Fiscal Interactions and the Costs of Controlling Pollution from Electricity

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Abstract

This paper quantifies the costs of controlling SO_2, carbon, and NO_x emissions from power generation, accounting for interactions between environmental policies and the broader fiscal system. We distinguish a dirty technology (coal) that satisfies baseload demand and a clean technology (gas) that is used during peak periods, and we distinguish sectors with and without regulated prices. Estimated emissions control costs are substantially lower than in previous models of fiscal interactions that assume a single, constant returns technology and competitive pricing. The results are reasonably robust to alternative scenarios, such as full price deregulation and market power in the deregulated sector.

Key Words: electricity generation, pollution control, fiscal interactions, price regulation, multiple technology

JEL Classification Numbers: Q28, H21, H23, L94

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Ian W. H. Parry*

1. Introduction

A recent literature in environmental economics has demonstrated that the costs of pollution control policies depend importantly on how the policies interact with preexisting tax distortions in the labor market.[1] To the extent that pollution controls increase production costs and product prices, they slightly reduce real household wages and economy-wide labor supply. The resulting efficiency loss in the labor market—termed the "tax-interaction effect"—can be substantial relative to partial equilibrium abatement costs, as the labor market is such a large share of GDP and there is a large wedge between the gross and net-of-tax wage. On the other hand, policies that raise revenue for the government, including emissions taxes and auctioned emissions permits, may produce an efficiency-enhancing "revenue-recycling effect," if revenues are used to reduce distortionary taxes or fund socially desirable spending.

Analyses of U.S. environmental policy and fiscal interactions have assumed firms are competitive and produce with a single, constant returns technology; consequently the private costs of emissions controls are fully passed on in higher product prices. However these assumptions are unrealistic for electricity generation, which is a major source of local and global pollution. Electricity accounts for 67% of economy-wide SO_2 emissions, 25% of NO_x emissions,[2] and, according to the U.S. Energy Information Administration (EIA 1998), it would account for around two-thirds of emissions reductions under an economy-wide carbon tax.

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[1] See Bovenberg and Goulder (2002) and Parry and Oates (2000) for reviews of the literature.

[2] From www.epa.gov/ttn/chief/trends/trends98.

In many states, generation prices are regulated and, unlike under competition, the opportunity cost of using grandfathered permits to cover emissions is not passed on to consumers in higher prices (Burtraw et al. 2001a, p. 7). But even if the electricity industry were fully deregulated, another important feature is that different technologies are often used to satisfy baseload and peak demand. At peak period infra-marginal production is often from coal plants, which have high emissions intensity, while marginal production is often from natural gas plants, which have lower emissions intensity (in the case of carbon and NO_x) or zero emissions (in the case of SO_2). Consequently, abatement costs for coal plants at peak period will not be fully passed on as higher prices. They will, at least in part, come at the expense of rents earned on infra-marginal production. By weakening the effect of abatement costs on product prices, both of these considerations—regulated prices and multiple technologies—imply a substantially smaller tax-interaction effect than predicted by previous models (e.g., Goulder et al. 1997).

Other complications are that, even in the deregulated sector, prices may not be competitively determined in the peak period (e.g., Borenstein et al. 2002). And, to the extent that there is imperfect competition, or prices are regulated, changes in electricity output itself will give rise to efficiency effects that are not captured in competitive models.

This paper examines how all these complications alter the costs and welfare effects (benefits minus costs) of policies to reduce utility emissions of SO_2, carbon, and NO_x. We analyze emissions permits with four approaches for allowance allocation, all of which have credibility in current political debate:

1. Grandfathering, which is the approach embodied in the existing SO_2 program;
2. Auctioning with revenues used to reduce distortionary taxes, as advocated by many economists;
3. Auctioning with revenues returned lump sum to households, which is sometimes advocated on distributional grounds to compensate households for electricity price increases
4. Allocating based on firm output.[3]

We integrate an electricity market model into a general equilibrium model with preexisting labor taxes. The electricity market consists of two distinct regions, one with regulated prices and the other with

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[3] For details on permit allocation mechanisms in competing multi-pollutant bills to reduce utility emissions, see www.rff.org/rff/Core/Research_Topics/Air/Multipollutant/Multipollutant-Legislation.cfm.

full price deregulation. Formulas are derived for the welfare effects of (economy-wide) emission permit policies under alternative allowance allocations. These formulas are calibrated to the control of actual and proposed SO_2, NO_x, and carbon policies. We then perform an extensive sensitivity analysis, varying the extent of price deregulation, emissions abatement, the dispersion in marginal costs across periods, and other factors and allowing for market power in the deregulated sector.[4] We summarize the main points as follows.

First, estimated policy costs can be quite different from those implied by a competitive, single-technology model, mainly because of the smaller tax-interaction effect. For example, the costs of reducing carbon emissions by 10% under grandfathered permits and revenue-neutral auctioned permits are computed at \$2.7 and –\$0.5 billion in the present model in the benchmark case. In contrast, with a single, constant returns technology model with competitive pricing, the costs of these policies are computed at \$5.2 and \$1.7 billion, respectively.

Second, relative policy costs are highly sensitive to the extent of abatement. For example, for grandfathered permits, policy costs are 48% lower in our model than in the competitive, single-technology model for a carbon reduction of 10%; they are 32% lower for a 45% reduction in SO_2, and they are 20% lower for a 70% reduction in NO_x. This is because the magnitude of fiscal interactions declines relative to the magnitude of pure abatement costs at higher levels of abatement.

Third, policy costs could be lower still if electricity prices were fully (rather than partially) deregulated. When prices are market-determined, and emissions predominantly come from infra-marginal technologies, only a small portion of abatement costs may be passed on in higher product prices. In comparison, under regulated, average cost pricing, a larger portion of abatement costs for infra-marginal technologies are reflected in higher prices.

Fourth, the results are reasonably robust to different scenarios for the dispersion in marginal costs across periods, the difference between average and (mean) marginal cost and market power in the deregulated sector.

Finally, as regards overall welfare effects, we find that the choice of permit allocation can matter for the direction of the welfare impact for carbon where auctioned permits with revenues returned in lump

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[4] For analytical tractability, we use a highly simplified, reduced from representation of the electricity market; our purpose is to provide, with rough numerical examples, a transparent framework for understanding how specific features of the electricity sector alter fiscal interactions, rather than detailed (though less transparent) computational estimates.

sum transfers reduce welfare while other permit policies increase it. This is not the case for SO_2 or NO_x where welfare is improved under all permit allocations, due to relatively high environmental benefits.

Sections 2 and 3 below describe the analytical model and parameter assumptions. Section 4 presents the quantitative results and sensitivity analysis. Section 5 offers conclusions and expands on the caveats.

2. Analytical Model

A. Assumptions

(i) Households. We consider a static model with two geographically separate electricity sectors, one with price regulation (denoted by *R*) and the other a free market sector with deregulated prices (denoted *M*). The representative household purchases electricity from both markets, during both a peak (*P*) and off-peak (*O*) period, and has utility function:

$$(2.1)\, u\{X,Y,l\}-\delta E \quad X=X\{X^{ij}; i=R,M; j=P,O\}$$

X denotes both sub-utility from, and aggregate consumption of, electricity; *Y* is all other market consumption; *l* is non-market time or leisure; and *E* is pollution emissions. Functions $u\{.\}$ and $X\{.\}$ are quasi-concave. δ is disutility per unit of emissions, assumed constant.[5] All electricity is used directly by households. In practice a portion is used as an intermediate good in the production of other goods. However, assuming constant returns in other industries, this consideration would not affect our results.

Households have a time endowment of $\overline{L}$ that is allocated between labor supply *L* and non-market time: $\overline{L}=L+l$. They receive (supernormal) profits of π through their ownership of firms in the

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[5] Marginal damages are approximately constant in the empirical literature discussed below. For local air pollution this is because mortality rates are roughly proportional to ambient concentrations; for global pollution it is because one year's emissions from the U.S. electricity sector have a small effect on the global atmospheric concentration of carbon dioxide.

The separability assumption in (2.1) implies that changes in environmental quality do not have feedback effects on the labor-leisure decision. Williams (2002) considers such feedback effects arising from pollution-induced health effects and finds them to be minor in size and ambiguous in sign.

electricity sector, and a lump-sum transfer of G from the government. There is a proportional tax of $0<t<1$ on non-government income.[6] The household budget constraint is:

$$(2.2)\, \Sigma_{ij} p^{ij} X^{ij} + Y = (1-t)(L+\pi) + G$$

where p^{ij} is the price of electricity in market i during period j and the price of Y and the gross household wage are normalized to unity.

Households choose electricity consumption, the other market good and leisure to maximize utility subject to the budget and time constraints, taking policy parameters, externalities, and profits as exogenous. We assume that that the resulting electricity demands are linear in prices over the relevant range,[7] and that cross-price effects between geographically separate markets are zero. Therefore:

$$(2.3)\, X^{ij} = X_0^{ij}\left\{1 + \eta^{iij}\frac{\Delta p^{ij}}{p_0^{ij}} + \eta^{ijk}\frac{\Delta p^{ik}}{p_0^{ik}}\right\}, k = P,\, O,\, k \neq j$$

0 denotes an initial value, prior to environmental regulation, Δ denotes the change in a variable from its initial value, η^{ijj} and η^{ijk} are the elasticity of demand for electricity in market i in period j with respect to their own price and the electricity price in the other period, respectively.

