported in the 1996 *Annual Energy Outlook*, by the 1990 quantity of each fuel burned. The α distribution parameters were calibrated based on the assumed elasticities of substitution and the identifying restriction that each industry utilized the cost-minimizing mix of inputs, or, equivalently, the restriction that in the absence of an emissions-control policy, the model will replicate the benchmark data.[23]

Finally, in the results below we compare outcomes in a second-best setting (with the labor tax) to those in a first-best setting (when the labor tax is set to zero). The initial quantity of emissions and gross domestic product are 23% higher in the first-best case. This means that, for a given proportionate reduction in emissions, the absolute gross cost in the first-best case is somewhat higher than the primary cost,[24] and conversely the absolute welfare gain is greater than the primary welfare gain, defined in (II.13) and (II.13′).

C. Policy Proposals and Carbon Damage Scenarios

The 1990 Earth Summit in Rio de Janeiro called for developed countries to stabilize carbon emissions at 1990 levels by 2000, and the U.S. subsequently committed to this target. The 1988 Toronto Conference on the Changing Atmosphere proposed an initial cut in carbon emissions to 80 percent of 1990 levels. Since baseline (that is, uncontrolled) carbon emissions would be increasing through time,

---

[22] Other studies use comparable values, for example Lucas (1990) and Browning (1987). The sum of Federal income, state income, payroll, and consumption taxes amounts to around 36% of net national product. This average rate is relevant for the participation decision. The marginal tax rate, which affects effort level and hours worked per employee, is higher because of various tax deductions.

[23] For a discussion of calibration methods for general equilibrium models, see Shoven and Whalley (1992).

[24] That is, environmental benefits minus the primary welfare gain.

these policies imply ever-larger reductions in carbon emissions relative to the baseline path. In our static analysis, we consider emissions reductions ranging from 0 to 25 percent. This seems roughly comparable to the range of emissions reductions (relative to the baseline path) that are called for over the next 10-20 years under the most important carbon abatement proposals.

We consider a range of estimates for benefits from carbon abatement. Central estimates in the literature are typically below \$25 per ton (for example, \$5 per ton in Nordhaus (1994)).[25] The "low" values for the central estimates reflect the notion that continued accumulation of greenhouse gases will not produce extreme changes in climate over the next century, and the idea that most economic activities are not exceptionally sensitive to modest climate change. In addition, discounting over long periods of time substantially reduces the benefit estimates, which are present values. However under extreme values for climate change, sensitivity of the economy to such change, or discount rates, much higher benefit estimates arise. Under an extreme scenario, Nordhaus (1991a), for example, estimates benefits to be \$66 per ton.[26] The simulations below aim to span a wide range of benefit scenarios, considering a range from 0 to 100 dollars per ton. In all cases, we assume marginal benefits are constant over the range of emissions reductions.[27]

IV. Results from the Numerical Model

A. Marginal Costs of Emissions Reduction

Figure 1 shows how the pre-existing labor tax affects the marginal cost of percentage reductions in carbon emissions. The bottom curve is the marginal cost when the labor tax rate is fixed at zero, and is roughly the same as that in Nordhaus (1991b). It has a zero intercept, and is upward sloping, reflecting the increasing difficulty of substituting fossil fuels for other inputs in production. In a first-best world, this same curve applies no matter whether the reduction is achieved by a tax or quota. When the initial pre-existing labor tax (t_{L0}) is 40 percent, the tax-interaction effect causes the marginal cost under the

---

[25] The first benefit estimate was \$7 per ton, by Nordhaus (1991a). Other estimates include \$12 (Peck and Teisberg (1993)) and \$20 (Fankhauser (1994)).

[26] The estimates have also been criticized for neglecting some ecosystem impacts, and possibly adverse effects on the distribution of world income, from climate change. Nordhaus (1993b) provides insightful commentary on these issues.

[27] This is a reasonable simplification, given that the emissions reductions considered below for the U.S. would only have a small impact on future atmospheric CO_2 concentrations.

quota to shift up to the top curve, which has a positive intercept of $25 per ton. Under the carbon tax, the marginal cost is the middle curve: that is, the tax-interaction effect net of the revenue-recycling effect raises the slope, without affecting the intercept. Therefore, the carbon tax can increase welfare so long as marginal benefits from emissions reduction are positive, while for the quota marginal benefits must exceed $25 per ton. These qualitative results were anticipated by the analytical model, and the intercept of the marginal cost under the quota is roughly similar in the analytical and numerical models.[28]

B. Total Costs of Emissions Reduction

Figure 2 shows the *total* cost of reducing carbon emissions under the tax and quota, expressed relative to the total cost of emissions reduction in a first-best setting with no pre-existing labor tax. For both policies, pre-existing taxes imply higher costs at all levels of abatement than would occur if the labor tax were zero. Under the carbon tax, the total costs are 27 percent higher when the labor tax is 0.4.[29] Under the quota policy, pre-existing taxes have a much greater impact. The total cost of a 5 percent emissions reduction, for example, is nine times higher with pre-existing taxes than without; the total cost of a 15 percent emissions reduction is slightly less than four times as high. The very high ratios reflect the fact that the marginal costs of abatement begin at a strictly positive level in a second-best setting, whereas they start at zero in the absence of prior taxes, as shown in Figure 1.

These results indicate that in a second-best setting, under a carbon quota (or grandfathered tradable permits) even "small" amounts of abatement involve large costs. Thus, for example, the cost of using a quota to reduce emissions by 5 percent is (a substantial) $2.75 billion per annum. These significant costs reflect the presence of the tax-interaction effect (and the absence of an offsetting revenue-recycling effect).[30]

---

[28] In addition, the intercept of the quota curve is similar to that implicit in the numerical model of Bovenberg and Goulder (1996a), which incorporates a much more detailed treatment of the tax system. In their model a carbon tax, where the revenues were returned as a lump sum transfer, reduces welfare unless marginal benefits from emissions reduction exceed $55 per ton. This policy would be equivalent to the above quota if there were no taxation of quota rents. In this case, the intercept of the marginal cost rises to $41.5 per ton (see Section V). The remaining discrepancy is explained, at least in part, because Bovenberg and Goulder (1996a) incorporate pre-existing taxes on gasoline which increase marginal abatement costs.

[29] The ratio of total costs between the first- and second-best setting is constant with respect to the amount of emissions reduction, in the carbon tax case. This is because the marginal net loss from the tax-interaction and revenue-recycling effects changes in proportion to the slope of the primary marginal cost of emissions reduction.

[30] Similar results to those in Figures 1 and 2 were obtained by Goulder *et al.* (1996), in their study of the SO_2 permit program. They estimated that the threshold benefit level below which an SO_2 quota cannot increase welfare is $109 per ton. In their equivalent of Figure 2, the cost of the 50% emissions reduction mandated by the program is 120% higher because of pre-existing taxes.