(ii) Firms. We assume firms are homogenous, both within and across markets, and can utilize two production technologies, "dirty" (D) and "clean" (C), which might be regarded as coal and gas respectively. The fraction of firms in the regulated and free market sectors are γ^R and γ^M respectively, where $\gamma^R + \gamma^M = 1$. Per capita production by firms, in each period, for each technology, and aggregated over firms, is:

$$(2.4a)\, X^{iP} = h^P(x_D^{iP} + x_C^{iP}),\ X^{iO} = h^O x_D^{iO}$$

$$(2.4b)\, X_D^i = h^P x_D^{iP} + h^O x_D^{iO},\, X_C^i = h^P x_C^{iP}$$

$$(2.4c)\, X^i = X^{iP} + X^{iO} = X_D^i + X_C^i$$

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[6] The assumption that labor and profit (or capital) income are taxed at the same rate seems a reasonable approximation (e.g., Lucas 1990).

[7] This is reasonable, given that proportionate changes in output are relatively modest in our simulations.

(2.4d) $X = \Sigma_i \gamma^i X^i$

where x denotes production per unit of time, h denotes the length of a (fixed) period of time, and X^i is total production for sector i. We normalize $h^P + h^O = 1$ so that h denotes a share in total time. Both technologies are used during the peak period in each market, but only the dirty technology is used during the off-peak period.

The representative firm's cost functions (expressed in labor units), excluding costs associated with environmental policies, are:

(2.5) $C_D\{x_D^{iP}, x_D^{iO}\} = F_D + h^P[\alpha_{D1}x_D^{iP} + \alpha_{D2}(x_D^{iP})^2/2] + h^O[\alpha_{D1}x_D^{iO} + \alpha_{D2}(x_D^{iO})^2/2]$;

$C_C\{x_C^{iP}\} = F_C + h^P \alpha_C x_C^{iP}$

where the αs are parameters, α_{D2}, α_C>0, and the Fs are (non-sunk) fixed costs. These functions imply an increasing marginal cost per unit of time for the dirty technology, and a constant marginal cost for the clean technology.[8]

Emissions per unit of output from clean and dirty production are e_D and e_C respectively, where $e_D > e_C$. Total emissions are:

(2.6) $E = \Sigma_i \gamma^i \left(e_D X_D^i + e_C X_C^i\right)$

The cost functions for reducing emissions per unit (e.g., operating post-combustion scrubbers or substituting low-sulfur coal for high-sulfur coal) are quadratic:

(2.7) $K_D\{-\Delta e_D^i\} = k_D(\Delta e_D^i)^2/2$; $K_C\{-\Delta e_C^i\} = k_C(\Delta e_C^i)^2/2$

where k_D, $k_C > 0$ are parameters.[9]

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[8] The increasing marginal cost for dirty plants may represent utilization of plants with progressively higher operating costs, or increasing opportunity costs as plant production approaches maximum capacity (overtime payments, less downtime for maintenance, etc.). Since gas-fired plants have a much smaller capacity, we approximate by assuming their average variable costs are constant. We do not model electricity transmission and distribution costs; roughly speaking, these are recovered through an access fee.

[9] The assumption of linear marginal abatement costs seems reasonable for SO_2 and NO_X (see Carlson et al. 2000, Figure 2, and Banzhaf et al. 2002, Figure 2). Possibilities for reducing carbon emissions per unit of clean and dirty production are very limited, and for that case we assume e_D and e_C are fixed (see below).

The other market good Y is produced competitively under constant returns.

(iii) Government. The government controls emissions by issuing a fixed quantity $\overline{E}$ of emissions permits that are tradable across firms and regions. In equilibrium when $E = \overline{E}$ there is one market price per permit, denoted τ. Fraction β of the permits are grandfathered to electricity producers and the remaining fraction $1-\beta$ are auctioned at the market price.

The government budget constraint is:

$$(2.8)\, t(L+\pi) + \tau(1-\beta)E = G$$

That is, revenue from taxes on labor and profits, and revenue from permit auctions, equals public spending. We assume that fraction θ of revenue from permit sales is used to reduce the income tax t, while fraction $1-\theta$ is used to reduce the lump-sum transfer G. Indirect revenue effects operating through changes in L and π are neutralized through changes in t.[10]

The government also sets the price in the regulated electricity sector. For this case, we assume that firms cannot pass on the opportunity cost of using freely allocated permits to cover emissions in

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[10] Evidence suggests that unanticipated revenue windfalls are more likely to finance increased government spending rather than tax reductions (e.g., Becker and Mulligan 2003). However this does not necessarily apply to anticipated revenue sources from new environmental policies, as the legislation usually specifies how revenues should be disbursed. In Europe there are numerous recent examples where environmental taxes have been introduced with the revenues specifically earmarked for other tax reductions (e.g., Hoerner and Bosquet 2001, p. 3). In the United States, which has primarily relied on emissions trading systems, permits have mainly been grandfathered to date. To the extent that permit auctions have been proposed, revenues have either been earmarked for compensating those adversely affected by regulation, or they are assumed to accrue to the Treasury. (See, for example, the details of the multi-pollutant bills at www.rff.org/rff/Core/Research_Topics/Air/Multipollutant/Multipollutant-Legislation.cfm.) The recent re-emergence of structural federal budget deficits may well increase the pressure for using new revenue sources for deficit reduction, which implies future tax reductions.

For federal programs, such as proposed multi-pollutant legislation, and proposed limits on carbon emissions in the McCain-Lieberman bill, it is at least conceivable that if permits were auctioned, revenues could be used to cut federal income taxes, thereby generating an efficiency gain. But even for regional programs, such as the Regional Clean Air Incentives Market program for SO_2 and NO_x emissions for metropolitan Los Angeles, revenues from any permit sales could, in principle, generate a similar efficiency gain. Since the tax wedge in the labor market reflects the combined effect of federal income taxes, payroll taxes, state income taxes, and local sales taxes, the efficiency gain from cutting state income or sales taxes is similar to that from cutting federal taxes.

higher prices (i.e., the cost of forgoing permit sales); they can only pass on abatement and permit purchase costs in higher prices (Burtraw et al. 2001a, p. 7).

(iv) Cost minimization. The representative firm chooses clean and dirty production per unit of time, and emissions per unit of output, to minimize production and emissions control costs, for given levels of peak and off-peak production. That is, firms solve

(2.9a) $\underset{x_D^{iP}, x_D^{iO}, x_C^{iP}, e_D, e_C}{Min} \quad C_D\{x_D^{iP}, x_D^{iO}\} + C_C\{x_C^{iP}\} + a_D X_D^i + a_C X_C^i - \tau\beta\overline{E}$ subject to (2.4)

where

(2.9b) $a_D\{\tau\} = \tau e_D + K_D\{.\}\, , a_C\{\tau\} = \tau e_C + K_C\{.\}$

a_D and a_C denote combined abatement and permit purchase costs (or costs from using rather than selling endowed permits), per unit of dirty and clean production respectively; these are identical across regions as firms have identical abatement technologies and face the same permit price. $\beta\overline{E}$ is the firm's (exogenous) permit endowment (which is identical across firms) and has market value $\tau\beta\overline{E}$.

From (2.4), (2.5), (2.7), and (2.9) we can obtain:

(2.10a) $\alpha_{D1} + \alpha_{D2} x_D^{iP} + a_D\{\tau\} = \alpha_C + a_C\{\tau\} \equiv MC^P ; \alpha_{D1} + \alpha_{D2} x_D^{iO} + a_D\{\tau\} \equiv MC^{iO}$;

(2.10b) $-k_D \Delta e_D = -k_C \Delta e_C = \tau$

(2.10c) $AC^i = c^i + \dfrac{a_D X_D^i + a_C X_C^i - \tau\beta\overline{E}}{X^i} ; c^i = \dfrac{C_D^i\{.\} + C_C^i\{.\}}{X^i}$

MC^P and MC^{iO} denote marginal production costs per unit of time in the peak and off-peak periods, including abatement/permit costs, and AC^i is the average cost of production across both periods for firms in sector *i*. From (2.10a) marginal production costs are equalized across clean and dirty production in the peak period, and across markets, because the marginal costs are constant. Marginal costs are lower in the off-peak period ($MC^{iO} < MC^P$), as it is not worthwhile to use the clean (constant marginal cost) technology. Marginal costs may also differ across markets in the off-peak period due to different production rates and rising marginal costs. From (2.10b) marginal abatement costs are equated to the permit price for dirty and clean production. And from (2.10c) average costs for firms in market *i* equal per-unit production costs, c^i, plus average abatement/permit costs per unit, net of the value of endowed permits.

(v) Competition, electricity prices, and profits. In practice there is potential for local market power in deregulated electricity markets when (a) demand rises to a point where small-scale (price-taking) operators are producing at full capacity, enabling a few large producers to reduce production without an offsetting expansion by fringe firms, and/or [Q: correct that it is and/or, or must both conditions be present?] (b) congestion on the grid prevents importation of power from generators in other regions. However, the mark-up of price over marginal cost is highly sensitive to the level and elasticity of demand, assumptions about the form of strategic behavior, availability of renewable generation, and so on (e.g., Borenstein et al. 1999, Stoft 2002, part 4). For our benchmark simulations we make the simpler assumption of marginal cost pricing in the free market sector, which is relaxed in the sensitivity analysis.

Electricity prices are determined as follows:

(2.11a) $p^{Rj} = AC^R$

(2.11b) $p^{MP} = \mu MC_0^P + \psi \Delta MC^P$, $p^{MO} = MC^{MO}$

(2.11c) $p = \Sigma_{ij} \gamma^i p^{ij} X^{ij} / X^i$

In the regulated sector price in each period equals average production cost. Note that, from (2.10c), the opportunity cost of using endowed permits to cover emissions is not passed on in higher product prices.[11] In the deregulated sector, $\mu \geq 1$ is the initial price/marginal cost ratio in the peak period, and ψ determines how prices respond to changes in marginal cost; however our benchmark assumptions are $\mu = \psi = 1$, so that electricity is competitively priced in both peak and off-peak periods. p denotes the economy-wide average electricity price, equal to a weighted average of prices across periods and sectors.

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[11] Implicitly, we assume a conventional cost-of-service type of regulation where price is immediately adjusted to reflect changes in operating costs. In practice, many regulated utilities operate under various forms of performance-based rates where rates are set according to expected average costs over some future period of time. This distinction is not so important for our analysis, which compares long-run equilibria with and without emissions limits.

Aside from the distortion in production levels due to non-marginal cost pricing, price regulation may also result in other inefficiencies, such as over-investment in capital or inadequate incentives for firms to lower costs over time (e.g., Joskow and Schmalensee 1986); these issues are beyond our scope.

Per capita profits from the electricity industry are

$$(2.12)\ \pi = \Sigma_i \gamma^i [\Sigma_j p^{ij} X^{ij} - AC^i X^i]$$

B. Welfare Effects of Environmental Policies

(i) Welfare components. The welfare change from the emission permit policy can be decomposed into four components (see Appendix):

$$(2.13) - (\delta / \lambda)\Delta E \quad - [K_C X_C + K_D X_D + \Sigma_i \gamma^i \Delta c^i X^i] + \Sigma_{ij} \gamma^i (p_0^{ij} - MC_0^{ij} + \Delta p^{ij} / 2)\Delta X^{ij} + t_0 \Delta L$$

where λ is the marginal utility of income.

The first component in (2.13) is the gain from the reduction in environmental damages, equal to the reduction in emissions ($-\Delta E$) times marginal damage expressed in dollars (δ / λ). The second component is a welfare loss from the cost of reducing the emissions intensity of production: it consists of (a) the pure abatement costs aggregated over dirty and clean production and (b) the change in variable production costs, excluding abatement/permit purchase costs, aggregated over all firms. The latter component reflects the costs of substituting clean production for dirty production at peak period.

The third component in (2.13) is the welfare effect from the change in electricity output. It consists of (a) the initial wedge between price (or marginal consumer benefit) and marginal production cost multiplied by the change in output for a particular sector and period and (b) the second order welfare loss from reducing output in the absence of other distortions (one-half times the increase in price times the change in output). These two components are aggregated across periods and sectors. The final component is the welfare change in the labor market. It equals the change in labor supply times the labor tax, where the latter reflects the wedge between the gross and net wage, or between the value marginal product of labor and the marginal opportunity cost of forgone non-market time.

(ii) Labor market effect. The final component can be decomposed as follows (see Appendix):

$$(2.14\text{a})\ t_0 \Delta L \ \approx\ M[\theta(1-\beta)\tau\overline{E} + t_0 \Delta\pi] \ - (1+M) t_0 \frac{\partial L}{\partial p} \Delta p$$

$$(2.14\text{b})\, M = \frac{-t_0 \partial L / \partial t}{L_0 + t_0 \partial L / \partial t} = \frac{\frac{t}{1-t}\varepsilon}{1 - \frac{t}{1-t}\varepsilon}$$

where $\varepsilon = [\partial L / \partial(1-t)](1-t)/L$ denotes a labor supply elasticity with respect to the net of tax household wage. *M* is the marginal excess burden of labor taxation, or efficiency cost of raising an extra dollar of tax revenue. It equals the (partial equilibrium) welfare loss from an incremental increase in the labor tax, divided by marginal tax revenue. We take *M* as constant.[12]

The first expression on the right in (2.14a) is the *revenue-recycling* effect, which consists of two components. One is the efficiency gain from using revenue from auctioned permits to cut distortionary labor taxes; this equals the marginal excess burden, times the permit revenue, times the fraction of that revenue used to cut labor taxes. The other is the efficiency effect from neutralizing changes in profit tax revenues by adjusting the income tax (again the change in revenues times the marginal excess burden). The second expression in (2.14a) is the *tax-interaction* effect. This is the welfare loss from the reduction in labor supply due to the reduction in the real household wage as the price of electricity increases. It equals the reduction in labor supply ($-(\partial L / \partial p)\Delta p$) multiplied by the labor tax wedge, plus the product of the marginal excess burden and the reduction in labor tax revenue ($-t_0(\partial L / \partial p)\Delta p$).

As in earlier studies, we assume that electricity and the other consumption good *Y* are equal substitutes for leisure.[13] The tax-interaction effect is then (see Appendix):

$$(2.15\text{a}) - (1+M)t_0 \frac{\partial L}{\partial p}\Delta p \approx MX_0 \Delta p$$

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[12] This is reasonable because the change in labor supply and labor tax in our simulations is very small.

Some previous studies distinguish two marginal excess burdens, depending on different compensated and uncompensated labor supply effects (e.g., Goulder et al. 1999). We avoid this complication by defining welfare changes purely by substitution (i.e., compensated) effects (see Appendix), and by choosing a compromise value for *M*.

[13] We are not aware of any empirical evidence that electricity is either a relatively strong or relatively weak leisure substitute. Two-thirds of electricity is used as an intermediate good in the production of consumption goods in general. This consideration strengthens the tendency for electricity to be an average leisure substitute.

where

(2.15b) $\Delta p = \gamma^{M} \psi \hat{a}^{M} + \gamma^{R} (\bar{a}^{R} - \beta \tau \bar{e}^{R} + \Delta c^{R})$

(2.15c) $\hat{a}^{M} = [a_{C} X^{MP} + a_{D} X^{MO}] / X^{M}$, $\bar{a}^{R} = [a_{D} X_{D}^{R} + a_{C} X_{C}^{R}] / X^{R}$, $\bar{e}^{R} = [e_{D} X_{D}^{R} + e_{C} X_{C}^{R}] / X^{R}$

The price increase is a weighted average of the increase in market and regulated prices. The increase in market price in the peak period depends on per-unit abatement/permit purchase costs for the clean (marginal) technology, and at off-peak period depends on per unit abatement/permit purchase costs for the dirty technology. The increase in regulated price (for both periods) is the abatement/permit purchase costs averaged over all regulated production ($\bar{a}^{R}$), less the value of grandfathered permits per unit of output ($\beta \tau \bar{e}^{R}$), plus the increase in average production costs (Δc^{R}).

(iii) Comparison with prior literature. The most important difference between our analysis and that in prior studies (e.g., Goulder et al. 1997, Parry et al. 1999, Fullerton and Metcalf 2001) is that the increase in average electricity price, and hence tax-interaction effect, is smaller. Previous studies assume constant returns, competition, and a single production technology. Under these conditions abatement/permit purchase costs are fully passed on in higher product prices. The price increase is smaller in our analysis for two main reasons. First, to the extent that permits are grandfathered ($\beta > 0$), and prices are regulated, the opportunity cost of using permits to cover emissions, $\tau \beta \bar{e}^{R}$, is not passed on in higher prices. Second, in the market sector, the abatement/permit purchase costs for the dirty technology in the peak period are not reflected in higher prices, because the increase in marginal cost depends on the cost increase for the marginal (i.e. clean) technology. If marginal production produces no emissions ($a_{C} = 0$), peak-period abatement costs in the market sector come entirely at the expense of infra-marginal rents, and there is no effect on the peak-period market price. Indeed with full price deregulation, no emissions from the clean technology, and a large share of total production at peak period, the price increase will be very limited.

Other differences are that we incorporate welfare effects from changes in electricity production due to non-competitive pricing (in the regulated sector, and in the market sector if there is imperfect competition). We also capture the change in tax revenue due to the reduction in the non-permit-rent component of profits, as abatement/permit purchase costs are not fully passed on in higher prices. This diminishes the revenue-recycling effect.

(iv) Output-based allocation. An allocation that divides permits among firms according to their market shares has the same incentive effect of a production subsidy (e.g., Fischer 2003). For this case the cost-minimization problem becomes:

$$(2.9\text{a}') \quad \underset{x_D^{iP}, x_D^{iO}, x_C^{iP}, e_D, e_C}{Min} \quad C_D\{x_D^{iP}, x_D^{iO}\} + C_C\{x_C^{iP}\} + a_D X_D^i + a_C X_C^i - s(X_D^i + X_C^i) \text{ subject to (2.4)}$$

where s is a perceived subsidy, equal to the value of extra permits obtained when an individual firm increases its production by one unit; in equilibrium $s \equiv \beta E / X$. Adjusting (2.15b), the electricity price increase is given by:

$$(2.15\text{b}') \, \Delta p = \gamma^M \psi(\hat{a}^M - s) + \gamma^R(\overline{a}^R + \Delta c^R - s)$$

Comparing with (2.15b), the electricity price increase is smaller than under grandfathered permits; the per-unit subsidy works to offset the higher prices from abatement/permit purchase costs in both the regulated and market sectors, while under grandfathered permits the price offset due to the failure to pass on the opportunity cost of freely allocated permits applies to the regulated sector only.