Figure 2 shows that, on efficiency grounds, pre-existing taxes put the quota policy at a considerable disadvantage relative to the tax policy. For all levels of emissions reduction up to 25 percent, the cost of the quota is more than double that of the tax. Therefore, whatever the benefits from reducing carbon emissions, there is a strong efficiency case for preferring the carbon tax to the carbon quota. Note that the relative discrepancy between the tax and quota declines with the level of abatement. The marginal tax-interaction effect is approximately constant, but marginal tax revenue and hence the marginal revenue-recycling effect are declining. This is because the carbon tax base (F in (II.13)) declines with abatement. Eventually, marginal tax revenue would become negative (when the downward sloping part of the Laffer curve is reached). In the limit, at 100% emissions reduction, the total cost of the tax and quota are identical. At this point, no revenues are raised under the tax, and hence there is no revenue-recycling effect and no difference between the tax and quota policies.[31]

C. Efficiency Impacts under Second-Best Optimal Emissions Reduction

The second-best optimal emissions reduction is easily inferred from Figure 1: it is where a given (constant) marginal benefits curve intersects the applicable marginal cost curve. The second-best optimal emissions reduction under the tax is approximately 90% of the optimal reduction when there is no pre-existing labor tax. Under the carbon quota, the optimal emissions reduction is zero if damages are below $25 per ton. If damages are "high", say $60 per ton, the optimal emissions reduction is 12% and 21.5% respectively, under the quota and tax, and 24.5% if there were no labor tax.

Figure 3 shows the maximum efficiency gain, as a function of damages per ton; that is, the efficiency gain from the second-best optimal emissions reduction, under each policy. For any level of damages, the maximum efficiency gain under the carbon tax is around 75% of the maximum gain when there is no labor tax. However for the carbon quota, the maximized efficiency gain is much less; even if damages are $70 per ton, the maximum efficiency gain is only $6.2 billion, or 25% of the maximized gain in a first-best setting.

D. Efficiency Impacts under the Pigouvian Rule

Figure 4 shows the efficiency impact under the carbon tax and quota, if the Pigouvian or first-best rule is followed: that is, if the regulation reduces carbon emissions by the same fraction as the optimal policy in a world without labor taxes. Under the carbon tax, the efficiency change is always positive, and around 70% of that when there is no pre-existing labor tax, for any level of damages.

---

[31] For more discussion of this see Goulder *et al.* (1996).

However, imposing the Pigouvian level of carbon quota *reduces* efficiency, unless damages exceed $75 per ton. This welfare loss can be substantial; for example, it is $4.4 billion, if damages per ton are $20. Even if damages are $100 per ton, the efficiency gain from the quota is only $7 billion, or 16% of that when there is no pre-existing labor tax. Thus, following the optimal policy rule implied by a first-best analysis can lead to perverse efficiency impacts.

V. Sensitivity Analysis

Table 2 summarizes the sensitivity of marginal abatement costs to a range of values for important parameters. We vary the elasticity of substitution among the intermediate inputs in production, the labor supply elasticity, the pre-existing labor tax rate, and the share of fossil fuels in the economy. In addition, we consider the implications of allowing quota rents to remain untaxed.

The elasticity of substitution among intermediate inputs in production drives the primary marginal cost of abatement. The larger this parameter, the easier it is to substitute other intermediate goods for fossil fuels, and the lower the (marginal) cost of emissions reduction. The overall marginal cost equals the primary marginal cost plus the marginal net loss from the tax-interaction and revenue-recycling effects. As shown in Rows 1a and b, this curve is somewhat sensitive to the production elasticity. However even when this elasticity is increased by 50%, the marginal cost under the quota still has a substantial intercept of $17 per ton.

A more elastic labor supply implies a greater substitution between consumption and leisure in response to changes in the real, net of tax wage. Thus, the revenue-raising and tax-interaction effects are larger when labor supply elasticity is larger. As illustrated in Row 2, when the labor supply elasticity is increased, the result is to increase the slope of the marginal cost curve for the carbon tax, and increase the intercept of the curve for the carbon quota. A range of 0 to 0.3 roughly spans estimates of the economy-wide uncompensated labor supply elasticity in the labor economics literature. This implies a range of $16.6 to $35.6 per ton for the quota intercept.

For a higher initial tax rate, the distortion between marginal social benefit and marginal social cost in the labor market is greater, hence the revenue-recycling and tax-interaction effects are larger. As illustrated in row 3, increasing the tax rate leads to a more than proportionate increase in marginal costs.[32]

[32] This is because the (marginal) tax-interaction and revenue-recycling effects are proportional to the marginal welfare cost of taxation, and this increases by more than in proportion to the tax rate.

In developing the data set used to calibrate the model, it was assumed that all sectors of the economy would grow at the same rate between the years 1990 and 2000, thus holding each industry's share of total output constant. However, row 4 illustrates that marginal costs from proportionate emissions reductions are not sensitive to changing the share of the fossil fuel sector in gross domestic product.

Finally, we have assumed that the rents generated by an emissions quota are taxed at the same rate as labor income. Thus, even the quota policy generates government revenue.[33] If quota rents are not taxed. the marginal cost of emissions reduction is greater, and has an intercept of $41.5 per ton (see row 5). A similar, though less substantial result would hold if quota rents were taxed at a lower rate than labor income, whereas if quota rents were taxed at a higher rate, the (marginal) cost of abatement would be lower.

VI. Conclusions and Caveats

In this paper we have used analytical and numerical general equilibrium models to examine the efficiency impacts of revenue-neutral carbon taxes and quotas (or grandfathered carbon permits) in a second-best setting with pre-existing labor taxes. For each of these policies, the efficiency costs are considerably higher than would be the case in the absence of prior taxes. These higher costs reflect the tax-interaction effect: the efficiency cost stemming from the regulation's impact on labor supply as a result of higher output prices and a reduction in the real wage.

Pre-existing taxes imply especially high costs in the case of carbon quotas or grandfathered carbon permits. While emissions taxes and auctioned permits enjoy a revenue-recycling effect that offsets much of the tax-interaction effect, quotas and grandfathered permits policies suffer a cost disadvantage because they cannot exploit the revenue-recycling effect. The disadvantage can be very large: our central estimate is that, in the presence of prior labor taxes, achieving a 5 percent reduction in carbon emissions is seven times more costly under a carbon quota than under a carbon tax; a 15 percent reduction is three times more costly.