(v) Model Solution. We cannot obtain explicit analytical solutions to the model, as price varies with production levels. But it is straightforward to solve the model by specifying a given τ, iterating over the electricity price until equilibrium is reached, and finding the τ that achieves a given target for emissions. Welfare effects are then computed using (2.13)–(2.15).

3. Parameter Values

We benchmark the model by using data from the Energy Information Administration (EIA) and from Haiku, a national electricity model,[14] and then provide an extensive sensitivity analysis. Data are for 2010, with figures expressed in current dollars. We begin with moderate, substantial, and intermediate emissions reductions for carbon, NO_x, and SO_2, respectively, each based on actual or proposed policies. Benchmark assumptions are summarized in Table 1.

Electricity data (prior to emissions regulation). Currently, well over half of generated electricity is subject to regulated prices, though this will diminish in the future with continued restructuring.[15] Based on the benchmark case of 2020 from Burtraw et al. (2001a), we assume $\gamma^R = \gamma^M = 0.5$; the sensitivity analysis considers full price deregulation. Production rates are taken to be equivalent, initially, across the regulated and free market sectors, for both peak and off-peak period. Hence, average and marginal costs are the same across sectors. Based on widely cited EIA projections, we assume baseline electricity generation X_0 of 4,105 million MWh in 2010, an economy-wide average generation price p_0 of \$40/MWh, and dirty and clean production shares (X_{D0}/X_0 and X_{C0}/X_0) of 0.54 and 0.46.[16] From EIA (1998, Figure 88), we assume that the marginal technology is the dirty and clean fuel 30% and 70% of the time respectively; thus $h^O = 0.3$, $h^P = 0.7$.

The initial difference in marginal production cost between peak and off-peak periods is zero when $x_D^{iO} = x_D^{iP}$; for the benchmark case we assume $x_D^{iO} = x_D^{iP}/2$. Using (2.4) and the aggregate production level, we obtain $X_0^{iP} = 3{,}714$, $X_0^{iO} = 391$, $x_{D0}^{iP} = 2{,}608$, $x_{C0}^{iP} = 2{,}698$, and $x_{D0}^{iO} = 1{,}304$. Given values for

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[14] Haiku contains considerable disaggregation across regions, time periods, seasons, and production technologies. See Carlson et al. (2000), Burtraw et al. (2001a and b), Palmer et al. (2001), Banzhaf et al. (2002), and Paul and Burtraw (2002).

[15] So far, 24 states have committed to competitive retail prices for electricity, seven states have recently delayed the transition, California has suspended competitive prices, and most of the states that remain committed have transition periods with price caps in effect through most of the next decade (Brennan et al. 2002).

[16] See www.eia.doe.gov/oiaf/aeo/pdf/aeotab_8.pdf. Dirty production includes coal and petroleum generation and clean production all other sources (renewables, gas, nuclear, etc.).

α_{D1} and α_{D2} (these parameters, along with fixed costs, are calibrated to carbon abatement cost estimates below), this implies peak and off-peak marginal costs of \$48.8 and \$9.0/MWh respectively, and a marginal cost averaged across periods of \$45.0/MWh (consistent with estimates from Haiku). In practice, there is considerable dispersion in marginal costs across regions, seasons, and time blocs, though, as discussed later, our results are not especially sensitive to different marginal cost distributions.

To begin with we assume marginal cost pricing under deregulation ($\mu = \psi = 1$). Given this and other assumptions, prior to environmental regulation, $AC^R = (p_0 - \gamma^M MC_0)/\gamma^R$ (from (2.11)). Using the above figures yields AC = \$35/MWh.

Based on EIA (1998) and Banzhaf et al. (2002, p. 16), we assume that when all electricity prices increase by 1%, the economy-wide demand for electricity falls by 0.3%, with the results not especially sensitive to other values. We assume that the own-price elasticities (when the price in one period increases while remaining constant in the other period) are (initially) the same across markets and periods, $\eta^{ijj} = \eta$. And we set η at double the economy-wide elasticity, choosing cross-price elasticities such that half of the own-price reduction in one period is due to reduced overall demand and half is due to substitution into the other time period.

SO_2. Title IV of the 1990 Clean Air Act Amendments caps annual utility SO_2 emissions at about 9 million tons by 2010. We assume emissions in the absence of controls would be 16 million tons, therefore $-\Delta E$ = 7 million.[17] All SO_2 emissions come from coal, thus $e_C^0 = 0$ and $-\Delta e_D = -\Delta E / X_D$ = 0.0032 tons/MWh. Carlson et al. (2000, p. 1312), estimate the permit price (τ) under the cap at \$290 per ton. Almost all the reduction comes from end-of-pipe treatment and substitution of low- for high-sulfur coal, rather than substitution between gas and coal, thus Δc = 0 (and very little of it comes from reduced final output). Using (2.10b) this gives k_D = 91,835.

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[17] From applying 1993 emissions rates to 2010 electricity production (seewww.epa.gov/airmarkt/emissions/score00/text00.pdf).

Estimated benefits of the SO_2 program are extremely large relative to costs, due to substantial estimated mortality effects. Based on Banzhaf et al.'s integrated assessment (2002), we assume marginal damages δ/λ of \$3500/ton.

Carbon. Carbon emissions from electricity with no abatement are assumed to be 689 million tons, with 86% and 14% from dirty and clean production, respectively (from EIA 2003, Table 19). This implies $e_D^0 = 0.2642$ and $e_C^0 = 0.0547$ tons/MWh. To start with, we consider an emissions reduction of 10%, based on the McCain-Lieberman bill, which would initially reduce utility emissions to 2000 levels (or 621 million tons).[18]

For calibration we use EIA's scenario (1998) for a carbon tax of \$67, which causes coal-fired generation to fall by 17.6% in 2010, and all other generation to increase by 12.9%.[19] We simplify by assuming there are no possibilities for reducing carbon emissions per unit of either dirty or clean generation: all emissions reductions per unit of electricity come from switching clean for dirty generation.[20] Solving (2.10a) for the initial equilibrium, the equilibrium with the emissions tax, and using an expression for the economy-wide marginal cost, gives $\alpha_{D1} = -30.1$, $\alpha_{D2} = .031$, and $\alpha_C = 48.8$.[21] And using (2.5) and (2.10c) for initial values, and $AC = 35$, gives fixed costs $F_D + F_C =$ \$39,335 million.

Most estimates of the external costs of carbon emissions (e.g., the future damage to agriculture and the costs of protecting valuable coastal regions against sea level rises) are below \$50 per ton, although these estimates are obviously subject to much dispute and a few studies obtain much larger

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[18] See www.rff.org/rff/News/Features/Understanding-the-McCain-Lieberman-Stewardship-Act.cfm.

[19] From EIA (1998), Tables ES1 and B8, "24 percent above" scenario.

[20] Although there are no economically viable post-combustion scrubbers for carbon, and all coal has the same carbon content, e_D might still be still be reduced by increasing generation efficiency. But these effects are relatively minor in EIA's analysis: emissions from coal-fired generation fall by 18.8%, only slightly larger than the reduction in generation (Table B19).

[21] That is, using $x_D^{iP} = 2608$ in (2.10a), then $x_D^{iP} = 2149$, $a_D = \tau e_D = 17.7$, and $a_C = \tau e_C = 3.7$, in (2.10a), and $x_D^{iO} = 1304$, $X^{iP} / X^i = 0.9$, and $X^{iO} / X^i = 0.1$ in the following expression for the initial economy-wide marginal cost: $45 = \alpha_C (X^{iP} / X^i) + (\alpha_{D1} + \alpha_{D2} x_D^O)(X^{iO} / X^i)$.

values (see the reviews by Tol et al. 2000 and Pearce 2003). For illustrative purposes, we adopt a value of \$50 per ton.

NO_x Baseline NO_x emissions are 5.9 million tons in Banzhaf et al. (2002), with 95% of emissions coming from dirty generation; thus $e_D^0 = 0.0025$ and $e_C^0 = 0.00016$ tons/MWh. The Jeffords four-pollutant bill would cap annual NO_x emissions at 1.5 million tons from 2008, while the Bush administration's "Clear Skies" proposal would cap NO_x emissions at 2.1 million tons in 2008.[22] For our benchmark we consider a cap of 1.8 million—an emissions reduction of 70%. In Banzhaf et al. (2002) the permit price at this cap is around \$900/ton, and 85% of emissions now come from dirty generation ($e_D = 0.00069$, $e_C = 0.00014$). From these figures we obtain $k_D = 489521$; we assume no possibilities for abatement at clean plants. Based on the results of Banzhaf et al.'s integrated assessment (2002, Table 2a), we assume $\delta = \$1000$/ton.