Indeed, carbon quotas or grandfathered carbon permits may be unable to generate positive efficiency gains. Our central estimate is that the marginal social cost of emissions reductions begins at

---

[33] For example, at a 10% emissions reduction, it generates rent tax revenues of $12.3 billion. However this is more than offset by the negative impact of the quota on reducing the labor tax base, and the overall revenue change is –$1.1 billion. In contrast, a carbon tax with the same effect on emissions produces a net revenue gain of $19 billion.

$25 per ton for these policies. By comparison, typical estimates of marginal social benefits from carbon emissions reductions are well below $25 per ton. This suggests that policies like carbon quotas and grandfathered carbon permits will be efficiency-reducing -- regardless of the level of carbon abatement. In contrast, carbon tax policies can be efficiency-improving (provided that the level of abatement is not too great) because the marginal social costs of emissions reduction start at zero. In general, our results indicate that ignoring pre-existing tax distortions can give rise to highly misleading conclusions about the sign, as well as the magnitude, of the efficiency impacts from carbon abatement policies.

Some limitations to our analysis deserve mention. The analytical and numerical models are static, ignoring in particular the dynamics of capital accumulation. Considering capital as well as labor would introduce another relevant consideration in assessing the overall efficiency impacts of carbon abatement policies: now these impacts would also depend on (1) pre-existing inefficiencies in relative taxation of labor and capital, and (2) the extent to which abatement policies shift the tax burden from one factor to another. Bovenberg and Goulder (1996b) indicate that for the U.S. economy, capital appears to be overtaxed relative to labor; that is, the marginal welfare cost of capital taxes appears to be higher than that of labor taxes. In this setting, carbon abatement policies that ultimately shift the tax burden toward labor will induce a beneficial tax-shifting effect that mitigates the efficiency costs. The reverse is true if abatement policies shift more of the tax toward capital. Empirical analysis by Bovenberg and Goulder suggests that abatement policies tend to shift the burden toward capital, since the energy sector is relatively capital intensive. Thus our exclusive focus on labor may have biased downward our assessment of efficiency costs.

Another limitation of our analysis is that it ignores pre-existing distortions attributable to non-tax factors such as non-competitive market structures. Browning (1994) suggests that non-tax distortions add another 30 per cent to the distortion in the labor market created by taxes. If so, incorporating non-tax distortions into our analysis would significantly increase the importance of second-best interactions and reduce the efficiency gains from carbon abatement policies.[34]

In other respects, however, our analysis may understate the efficiency gains from carbon abatement policies. First, by employing static models we disregard dynamic issues associated with the benefits from carbon abatement. Marginal damages from carbon emissions (or benefits from emissions abatement) could increase with CO_2 concentrations (for example, the concentration-damage relationship could exhibit significant threshold effects). If this is the case, and if CO_2 concentrations continue to rise, then marginal damages from CO_2 emissions (marginal benefits from abatement) will increase over time.

[34] On the significance of monopoly price distortions, in particular, see also Oates and Strassmann (1984).

Under such circumstances, even if the carbon quota cannot currently generate efficiency gains, it is possible that efficiency gains could result if this policy were introduced at some future point in time. (In efficiency terms, of course, it is always better to adopt the carbon tax.) Second, carbon abatement policies -- particularly carbon taxes -- can produce dynamic efficiency gains by stimulating the invention and diffusion of less-carbon-intensive production technologies. This is especially important to the extent that there are market failures in the research market that have not been fully corrected by other government policies.[35] Third, the prospects for efficiency gains also improve if one considers ancillary benefits from carbon abatement policies, such as benefits from the reduction in other fossil fuel-related pollutants (e.g. sulfur oxides, nitrogen oxides and particulates).

Finally, our analysis ignores distributional considerations. The decision whether to introduce a carbon tax or carbon quota fundamentally affects the distribution of wealth between taxpayers, on the one hand, and owners and employees of fossil-fuel-producing firms, on the other. Quota policies leave rents in producers' hands, while carbon taxes effectively tax these rents away. Some analysts might invoke these distributional impacts to favor the quota over the tax. The second-best issues examined in this paper do not diminish the importance of these distributional considerations, but at the same time they indicate that forgoing the redistribution towards taxpayers has efficiency costs that are much greater than would be suggested by a first best analysis.

[35] For further discussion of this issue, see, for example, Smulders (1996).

References

Ballard, Charles, L., John B. Shoven and John Whalley, 1985. "General Equilibrium Computations of the Marginal Welfare Cost of Taxes in the United States." *American Economic Review* 75:128-38.

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

Bovenberg, A. Lans and F. van der Ploeg, 1994. "Environmental Policy, Public Finance and the Labor Market in a Second-Best World." *Journal of Public Economics* 55: 349-90.

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

Bovenberg, A. Lans and Lawrence H. Goulder, 1996b. "Costs of Environmentally-Motivated Taxes in the Presence of other Taxes: General Equilibrium Analyses." *National Tax Journal*, forthcoming.

Browning, Edgar K., 1987. "On the Marginal Welfare Cost of Taxation." *American Economic Review* 77:11-23.

Browning, Edgar K., 1994. "The Non-Tax Wedge." *Journal of Public Economics* 53:419-433.

Browning, Edgar K., 1996. "The Welfare Cost of Monopoly and other Output Distortions." *Journal of Public Economics*, forthcoming.

Deaton, Angus, 1981. "Optimal Taxes and the Structure of Preferences." *Econometrica* 49:1245-59.

Feldstein, Martin, 1995. "The Effect of Marginal Tax Rates on Taxable Income: A Panel Study of the 1986 Tax Reform Act." *Journal of Political Economy* 103: 551-72.

Fankhauser, Samuel, 1994. "The Social Costs of Greenhouse Gas Emissions: An Expected Value Approach." *The Energy Journal*, 15:157-84.

Fullerton, Don and Gilbert Metcalf, 1996. "Environmental Controls, Scarcity Rents, and Pre-Existing Distortions." working paper, University of Texas-Austin and Tufts University.

Goulder, Lawrence H., 1995. "Effects of Carbon Taxes in an Economy with prior Tax Distortions: An Intertemporal General Equilibrium Analysis." *Journal of Environmental Economics and Management* 29:271-97.

Goulder, Lawrence H., Ian W.H. Parry and Dallas Burtraw, 1996. "Revenue-Raising vs. Other Approaches to Environmental Protection: The Critical Significance of Pre-Existing Tax Distortions." NBER Working Paper No. 5641.

Hoel, Michael, 1991. "Efficient International Agreements for Reducing Emissions of CO_2." *The Energy Journal* 12:93-107.

Jorgenson, Dale, W. and Peter J. Wilcoxen, 1995. "Reducing U.S. Carbon Emissions: An Econometric General Equilibrium Assessment," in Darius Gaskins and John Weyant (eds.), *Reducing Global Carbon Dioxide Emissions: Costs and Policy Options*. Stanford, CA: Stanford University Press.