Marginal excess burden. Based on prior literature, we assume $M = 0.25$ in the benchmark, and consider values between 0.15 and 0.40 in the sensitivity analysis. The profit tax is set at $t = 0.4$.[23]

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[22] See www.rff.org/rff/Core/Research_Topics/Air/Multipollutant/Multipollutant-Legislation.cfm.

[23] Prior models (e.g. Goulder et al. 1997, Parry et al. 1999) assume the combined effect of income, payroll and sales taxes implies a labor income tax of 40%; they assume the same tax applies to profit income. Based on reviews by Blundell and MaCurdy (1999) and Fuchs et al. (1998), a plausible estimate for the economy-wide labor supply elasticity ε (averaging over males and females and the hours worked and participation elasticities) is around 0.15 to 0.5 (this spans the range across compensated and uncompensated estimates). Using (2.14b), we obtain the above values for *M*.

4. Quantitative Results

A. Benchmark Results

Tables 2 through 4 present benchmark estimates of efficiency costs, and welfare effects, of the SO_2 allowance program, and proposed policies for carbon and NO_x, under the four alternative scenarios for permit allocation. We show estimates for the "multi-technology" model, which is the model described above, and a "single-technology" model with constant returns, competition, and the same emission rates for marginal and infra-marginal production. The latter assumptions replicate those of previous fiscal interaction models (e.g., Goulder et al. 1997, Parry et al. 1999). All figures are in current $ millions per annum.

SO_2. In the single-technology model under grandfathered permits, nearly all of the emissions reduction comes from abatement activity, and very little from reducing electricity output: abatement costs are $999 million and the efficiency costs of reduced output are $12 million (see Table 2). The tax-interaction effect is $902 million, almost as large as abatement costs. Auctioning permits and using the revenue to cut income taxes yields an efficiency gain of $648 million. Under grandfathered permits, recycling of indirect revenues taxation of permit rents yields an efficiency gain of $259 million. On net, fiscal interactions raise the costs of grandfathered permits (relative to the costs of abatement and reduced output) by 64%, the costs of revenue-neutral auctioned permits by 25%, and the costs of auctioned permits with revenues returned in lump-sum transfers to households by 89%. With output-based allocation the tax-interaction effect is much smaller, as the effective production subsidy serves to dampen the product price increase, and hence the impact on lowering real wages: fiscal interactions raise the cost of this policy by 25%.[24]

Results from the multi-technology model are noticeably different for several reasons. Most important, the tax-interaction effect is dramatically reduced, from $902 million to $496 million under auctioned permits, as the effect on product prices and the real wage is weaker (see the discussion of Equation 2.15b above). The tax-interaction effect is smaller still under grandfathered permits ($192 million), because the opportunity cost of using freely allocated permits to cover emissions is not passed

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[24] These numerical results are consistent with those in Goulder et al. (1997).

on in higher product prices under regulated pricing. Under output-based allocation the tax-interaction effect actually becomes negative, as the overall effect of this policy is to slightly reduce the product price.

Another difference is that there is a welfare gain from reduced electricity output under grandfathered and auctioned permits. However, this welfare gain is much less important than the savings from the smaller tax-interaction effect. A further difference is that there is now a negative component to the revenue-recycling effect. Profits (excluding any permit rents) fall as abatement/permit purchase costs are not fully passed on in higher prices but are in part borne at the expense of producer surplus.
Overall, costs are lower in the multi-technology model, compared with the single-technology model, by 32–35% for grandfathered and revenue-neutral permits, and by 18–23% for auctioned permits with lump-sum replacement and output-based allocation (see "relative cost" row, Table 2).

Nonetheless, according to our estimates, the emissions control mandated by the SO_2 program is easily welfare-enhancing overall, regardless of permit allocation and of the assumed model—welfare gains vary between $23.0 and $23.7 billion across all the policy scenarios in Table 2. The reason is that assumed environmental benefits are more than an order of magnitude larger than policy costs.

Carbon. The results for carbon are particularly striking, as shown in Table 3. Under grandfathered permits the cost of the tax-interaction effect is $6,276 million in the single-technology model while in the multi-technology model it is $2,327 million; the overall costs of grandfathered permits are 48% lower in the multi-technology model. The cost of revenue-neutral auctioned emissions permits is actually slightly *negative* in the multi-technology model, while its cost is positive $1,737 million in the single-technology model. The tax-interaction effect is smaller than the revenue-recycling effect under revenue-neutral auctioned permits in the multi-technology model because of the smaller increase in product prices. Under grandfathered and auctioned permits the reduction in electricity output in the regulated sector produces a modest welfare gain; under the output-based allocation, output increases slightly.

Other differences are that a higher portion of the total emissions reduction comes from substituting clean for dirty production under grandfathered and auctioned permits, and less from reduced final output in the multi-technology model, as a smaller portion of abatement costs are passed on in higher product prices. The revenue-recycling effect under auctioned permits is also larger than in the single-technology model. The overall demand for emissions is less elastic, and therefore requires a higher tax rate to achieve a given total emissions reduction, due to the weaker effect of abatement costs on price and output in the multi-technology model.

The greater importance of fiscal interactions relative to pure abatement costs in the case of carbon compared with SO_2 is mainly due to the difference in abatement levels: the carbon emissions reduction is 10% below baseline levels, while the SO_2 emissions reduction is 45%. As emphasized in earlier literature (e.g., Goulder et al. 1997, Goulder et al. 1999), revenues from emissions permits, and hence the revenue recycling effect, diminish in size relative to pure abatement costs as the proportionate reduction in emissions rises. As regards the tax-interaction effect, it is a first-order (i.e., a rectangle) welfare loss in the labor market and is roughly proportional to the extent of abatement (through the product price increase). In contrast, pure abatement costs are second order and increase, approximately, with the square of the abatement level.

In terms of social welfare the choice of permit allocation, and also the choice of model, can crucially affect the direction of the estimated welfare change. Auctioned permits produce a welfare gain of \$3,897 million in the multi-technology model if revenues are used to cut distortionary taxes, but a welfare loss of \$2,967 million if revenues are returned lump sum. And grandfathered permits produce a net welfare loss of \$1,783 million in the single-technology model, but a welfare gain of \$758 million in the multi-technology model.

NO_x. Results for NO_x are shown in Table 4. Total costs are lower in the multi-technology model than in the single-technology model by 14–20% across the four policies. These relative cost differences are less striking than those for either SO_2 or carbon; this is because the proportionate emissions reduction is greater (70%) and therefore the revenue-recycling and tax-interaction effects are smaller in size relative to abatement costs. Welfare effects from changes in output are relatively small, as reductions in emissions per unit of output account for nearly all of the total emissions reduction. All the policy instruments improve social welfare overall—welfare gains vary between \$1,935 and \$2,242 million in the multi-technology model.

B. Sensitivity Analysis

Size of Unregulated Sector. In Table 5 we report results from the multi-technology model with full deregulation ($\gamma^M = 1$). In this case, price is determined entirely by marginal technologies and the price differential between grandfathered and auctioned permits disappears.

For SO_2 in the peak period the marginal technology has zero emissions, hence its marginal cost is unaffected by permit policies. Marginal costs only rise in the off-peak period, when the marginal technology is the dirty one. Comparing Tables 2 and 5, the tax-interaction effect is lower under all permit policies for SO_2 in the multi-technology model with full price deregulation. (With average-cost pricing, a portion of the peak-period abatement costs for infra-marginal technologies are passed on in higher prices.)

Another difference between the multi-technology model with partial and full deregulation is that in the latter case the welfare loss from the profits component of the revenue-recycling effect is about twice as large (for SO_2), and this partly offsets the smaller tax-interaction effect. This is because a greater portion of abatement/permit purchase costs come at the expense of firm profits. Therefore, there is larger revenue loss associated with the erosion of profits. Finally, the modest welfare gain from the reduction in output stemming from the excess of marginal cost over price in the regulated sector is entirely eliminated under full deregulation.[25]

Comparing Table 5 with Tables 2 through 4, for all three pollutants, costs in the multi-technology model with full deregulation, relative to those in the single-technology model, are either roughly the same as with partial deregulation, or significantly lower. In particular, the tax-interaction effect under auctioned carbon permits is almost halved, again because a larger portion of abatement costs for the infra-marginal technology are absorbed by lower profits rather than passed on in higher prices.

Extent of Abatement. Table 6 illustrates how results vary with the extent of abatement. We express overall costs from both the multi-technology and single-technology models relative to the combined costs of abatement and reduced output in the single technology model, for a given emissions reduction. Results are shown for grandfathered permits and revenue-neutral auctioned permits.

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[25] In fact, welfare effects from the reduction in output are less than \$1 million (aside from the output-based allocation) while they amount to \$12 million in the single-technology model. This is because prices increase by only 0.3% compared with 2.2% in the single-technology model.

In the single-technology model, overall costs of grandfathered permits relative to pure abatement/output costs decline with the extent of abatement; for example for SO_2 overall costs are 145%, 64%, and 38% higher than abatement/output costs for emissions reductions of 20%, 45%, and 70%, respectively. And the proportionate increase in costs due to fiscal interactions is roughly the same across different pollutants, at a given level of abatement (compare the 45% emissions reduction for SO_2 and NO_x or the 20% reduction for all three pollutants). The net loss from the tax-interaction and revenue-recycling effects under auctioned permits raises that policy's costs by 25–36%, regardless of the extent of abatement.[26]

In the multi-technology model, the cost ratios in Table 6 are lower than in the single-technology model, for all pollutants and all abatement levels considered; for auctioned permits the cost ratios are below unity for modest abatement levels, implying a net welfare gain from fiscal interactions (rather than a net welfare loss, as in the single-technology models). The lower cost ratios in the multi-technology model are due to the smaller tax-interaction effect.

Market power in the deregulated sector. We illustrate how market power might affect the analysis in the case of SO_2. We consider scenarios where the initial price-marginal cost ratio in the deregulated sector is 1.1 and 1.4 in the peak period (maintaining baseline production levels for peak and off-peak periods).[27] Results are summarized in Table 7 for grandfathered permits and revenue-neutral auctioned permits.

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[26] All these results have been discussed at length in prior literature (see Goulder et al. 1997, Goulder et al. 1999).

[27] It is difficult to pin down a "best estimate" for the price-marginal cost markup. Simulations from models where a competitive fringe produces at full capacity when demand exceeds a certain threshold, leaving an oligopoly of several large producers, suggest price-marginal cost markups anywhere from 0 to well over 100% (e.g., Borenstein et al. 1999, Figure 3; Borenstein and Bushnell 1999). And a recent study based on averaged monthly data for California by Borenstein et al. (2002) finds near competitive pricing for 1998 to 1999, but that prices rose to roughly twice marginal costs during the peak summer months of 2000. In both cases the very high markups apply to only a minor share of what we have defined as peak electricity sales. (In our analysis peak sales account for 90% of annual electricity sales in the deregulated sector.)

Given the homogeneity of electricity output and if prices are determined in, say, an auction then firms might have close to no market power when there is plenty of capacity (because the firm demand curve is almost perfectly elastic). It therefore seems reasonable to maintain the assumption of competitive pricing in the off-peak period.

For SO_2 the marginal technology in the peak period has zero emissions; abatement costs are incurred only in the off-peak period when the marginal technology is coal. In the free market sector there is a shift in output from the off-peak period to the peak period. In one scenario, we assume the extra peak demand is accommodated entirely by extra production with no effect on peak period price. Unlike in the benchmark case, the extra peak production leads to an efficiency gain because of the price-marginal cost margin, and this moderately reduces overall policy costs (comparing Table 7 with the relative cost row in Table 2). In another scenario we assume that extra peak-period demand is reflected entirely by higher prices, with no change in production. Here there is no efficiency gain from extra peak period output; instead the tax-interaction effect is increased, though this is partly offset by the recycling of higher profit tax revenues. Overall costs for grandfathered and auctioned permits increase to around 75% of their costs in the single technology model (Table 7). The case of carbon is a little more complex because marginal costs in the peak period increase. To the extent they may not be fully passed on in higher prices because of imperfect competition, the tax-interaction effect could be somewhat smaller than in the benchmark case.

Other parameters. In the first set of rows in Table 8 we vary the dispersion in (initial) marginal production costs between the peak and off-peak periods, keeping the mean marginal cost, average cost, electricity price, and total production constant. We vary the off-peak marginal cost between its minimum and maximum value by altering production rates per unit of time; we also consider different scenarios for the relative length of the peak and off-peak periods, and therefore the fraction of the time that the marginal technology is the dirty one. The results, illustrated for the case of SO_2, are not very sensitive to these variations. The welfare effect from the change in output is approximately the same for a given mean marginal cost, regardless of the dispersion of marginal costs between peak and off-peak periods. Moreover, even though the marginal costs in the unregulated sector, averaged across peak and off-peak periods, become more sensitive to abatement costs at dirty plants, the longer the duration of the off-peak period, the overall effect on product prices and the tax-interaction effect remains modest across the parameter variations considered.

Moderately more important is the (mean) gap between (mean) marginal production cost and average cost, and hence the gap between price and marginal cost. We consider scenarios where the average production cost is \$25/MWh, \$45/MWh, and \$55/MWh, which imply differences between (mean) marginal production cost and average cost of \$20/MWh, \$0/MWh, and –\$10/MWh, respectively, or differences between (mean) marginal production cost and price of \$10/MWh, \$0/MWh, and –\$5/MWh, respectively. The results are noticeably (though not drastically) affected. For example, the costs of revenue-neutral auctioned permits in the multi-technology model vary between 57% and 78% of their costs in the single-technology model. The differences are due almost entirely to different efficiency effects from induced changes in output; the revenue-recycling and tax-interaction effects are essentially unchanged.

Relative (though not necessarily absolute) costs in the single- and multi-technology models are slightly to moderately sensitive to varying other parameters, including the slope of the marginal abatement cost curve, the electricity demand elasticity, and the marginal excess burden of taxation (see Table 8).

5. Conclusion

Recent literature has emphasized that interactions with the broader fiscal system can importantly affect the costs of environmental (and other regulatory) policies. This paper extends this literature to account for certain specific features of electricity generation, which is a major contributor to local and global pollution. These features include (a) the distinction between dirty (coal) technologies, which are assumed to be marginal only in off-peak periods, and clean (gas) technologies, which are assumed to be marginal in peak periods and (b) non-competitive pricing. The analysis is applied to current and proposed controls on utility emissions of SO_2, carbon, and NO_x.

The paper shows that allowing for these features significantly diminishes welfare losses from the tax-interaction effect—that is, the exacerbation of labor tax distortions due to the effect of regulations on raising product prices and reducing real household wages. The results are reasonably robust to a wide range of scenarios, such as full price deregulation, the extent of imperfect competition in the deregulated sector, and the extent of dispersion in marginal production costs across time of day. Results are most striking in the case of carbon where proposed proportionate emissions reductions are the most moderate. For example, the costs of reducing carbon emissions by 10% under grandfathered permits and revenue-neutral auctioned permits are computed at \$2.7 and –\$0.5 billion in the present model in the benchmark case; in contrast, with a single, constant returns technology model with competitive pricing, the costs of these policies are computed at \$5.2 and \$1.7 billion, respectively.

One limitation is that we use a highly aggregated model of both the electricity market and labor market. In practice labor supply elasticities may vary across regions, and certainly the relative burden of emissions mitigation costs varies across regions with different emissions intensities of production. If these factors are positively (or negatively) correlated, the aggregate costs of fiscal interactions will be larger (or smaller) than predicted above.

References

Banzhaf, Spencer, Burtraw, Dallas, and Karen Palmer. 2002. "Efficient Emission Fees in the U.S. Electricity Sector." Discussion Paper 02-45. Washington, DC: Resources for the Future.

Becker, Gary S., and Casey Mulligan. 2003. "Deadweight Costs and the Size of Government." *Journal of Law and Economics* XLVI: 293–340.

Blundell, Richard W., and Thomas MaCurdy. 1999. "Labor Supply: A Review of Alternative Approaches." In O. Ashenfelter and D. Card (eds.), *Handbook of Labor Economics*, pp. 1559–1695, North-Holland: Amsterdam.

Borenstein, Severin, and James B. Bushnell. 1999. "An Empirical Analysis of the Potential for Market Power in California's Electricity Industry." *Journal of Industrial Economics* XLVII: 285–323.

Borenstein, Severin, James B. Bushnell, and Christopher R. Knittel. 1999. "Market Power in Electricity Markets: Beyond Concentration Measures." *Energy Journal* 20: 65–88.

Borenstein, Severin, James B. Bushnell, and Frank A. Wolak. 2002. "Measuring Market Inefficiencies in California's Restructured Wholesale Electricity Market." *American Economic Review* 92: 1376–1405.

Bovenberg, A. Lans, and Lawrence H. Goulder. 2002. "Environmental Taxation." In A. Auerbach and M. Feldstein, eds., *Handbook of Public Economics* (second edition. forthcoming). New York: North-Holland.

Brennan, Timothy J., Karen L. Palmer, and Salvador A. Martinez. 2002. *Alternating Currents: Electricity Markets and Public Policy*. Washington, DC: Resources for the Future.

Burtraw, Dallas, Karen L. Palmer, Ranjit Bharvirkar, and Anthony Paul. 2001a. "The Effect of Allowance Allocation on the Cost of Carbon Emissions Trading." Discussion Paper 01-30. Washington, DC: Resources for the Future.

Burtraw, Dallas, Karen Palmer, Ranjit Bharvirkar, and Anthony Paul, 2001b. "Cost-Effective Reduction of NO_x Emissions from Electricity Generation." Discussion Paper 00-55. Washington, DC: Resources for the Future.

Carlson, Curtis, Dallas Burtraw, Maureen Cropper, and Karen Palmer. 2000. "SO_2 Control by Electric Utilities: What are the Gains from Trade?" *Journal of Political Economy* 108: 1292–1326.

EIA. 1998. *Impacts of the Kyoto Protocol on US Energy Markets and Economic Activity*. Washington, DC: U.S. Energy Information Administration.

EIA. 2003. *Annual Energy Outlook 2003*. Washington, DC: U.S. Energy Information Administration. Available at: www.eia.doe.gov/oiaf/aeo/index.html.

Fischer, Carolyn, 2003. "Output-Based Allocation of Environmental Policy Revenues and Imperfect Competition." Discussion Paper 02-60. Washington, DC: Resources for the Future.