Lucas, Robert E., 1990. "Supply-Side Economics: An Analytical Review." *Oxford Economic Papers* 42:293-316.

Manne, Alan S. and R. Richels, 1992. *Buying Greenhouse Insurance*. Cambridge: MIT Press.

Nordhaus, William D., 1991a. "To Slow or Not to Slow: The Economics of the Greenhouse Effect." *The Economic Journal* 101:920-37.

Nordhaus, William D., 1991b. "The Cost of Slowing Climate Change: A Survey." *The Energy Journal* 12:37-65.

Nordhaus, William D., 1993a. "Optimal Greenhouse Gas Reductions and Tax Policy in the "DICE" Model." *American Economic Review*, 83:313-17.

Nordhaus, William D., 1993b. "Reflections on the Economics of Climate Change." *Journal of Economic Perspectives* 7:11-26.

Nordhaus, William D., 1994. *Managing the Global Commons: The Economics of Climate Change*. Cambridge, MA: MIT Press.

Oates, Wallace E., 1995. "Green Taxes: Can we Protect the Environment and Improve the Tax System at the Same Time?" *Southern Economic Journal* 61:914-22.

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

Oates, Wallace E. and Diana L. Strassmann, 1984. "Effluent Fees and Market Structure." *Journal of Public Economics* 24:29-46.

Parry, Ian W. H., 1995. "Pollution Taxes and Revenue Recycling." *Journal of Environmental Economics and Management* 29:S64-77.

Parry, Ian W.H., 1996. "Environmental Taxes and Quotas in the Presence of Distorting Taxes in Factor Markets." *Resource and Energy Economics*, forthcoming.

Peck, Stephen C. and Thomas J. Teisberg, 1993. "Global Warming Uncertainties and the Value of Information: An Analysis using CETA." *Resource and Energy Economics* 15:71-98.

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

Repetto, Robert, Roger C. Dower, Robin Jenkins and Jacqueline Geoghegan, 1992. *Green Fees: How a Tax Shift Can Work for the Environment and the Economy*. Washington DC: World Resources Institute.

Russek, Frank, 1994. "Taxes and Labor Supply." working paper, Congressional Budget Office.

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

Shoven, John B., and John Whalley, 1992. *Applying General Equilibrium.* Cambridge, MA: Cambridge University Press.

Smulders, Sjak, 1996. "Should Environmental Standards be Tighter if Technological Change is Endogenous?" Working paper, Faculty of Economics, Tilburg University.

Tietenberg, Tom H., 1991. "Economic Instruments for Environmental Regulation," in Dieter Holm (ed.) *Economic Policy Towards the Environment,* Cambridge, MA: Blackwell.

Varian, Hal R., 1992. *Microeconomic Analysis.* New York: W. W. Norton and Co.

Appendix A: Analytical Derivations

Deriving Equation (II.8)

Given constant returns to scale, payments to inputs in the C_F industry exhaust value product (from Euler's theorem), that is:

(A1) $$p_F C_F = (\tau_F + q_F)F_F + q_N N_F + L_F$$

where q_F and q_N are the supply prices of the intermediate goods *F* and *N*, and the purchase price of fossil fuels includes the carbon tax. Totally differentiating (A1) gives:

(A2) $$dp_F C_F + p_F dC_F = d\tau_F F_F + (\tau_F + q_F)dF_F + q_N dN_F + dL_F$$

because q_F and q_N are determined by marginal product of labor in the *F* and *N* industries, and the gross wage, which are all constant. From differentiating the production function (II.2), we obtain

(A3) $$dC_F = \frac{\partial C_F}{\partial L_F}dL_F + \frac{\partial C_F}{\partial F_F}dF_F + \frac{\partial C_F}{\partial N_F}dN_F$$

Also, from the first order conditions for profit maximization, the marginal products equal the input price divided by the product price, or

(A4) $$\frac{\partial C_F}{\partial L_F} = \frac{1}{p_F}; \qquad \frac{\partial C_F}{\partial F_F} = \frac{\tau + q_F}{p_F}; \qquad \frac{\partial C_F}{\partial N_F} = \frac{q_N}{p_F}$$

Substituting (A4) in (A3), multiplying through by p_F, and subtracting from (A2) gives the expression for $dp_F/d\tau_F$ in (II.8). The same procedure gives the analogous expression for $dp_N/d\tau_F$.

Deriving Equation (II.9)

From the cost minimization problem for firms in the C_F and C_N industries, we can derive the demands for inputs, conditional on the level of output, and input prices. Input prices can be summarized by τ_F, since q_F, q_N and the gross wage are all fixed. Therefore, the conditional demands for fossil fuel are:

(A5) $$F_F(\tau_F, C_F); \qquad F_N(\tau_F, C_N)$$

In equilibrium, the final output produced by firms equals that demanded by households. Therefore, substituting the expressions for C_F and C_N from (II.5) into (A5), and noting from (II.8) that changes in product prices are determined by changes in τ_F, the equilibrium quantity of fossil fuels is summarized by (II.9).

Deriving Equation (II.14)

Using (II.5), (II.12) and (II.13), the tax-interaction effect can be expressed

$$\partial W^I = -\frac{L}{L + t_L(\partial L/\partial t_L)}\left(\frac{\partial L/\partial t_L}{\partial L/\partial t_L}\right)t_L\frac{\partial L}{\partial \tau_F^t} = \frac{ZL}{\partial L/\partial t_L}\left\{\frac{\partial L}{\partial p_F}\frac{dp_F}{d\tau_F^t} + \frac{\partial L}{\partial p_N}\frac{dp_N}{d\tau_F^t}\right\}$$

Substituting the Slutsky equations, and from (II.8) and (II.9) gives

(A6) $$\partial W^I = ZL\left\{\frac{(\partial L^c/\partial p_F)(F_F/C_F) + (\partial L^c/\partial p_N)(F_N/C_N) - (\partial L/\partial I)F}{(\partial L^c/\partial t_L) - (\partial L/\partial I)L}\right\}$$

where "c" denotes a compensated coefficient, and I denotes disposable household income. From the Slutsky symmetry property:

(A7) $$\frac{\partial L^c}{\partial p_F} = \frac{\partial C_F}{\partial(1-t_L)}; \qquad \frac{\partial L^c}{\partial p_N} = \frac{\partial C_N}{\partial(1-t_L)}$$

Also, from differentiating the household budget constraint (II.4):

(A8) $$\frac{\partial L^c}{\partial t_L} = -\frac{\partial L^c}{\partial(1-t_L)} = -\left\{p_F\frac{\partial C_F}{\partial(1-t_L)} + p_N\frac{\partial C_N}{\partial(1-t_L)}\right\}$$

(since the first order effect L is neutralized in a compensated price change). Making these substitutions in (A6), and multiplying by $1-t_L$, we obtain (II.14), where

$$\eta_{FI}^c = \frac{\partial C_F^c}{\partial(1-t_L)}\frac{1-t_L}{C_F}; \quad \eta_{NI}^c = \frac{\partial C_N^c}{\partial(1-t_L)}\frac{1-t_L}{C_N}; \quad \eta_{LI} = \frac{\partial L}{\partial I}\frac{(1-t_L)L}{L};$$

$$h_F = \frac{F_F}{F}; \quad h_N = \frac{F_N}{F}; \quad s_F = \frac{p_F C_F}{L}; \quad s_N = \frac{p_N C_N}{L}$$

Note that, assuming carbon tax revenues are negligible relative to total gross labor income,

(A9) $$L = p_F C_F + p_N C_N$$

that is, gross labor income equals the value of output.