Fuchs, Victor R., Alan B. Krueger, and James M. Poterba. 1998. "Economists' Views about Parameters, Values and Policies: Survey Results in Labor and Public Economics." *Journal of Economic Literature* 36: 1387–1425.

Fullerton, Don, and Gilbert E. Metcalf. 2001. "Environmental Controls, Scarcity Rents, and Pre-Existing Distortions." *Journal of Public Economics* 80: 249–268.

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* 28: 708–31.

Goulder, Lawrence H., Ian W.H. Parry, Roberton C. Williams, and Dallas Burtraw. 1999. "The Cost-Effectiveness of Alternative Instruments for Environmental Protection in a Second-Best Setting." *Journal of Public Economics* 72: 329–360.

Hoerner, Andrew J., and Benoit Bosquet. 2001. *Environmental Tax Reform: The European Experience*. Washington, DC: Center for a Sustainable Economy.

Joskow, Paul R., and Richard Schmalensee. 1986. "Incentive Regulation for Electric Utilities." *Yale Journal on Regulation* 4: 1–50.

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

Palmer, Karen, Dallas Burtraw, Ranjit Bharvirkar, and Anthony Paul. 2001. "Restructuring and the Cost of Reducing NO_x Emissions in Electricity Generation." Discussion Paper 01-10. Washington, DC: Resources for the Future.

Parry, Ian W.H., and Wallace E. Oates. 2000. "Policy Analysis in the Presence of Distorting Taxes." *Journal of Policy Analysis and Management* 19: 603–614.

Parry, Ian W.H., Roberton C. Williams, and Lawrence H. Goulder. 1999. "When Can Carbon Abatement Policies Increase Welfare? The Fundamental Role of Distorted Factor Markets." *Journal of Environmental Economics and Management* 37: 52–84.

Paul, Anthony, and Dallas Burtraw, 2002. "The RFF Haiku Electricity Market Model." Discussion Paper, Washington, DC: Resources for the Future.

Pearce, David. 2003. “The Social Cost of Carbon and Its Policy Implications.” *Oxford Review of Economic Policy* 19: 362– 384.

Stoft, Steven. 2002. Power System Economics: Designing Markets for Electricity. Piscataway, NJ: IEEE Press.

Tol, Richard S.J., Samuel Fankhauser, Richard Richels, and J. Smith. 2000. “How Much Damage Will Climate Change Do? Recent Estimates.” *World Economics* 1: 179– 206.

Williams, Roberton C. III. 2002, “Environmental Tax Interactions When Pollution Affects Health or Productivity.” *Journal of Environmental Economics and Management* 44: 261– 270.

Appendix

Deriving (2.13)

Using (2.1), (2.2) and duality, the household optimization problem can be expressed:

$$\text{(B1)} \qquad z\{p^{MP}, p^{MO}, p^{RP}, \pi, G, t, \bar{u}\} =$$

$$\underset{X^{ij}, Y, L}{Min}\ \Sigma_{ij} p^{ij} X^{ij} + Y - G - (1-t)(L+\pi) + \lambda[u\{X, Y, \bar{L} - L\} - \bar{u}]$$

where z(.) is the expenditure function, λ is a Lagrange multiplier, $\bar{u}$ is a given (optimized) level of utility, and we have defined utility gross of environmental benefits. The first order conditions yield the compensated demand and labor supply functions:

$$\text{(B2)}\ X^{ij} = X^{ij}(p^{iP}, p^{iO}, t)\,;\, Y = Y(p^{iP}, p^{iO}, t)\,;\, L = L(p^{iP}, p^{iO}, t)$$

These functions are independent of π and G as any income effects are implicitly neutralized in the expenditure function.

Differentiating (B1) yields:

$$\text{(B3)}\ \frac{\partial z}{\partial p^{ij}} = X^{ij}\,;\, \frac{\partial z}{\partial \pi} = -(1-t)\,;\, \frac{\partial z}{\partial G} = -1\,;\, \frac{\partial z}{\partial t} = L + \pi$$

The welfare cost of emissions permits is given by:

$$\text{(B4)}\ W \equiv z\{p^{MP}, p^{MO}, p^{R}, \pi, G, t, \bar{u}\} - z\{p_0^{MP}, p_0^{MO}, p_0^{R}, \pi_0, G_0, t_0, \bar{u}\}$$

That is, the compensation that must be paid to households to keep utility constant at $\bar{u}$ following the policy change. Here we look at the case when *t* adjusts to maintain government budget balance (*G* is fixed)—the derivation is similar when *G* rather than *t* is adjusted.

From a second order Taylor series expansion of (B4) (with *G* fixed):

$$\text{(B5)}\ W \approx \Sigma_{ij} \frac{\partial z}{\partial p^{ij}} \Delta p^{ij} + \Sigma_{ij} \Sigma_{mn} \frac{\partial^2 z}{\partial p^{ij} \partial p^{mn}} \frac{\Delta p^{ij} \Delta p^{mn}}{2} + \frac{\partial z}{\partial t} \Delta t + \frac{\partial^2 z}{\partial t^2} \frac{\Delta t^2}{2} + \Sigma_{ij} \frac{\partial^2 z}{\partial t \partial p^{ij}} \Delta t \Delta p^{ij}$$

$$+ \frac{\partial z}{\partial \pi} \Delta \pi + \frac{\partial^2 z}{\partial \pi^2} \frac{\Delta \pi^2}{2} + \frac{\partial^2 z}{\partial \pi \partial t} \Delta \pi \Delta t + \Sigma_{ij} \frac{\partial^2 z}{\partial \pi \partial p^{ij}} \Delta p^{ij} \Delta \pi\,,\ m = M, R;\ n = P, O$$

Substituting (B3), and various differentials of (B3), into (B5) yields, after some manipulation:

$$\text{(B6)}\, W \approx \Sigma_{ij} X^{ij} \Delta p^{ij} + \Sigma_{ij} \Sigma_{mn} \frac{\partial X^{ij}}{\partial p^{mn}} \frac{(\Delta p^{mn})^2}{2} + (L_0 + \pi_0)\Delta t + \Delta t(L - L_0)$$

$$- \frac{\partial (L+\pi)}{\partial t} \frac{\Delta t}{2} - (1-t)\Delta\pi + \Delta\pi\Delta t$$

where

$$\text{(B7)}\, L - L_0 = \frac{\partial (L+\pi)}{\partial t}\Delta t + \frac{\partial (L+\pi)}{\partial p}\Delta p$$

From the government budget constraint (2.8), and equating ex ante and ex post tax revenues, we can obtain:

$$\text{(B8)}\, \Delta t = t - t_0 = -\frac{(1-\beta)\tau E - t(L_0 - L + \pi_0 - \pi)}{L_0 + \pi_0}$$

From (B6) and (B8) we can obtain, after some manipulation:

$$\text{(B9)}\, W \approx \Sigma_{ij} X_0^{ij} \Delta p^{ij} + \Sigma_{ij} \Delta X^{ij} \Delta p^{ij} / 2 - (1-\beta)\tau E + t_0 (L_0 - L) - \Delta\pi$$

(here we have ignored a term in $\Delta\pi\Delta t$ and in Δt^2, because Δt is very small).

Using (2.5), (2.10) and (2.12), the change in profits is:

$$\text{(B10)}\, \Delta\pi = [\Sigma_{ij} p^{ij} X^{ij} - \Sigma_i (\alpha_C + a_C) X_C^{iP} - \Sigma_{ij} (\alpha_{D1} + \alpha_{D2} X_D^{ij} / 2 + a_D) X_D^{ij} + \beta\tau E]$$

$$-[\Sigma_{ij} p_0^{ij} X_0^{ij} - \Sigma_i \alpha_C X_{C0}^{iP} - \Sigma_{ij} (\alpha_{D1} + \alpha_{D2} X_{D0}^{ij} / 2) X_{D0}^{ij}]$$

Using (2.10) we can obtain, after some manipulation:

$$\text{(B11)}\, \Delta\pi = \Sigma_{ij} (p^{ij} - p_0^{ij}) X^{ij} - (p_0^{ij} - MC_0^{ij})(X_0^{ij} - X^{ij}) - [k_D\{.\}X_D + k_C\{.\}X_C]$$

$$-(1-\beta)\tau E - \Sigma_{ij} \alpha_{D2} (X_{D0}^{ij} - X_D^{ij})^2 / 2$$

From (B9) and (B11) we can obtain (2.13).

Deriving (2.14)

For the case when *t* adjusts to maintain budget balance ($\theta = 1$), equating ex ante and ex post tax revenues gives (using (2.6)):

$$\text{(C1)}\, t_0(L_0+\pi_0)=(t_0+\Delta t)(L_0+\Delta L+\pi)+(1-\beta)\tau E$$

Substituting (B7) in (C1) and canceling terms we obtain, after some manipulation:

$$\text{(C2)}\, \Delta t \approx -\frac{(1-\beta)\tau E + t_0 \Delta\pi + t_0 \dfrac{\partial L}{\partial p}\Delta p}{t_0 \dfrac{\partial L}{\partial t} + L_0 + \pi_0}$$

Here we have ignored terms in $\Delta\pi\Delta t$, $\Delta p\Delta t$ and Δt^2, because Δt is very small. Note also that $t_0 \frac{\partial L}{\partial t} + L_0 + \pi_0 \approx t_0 \frac{\partial L}{\partial t} + L_0$, because electricity profits are very small relative to total labor income in the economy. Substituting (B7) and (C2) in $-t_0(L_0 - L)$, and using this approximation, we can obtain (2.14).