Deriving Equation (II.13′)

Totally differentiating the government budget constraint (II.10′) yields:

(II.11′) $$\frac{dt_L}{d\tau_F^q} = -\frac{t_L\left\{F + \tau_F^q\frac{dF}{d\tau_F^q} + \frac{\partial L}{\partial \tau_F^q}\right\}}{L + \pi + t_L\frac{\partial L}{\partial t_L}}$$

The indirect utility function now includes net income from quota rents, $(1-t_L)\pi$. Equations (II.7) and (II.8) are the same as before, except that $\partial v/\partial t_L = -\lambda(L+\pi)$. Differentiating the indirect utility function with respect to τ_F^q, making the analogous substitutions to before, and using:

$$\frac{\partial v}{\partial[(1-t_L)\pi]}\frac{d[(1-t_L)\pi]}{d\tau_F^q}=\lambda\left\{(1-t_L)\left[F+\tau_F^q\frac{dF}{d\tau_F^q}\right]-\pi\frac{dt_L}{d\tau_F^q}\right\}$$

gives, after some manipulation, (II.13′).

Deriving Equation (II.15)

Using (II.12′) and (II.13′), when $\tau_F^q = \pi = 0$, gives:

(A10) $$\partial W^I - \partial W^R = t_L \frac{L\left(-\frac{\partial L}{\partial \tau_F^q}\right)+t_L F\frac{\partial L}{\partial t_L}}{L+t_L\frac{\partial L}{\partial t_L}}$$

Changes in τ_F^q affect rents, therefore:

(A11) $$\frac{\partial L}{\partial \tau_F^q}=\frac{\partial L^u}{\partial \tau_F^q}+\frac{\partial L}{\partial I}\frac{\partial[(1-t_L)\pi]}{\partial \tau_F^q}=\frac{\partial L^u}{\partial \tau_F^q}+\frac{\partial L}{\partial I}(1-t_L)F^0$$

where "u" denotes uncompensated. Substituting (A11) and the Slutsky equations for $\partial L^u/\partial \tau_F^q$ and $\partial L/\partial t_L$ in (A10), and multiplying and dividing by $t_L \partial L^c/\partial t_L$ gives:

(A12) $$\partial W^I - \partial W^R = F^0\left\{\frac{(\partial L^c/\partial \tau_F^q)L}{(\partial L^c/\partial t_L)F^0}-t_L\right\}\frac{t_L(-\partial L^c/\partial t_L)}{L+t_L\partial L/\partial t_L}$$

Substituting

$$\frac{\partial L^c}{\partial \tau_F^q}=\frac{\partial L^c}{\partial p_F}\frac{dp_F}{d\tau_F^q}+\frac{\partial L^c}{\partial p_N}\frac{dp_N}{d\tau_F^q},$$

(II.8), (A7), (A8), (A9), and the definitions of η_{FI}^c and η_{NI}^c, when these elasticities are equal, in (A12) gives (II.15), where

$$\varepsilon^u=\frac{\partial L}{\partial(1-t_L)}\frac{1-t_L}{L};\quad \varepsilon^c=\frac{\partial L^c}{\partial(1-t_L)}\frac{1-t_L}{L}$$

Appendix B: The Numerical Model

Except where otherwise noted, i ranges over L, F_N, F_C, F_P, E, I, and N, which represent inputs in production. Similarly, j ranges over F_N, F_C, F_P, E, I, G, C_I, and C_N, which represent goods produced.

I. Parameters

Firm Behavior Parameters

a_{ij}	distribution parameter for input i in production of good j
r_j	substitution parameter for production of good j
	(note: $\rho_j=(\sigma_j-1)/\sigma_j$ where r_j is the elasticity of substitution in production of j

Household Behavior Parameters

$\overline{L}$	total labor endowment
$\alpha_l, \alpha_{CF}, \alpha_{C_N}, \alpha_{C_I}$	distribution parameters for utility function
r_C , r_U	substitution parameters for utility function

Government Policy Parameters

$\overline{e}$	carbon emissions target
$\overline{e}_j$	carbon quota for industry j
G	government spending (transfers to households, in real terms)

Emissions Parameters

b_j	emissions of carbon per unit of good j used
	(note: b_j is non-zero only for j ranging over F_N, F_C, and F_P)

II. Endogenous Variables

a_{ij}	use of input i per unit of output of good j
C_I and C_N	aggregate demands for energy-intensive and non-intensive final goods
C	aggregate demand for composite consumption good
AD_i	aggregate demand for good i
X_j	aggregate supply of good j
L	aggregate labor supply
l	leisure or non-market time

p_C	price of composite final good
p_j	price of good j
π	total carbon quota rents
REV	government revenue
e_i	carbon emitted from use of good i (note: here i ranges only over F_N, F_C, and F_P)
e	total carbon emissions
U	total consumer utility
ϕ	utility associated with carbon emissions
X_{ij}	use of good i in production of good j

III. Equations

Production Functions and Optimal Input Intensities

In all industries, output is produced according to:

(B1) $$X_j = \left(\sum_i \alpha_{i,j} X_{i,j}^{\rho_j}\right)^{\frac{1}{\rho_j}},\ i = \{F_N, F_C, F_P, E, I, N, L\},\ j = F_N, F_C, F_P, E, I, N, C_I, C_N$$

Profit for industry j is given by

(B2) $$\pi_j = (p_j - \beta_j \tau_t) X_j - \sum_I p_i X_{i,j}$$

Differentiating profit with respect to the inputs X_{ij} yields the first order condition for the optimal input mix:

(B3) $$a_{ij} \equiv \frac{X_{ij}}{X_j} = \alpha_{ij}^{\frac{1}{1-\rho_j}} \left(\frac{p_j - \beta_j \tau_t}{p_i}\right)^{\frac{1}{1-\rho_j}}$$ (note: b_j=0 for j=E, I, N, C_I, C_N)