For the case when *G* adjusts to maintain budget balance ($\theta = 0$), $\Delta t = 0$.

Deriving (2.15)

From Slutsky symmetry:

$$\text{(D1)} -\frac{\partial L}{\partial p} = \frac{\partial X}{\partial(1-t)}$$

That is, the effect on leisure from an incremental increase in the price of *X* equals the effect on leisure from an incremental increase in the price of leisure (1– *t*). When *X* is (initially) an average substitute for leisure:

$$\text{(D2)} \frac{\partial X}{\partial(1-t_0)}\frac{1-t_0}{X_0} = -\frac{\partial L}{\partial t}\frac{1-t_0}{L_0}$$

That is, *X* changes in the same proportion to labor supply following an increase in the net wage. Substituting (D1) and (D2) in the formula for the tax-interaction effect in (2.14), and using the definition of *M*, we can obtain (2.15a).

Using (2.10) and (2.11):

$$\text{(D3)}\, \Delta p^{MP} = \psi a_C, \Delta p^{MO} = a_D, \Delta p^R = \Delta c^R + \frac{a_D X_D^R + a_C X_C^R - \tau\beta\overline{E}}{X^R}$$

Equation (2.15c) follows from (D3), (2.6), and (2.11c).

Tables

Table 1. Parameter Values for Benchmark Simulations

Parameter		Benchmark Value	
Baseline electricity parameters and initial values			
Total electricity output, million MWh		4,105	
fraction of output by dirty plants		0.54	
fraction of output by clean plants		0.46	
average generation price, $/MWH		40	
fraction of firms in regulated sector		0.5	
economy-wide marginal production cost, $MWh		45	
fraction of production in off-peak period		0.10	
marginal production cost in off-peak period, $MWh		9.0	
marginal production cost in peak period, $MWh		48.8	
average cost, $MWh		35	
own price elasticity of demand for electricity		-0.3	
Environmental parameters	**SO_2**	**Carbon**	**NO_X**
Unregulated emissions, million tons	16	689	5.9
fraction of total initial emissions at dirty plants	1.0	0.86	0.95
emissions cap, million tons	9.0	620	1.8
permit price at cap (auctioned permits), $/ton	290	52	900
slope of MAC at dirty plants	91,835	∞	489,521
slope of MAC at clean plants	∞	∞	∞
marginal benefit from abatement $/ton	3,500	50	1000
Fiscal parameters			
Marginal excess burden of labor taxation		0.25	
Income tax		0.4	

Table 2. Costs of SO_2 Emissions Reduction

($ million)

	grand-fathered permits	auctioned permits revenue-neutral	auctioned permits lump-sum replacement	output-based allocation
Single technology model				
abatement costs	999	999	999	1,013
output effects	12	12	12	1
revenue-recycling effect				
permit sales	0	-648	0	0
profits	-259	0	0	0
tax-interaction effect	902	902	902	253
total cost	1,654	1,265	1,913	1,267
Benefits - costs	22,842	23,231	22,583	23,245
Multiple technology model				
abatement costs	975	976	976	976
output effects	-58	-155	-155	34
revenue-recycling effect				
permit sales	0	-638	0	0
profits	19	148	148	145
tax-interaction effect	192	496	496	-111
total cost	1,127	827	1,465	1,043
relative cost	0.68	0.65	0.77	0.82
Benefits - costs	23,365	23,678	23,040	23,454

Table 3. Costs of Carbon Emissions Reduction

($ million)

	grand-fathered permits	auctioned permits revenue-neutral	 lump-sum replacement	output-based allocation
Single technology model				
abatement costs	698	698	698	2,123
output effects	576	576	576	4
revenue-recycling effect				
permit sales	0	-5,814	0	0
profits	-2,326	0	0	0
tax-interaction effect	6,276	6,276	6,276	533
total cost	5,225	1,737	7,550	2,660
Benefits - costs	-1,783	1,706	-4,108	791
Multiple technology model				
abatement costs	1,413	1,155	1,155	1,720
output effects	-270	-541	-541	420
revenue-recycling effect				
permit sales	0	-8,064	0	0
profits	-759	987	987	1,221
tax-interaction effect	2,327	6,001	4,801	-2,289
total cost	2,711	-462	6,401	1,071
relative cost	0.52	-0.27	0.85	0.40
Benefits - costs	758	3,897	-2,967	2,384

Table 4. Costs of NO_X Emissions Reduction
($ million)

	grand-fathered permits	auctioned permits revenue-neutral	auctioned permits lump-sum replacement	output-based allocation
Single technology model				
abatement costs	1,837	1,837	1,837	1,841
output effects	11	11	11	3
revenue-recycling effect				
permit sales	0	-404	0	0
profits	-161	0	0	0
tax-interaction effect	865	865	692	460
total cost	2,552	2,310	2,540	2,304
Benefits - costs	1,551	1,793	1,562	1,797
Multiple technology model				
abatement costs	1,827	1,828	1,828	1,827
output effects	-89	-152	-152	-30
revenue-recycling effect				
permit sales	0	-405	0	0
profits	16	99	99	95
tax-interaction effect	294	489	391	98
total cost	2,048	1,859	2,166	1,991
relative cost	0.80	0.80	0.85	0.86
Benefits - costs	2,052	2,242	1,935	2,107

Table 5. Sensitivity with respect to Full Price Deregulation
(absolute costs from the multi-technology model)

	grand-fathered permits	auctioned permits		output-based allocation
		revenue-neutral	lump-sum replacement	
SO$_2$				
abatement costs	975	975	975	975
output effects	0	0	0	-3
revenue-recycling effect				
permit sales	0	-638	0	0
profits	37	292	292	286
tax-interaction effect	154	154	154	-467
total cost	1,165	783	1,421	791
relative cost	0.70	0.62	0.74	0.63
Carbon				
abatement costs	899	900	900	1,403
output effects	162	170	170	367
revenue-recycling effect				
permit sales	0	-7,294	0	0
profits	-1,131	1,756	1,756	2,229
tax-interaction effect	3,211	3,284	3,284	-4,831
total cost	3,141	-1,184	6,109	-833
relative cost	0.60	-0.68	0.81	-0.31
NO$_x$				
abatement costs	1,792	1,792	1,792	1,792
output effects	1	1	1	0
revenue-recycling effect				
permit sales	0	-402	0	0
profits	35	194	194	186
tax-interaction effect	255	259	259	-132
total cost	2,082	1,844	2,246	1,846
relative cost	0.82	0.80	0.86	0.80

Table 6. Sensitivity With Respect to Extent of Abatement

(Overall costs relative to combined abatement costs and output effects in single-technology model)

Emissions abatement level (%)	single technology model		multi-technology model	
	grandfathered permits	auctioned permits	grandfathered permits	auctioned permits
Carbon				
5	7.07	1.36	3.35	-1.30
10	4.10	1.36	2.13	0.84
20	2.59	1.36	1.45	1.23
SO_2				
20	2.45	1.25	1.19	0.78
45	1.64	1.25	1.14	1.01
70	1.38	1.25	1.13	1.09
NO_x				
20	2.45	1.25	0.83	-0.66
45	1.62	1.25	1.27	0.89
70	1.38	1.25	1.13	1.05

Table 7. Sensitivity with respect to Market Power in the Deregulated Sector
(ratio of costs in multi-technology model to costs in single-technology model)

Initial price-MC ratio in peak period	grandfathered permits		auctioned permits	
	price constant	output constant	price constant	output constant
SO_2				
1.1	0.65	0.76	0.61	0.77
1.4	0.56	0.76	0.49	0.77

Table 8. Sensitivity with respect to Other Parameters

(ratio of costs in multi-technology model to costs in single-technology model for SO_2)

		grand-fathered permits	auctioned permits revenue-neutral	auctioned permits lump-sum replacement	output-based allocation
Benchmark		0.68	0.65	0.77	0.82
1. Dispersion in marginal costs across periods					
relative size of off-peak period	Dispersion in marginal cost				
benchmark	maximized	0.68	0.71	0.80	0.80
	minimized	0.70	0.66	0.78	0.84
halved	maximized	0.67	0.64	0.76	0.80
	minimized	0.68	0.65	0.77	0.82
increased to size of peak period	maximized	0.69	0.66	0.78	0.83
	minimized	0.72	0.69	0.80	0.88
2. Difference between (mean) marginal cost and average cost					
\$20/MWh		0.65	0.57	0.71	0.83
\$0/MWh		0.70	0.72	0.82	0.81
-\$10/MWh		0.72	0.78	0.86	0.81
3. Slope of marginal abatement cost curve					
reduced 25%		0.69	0.66	0.81	0.83
increased 25%		0.67	0.64	0.80	0.81
4. Electricity demand elasticity					
$\eta = -.2$		0.69	0.68	0.79	0.81
$\eta = -.7$		0.66	0.56	0.71	0.84
5. Marginal excess burden					
M = .15		0.75	0.70	0.79	0.88
M = .4		0.61	0.58	0.75	0.75