Equations (B2) and (B3) assume that carbon regulation is accomplished through a carbon tax. Firm behavior will be identical under a carbon quota. In this case, profit for industry j is:

(B4) $$\pi_j = p_j X_j - \sum_I p_i X_{i,j}$$

with the constraint that industry emissions equal the industry emissions quota $\bar{e}_j$

(B5) $$\beta_j X_j = \bar{e}_j$$

Maximizing profit under this constraint yields the Lagrangian function

(B6) $p_j X_j - \sum_i p_i X_{i,j} - \lambda_j(\beta_j X_j - \bar{e}_j)$

If the carbon quota is set such that the shadow price of carbon emissions λ_j equals τ_t the Lagrangian function in equation (B6) is equal to the profit function in equation (B2) with an additional constant term $\tau_t \bar{e}_j$, which represents quota rents.[36] Therefore, the first-order conditions resulting from this maximization will be the same as from maximizing equation (B2), implying that the carbon quota can be modeled as a virtual carbon tax in determining firm behavior.

Finally, substituting equations (B1) and (B3) into equation (B2) and differentiating with respect to the quantity produced, X_j yields an equation for the output price:

(B7) $p_j = \sum_i p_i a_{ij} + \tau \beta_j$

where τ is either the carbon tax or virtual carbon tax, depending on whether the pollution-control policy is a tax or a quota. Solving this equation simultaneously for all intermediate goods yields the price vector for the intermediate goods.

Household Utility Function: Labor Supply and Final Good Demands

The representative household's utility function is:

(B8) $U = U(l, C_I, C_N, e) = (\alpha_l l^{\rho_u} + \alpha_C C^{\rho_u})^{\frac{1}{\rho_u}} + \phi(e)$

where C represents composite consumption:

(B9) $C = (\alpha_{C_I} C_I^{\rho_C} + \alpha_{C_N} C_N^{\rho_C})^{\frac{1}{\rho_C}}$

The household maximizes utility subject to the budget constraint:

(B10) $p_{C_I} C_I + p_{C_N} C_N = p_L(1 - t_L)L + (1 - t_R)\pi + p_C G$

and the time endowment $l + L = \bar{L}$.This maximization yields the following equations which express the household's behavior:

[36] This assumes that the shadow price of carbon emissions will be the same across all polluting industries, as would be the case under a tradable quota, but not necessarily the case under a non-tradable quota. If the shadow price differed across industries, firm behavior could still be modeled with a virtual tax, but the virtual tax would also vary across industries. In the rest of this analysis, we assume that the virtual tax is constant across industries.

(B11) $$a_{C_I} \equiv \frac{C_I}{C} = \left[\alpha_{C_I} + \alpha_{C_N} \left(\frac{\alpha_{C_I} p_{C_N}}{\alpha_{C_N} p_{C_I}} \right)^{\frac{\rho_C}{\rho_C - 1}} \right]^{\frac{1}{\rho_C}}$$

(B12) $$a_{C_N} \equiv \frac{C_N}{C} = \left[\alpha_{C_N} + \alpha_{C_I} \left(\frac{\alpha_{C_N} p_{C_I}}{\alpha_{C_I} p_{C_N}} \right)^{\frac{\rho_C}{\rho_C - 1}} \right]^{\frac{1}{\rho_C}}$$

(B13) $$p_C = p_{C_I} a_{C_I} + p_{C_N} a_{C_N}$$

(B14) $$l = \frac{p_L(1 - t_L)\overline{L} + p_C G + (1 - t_R)\pi}{p_L(1 - t_L) + p_C \left[\frac{\alpha_l p_C}{\alpha_C p_L (1 - t_L)} \right]^{\frac{1}{\rho_U - 1}}}$$

(B15) $$L = \overline{L} - l$$

(B16) $$C = p_C^{-1}\left[p_L(1 - t_L)L + p_C G + (1 - t_R)\pi \right]$$

Combining (B16) with (B10) or (B11) yields the optimal levels of C_I and C_N.

Government

Government revenues finance a fixed level of real government transfers to households, G. Revenues (REV) are determined by:

(B17) $$REV = t_L L + \tau_t e + t_R \pi$$

where $\pi = \tau_q \bar{e}$, τ_q is the virtual carbon tax in the emissions quota case, and τ_t is the actual carbon tax. Under a carbon tax, the reverse is true.

Throughout most of this analysis, we assume that the tax on rents is the same as the tax on labor income, thus:

(B18) $$t_R = t_L$$

Aggregate Demand and Supply

Aggregate demand for the two final goods is determined by the household, through equation (B16) and equation (B10) or (B11). Aggregate demand for labor and for the six intermediate goods is determined from the use of each good in production, yielding

(B19) $AD_i = \sum_j X_{ij}$

Since production of all goods follows constant returns to scale, supplies of both final goods and the six intermediate goods are determined by demand. Thus

(B20) $X_{C_I} = C_I$

(B21) $X_{C_N} = C_N$

(B22) $X_i = AD_i$ for i ranging over F_N, F_C, F_P, E, I, and N

Solving this last equation simultaneously for all values of i yields aggregate supplies and demands for the intermediate goods.

IV. Equilibrium Conditions

The equilibrium conditions are:

(B23) $L = AD_L$

(B24) $e = \overline{e}$

(B25) $REV = p_C G$

To solve the model, we compute the values of τ and t_L that satisfy (B24) and (B25), using p_L as the numeraire. By Walras's Law, if two of the three equilibrium conditions hold, the third will also hold, so the vector of primary prices that satisfies (B24) and (B25) also satisfies (B23).

Table 1

Benchmark Data for the Numerical Model

All data in millions of 1990 dollars except carbon emissions in millions of tons

	F_N	F_C	F_P	E	I	N	C_I	C_N	l	Total Input Value
F_N	22893.2	48.1	26972.7	5931.1	13464.0	23998.5	70785.9	310.9		164404.3
F_C	0.1	2989.6	63.0	19865.9	2937.0	1594.6	743.9	14.5		28208.8
F_P	9702.5	455.1	56404.3	8716.6	30947.6	38741.8	133540.2	7863.1		286371.3
E	887.6	963.1	2848.0	55.7	24880.9	89298.7	63684.5	59.3		182677.8
I	17665.3	4207.8	31560.5	8991.5	363123.3	707575.9	160005.2	11611.9		1304741.6
N	16241.6	6611.7	34141.1	40269.6	288721.8	4674493.8	383045.3	3479102.3		8922627.1
L	97013.8	12933.4	134381.7	98847.4	580666.8	3386924.0			3868637.1	8179404.2
Total Output Value	164404.2	28208.8	286371.3	182677.8	1304741.6	8922627.3	811805.0	3498962.1		
e	358.7	628.0	762.3							1749.0

Table 2

Marginal Abatement Costs Under Alternative Parameter Values and Model Specifications

	Carbon Emissions Quota			Carbon Tax		
	0%	10%	20%	0%	10%	20%
Central Case	25.4	55.0	100.1	0.1	21.0	55.3
1. Production Elasticities						
a. elasticities 3/2 of base elasticity	17.2	35.0	61.4	0.1	13.5	34.4
b. elasticities 2/3 of base elasticity	36.9	86.7	163.6	0.2	32.8	90.0
2. Labor Supply Elasticities						
a. uncompensated labor supply elasticity=0.0	16.6	41.7	81.0	0.1	19.4	51.3
b. uncompensated labor supply elasticity=0.30	35.6	70.2	122.1	0.1	22.9	60.0
3. Baseline tax rate						
a. t_L=0.6	62.6	113.2	188.0	0.2	29.4	77.3
b. t_L=0.2	9.7	30.9	64.6	0.1	18.2	48.0
c. t_L=0.0	0.1	16.5	43.4	0.1	16.5	43.4
4. Share of Fossil Fuels in GDP						
a. share doubled	24.8	53.0	94.8	0.1	20.8	54.0
b. share halved	25.8	56.3	103.4	0.2	21.3	56.2
5. Quota rents not taxed	41.5	77.2	130.9	n/a	n/a	n/a

Figure 1
Marginal Cost of Emissions Reduction

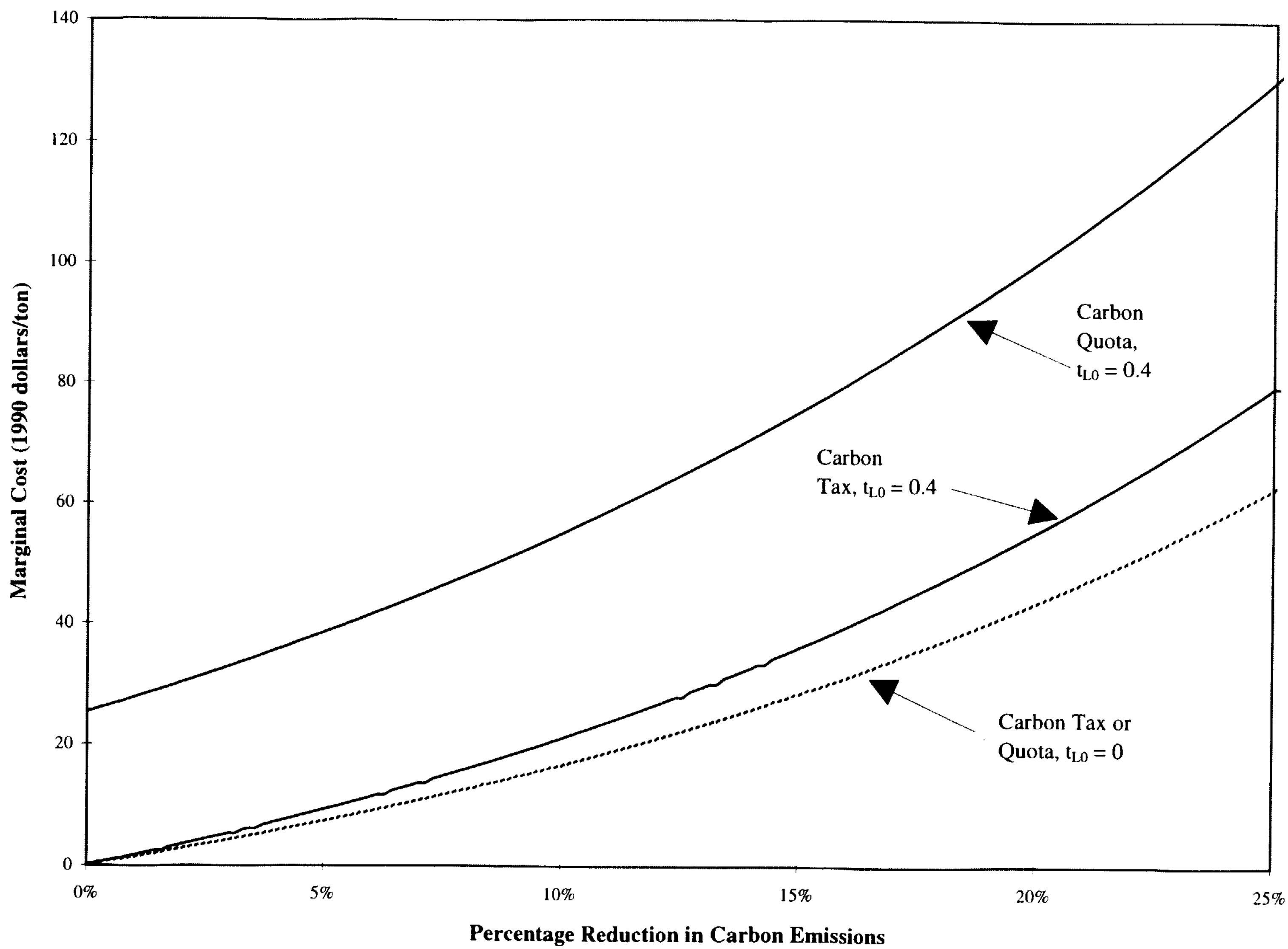

Figure 2
Ratio of Second-Best to First-Best Total Costs

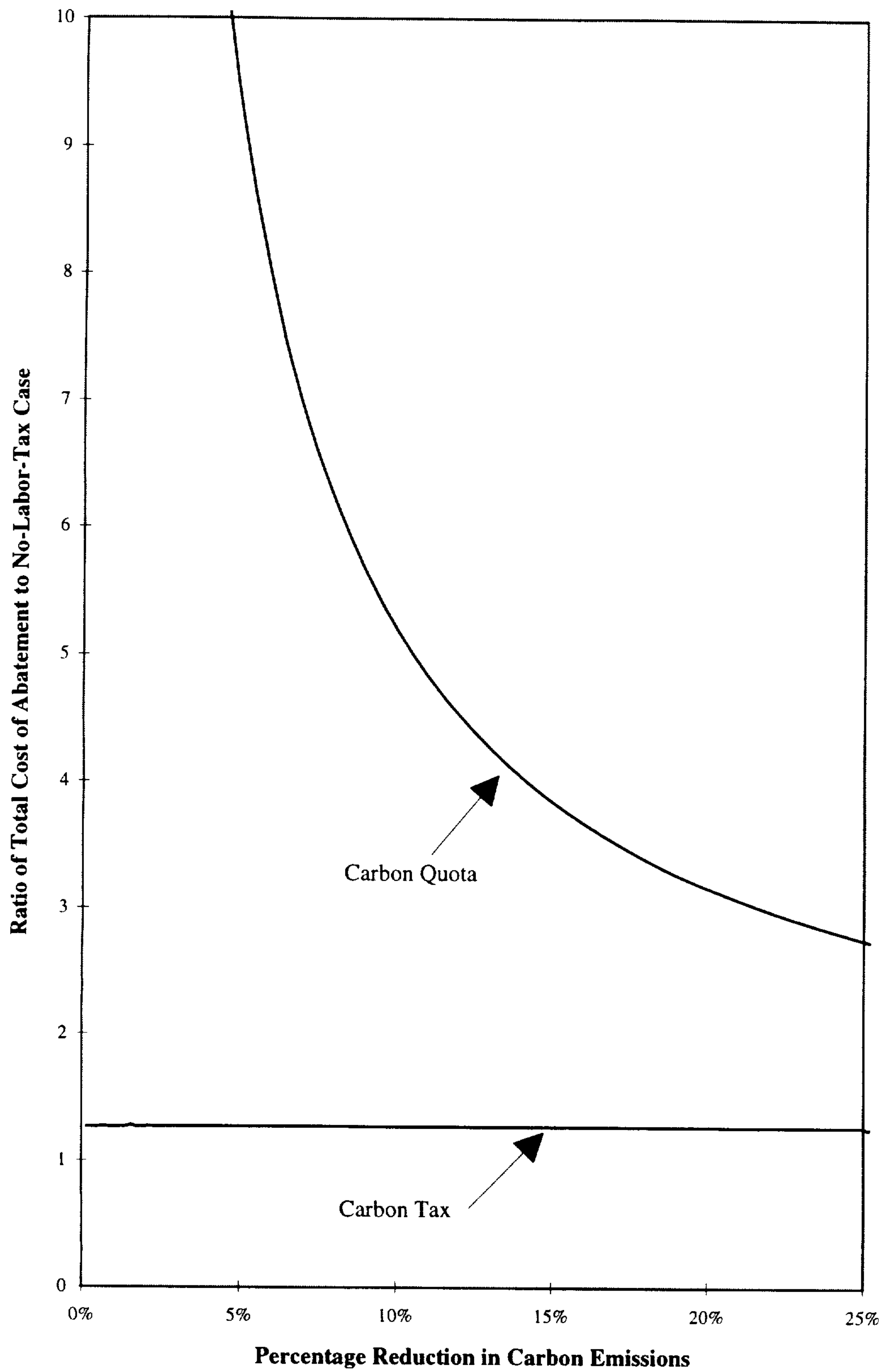

Figure 3
Net Efficiency Gain from the Optimal Level of Regulation

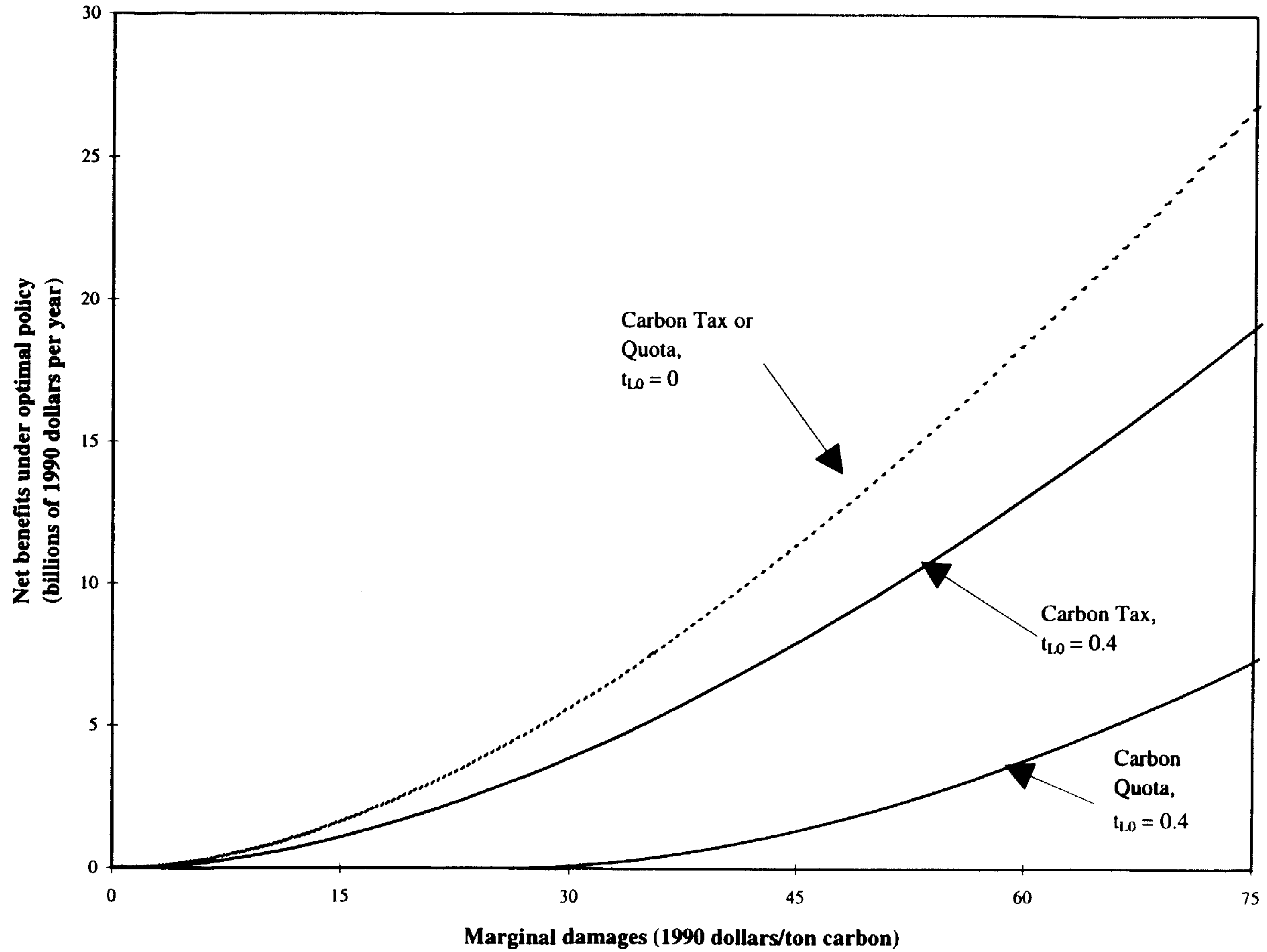

Figure 4
Net Efficiency Gain Under the Pigouvian Rule