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ABSTRACT

This paper explores how the costs of meeting given aggregate targets for pollution emissions change with the imposition of the requirement that key pollution-related industries be compensated for potential losses of profit from the pollution regulation. Using analytically and numerically solved equilibrium models, we compare the incidence and economy-wide costs of emissions taxes, fuel (intermediate input) taxes, performance standards and mandated technologies in the absence and presence of this compensation requirement. Compensation is provided either through lump-sum industry tax credits or industry-specific cuts in capital tax rates. We decompose the added costs from the compensation requirement into (1) an increase in "intrinsic abatement cost," reflecting a lowered efficiency of pollution abatement, and (2) a "lump-sum compensation cost" that captures the efficiency costs of financing the compensation. The compensation requirement affects these components differently and thus can alter the cost-rankings of policies. When compensation is provided through tax credits, the lump-sum compensation cost is higher under the emissions tax than under performance standards and mandated technologies -- a reflection of the emission tax's higher compensation requirements. If in this setting the required pollution reduction is modest, imposing the compensation requirement causes the emissions tax to become more costly than command and control policies. In contrast, if required abatement is extensive, the emissions tax emerges as the most cost-effective policy because its relatively low intrinsic abatement costs assume greater importance.

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1 Introduction

A critical environmental policy decision is the choice of policy instrument to achieve given aggregate targets for pollution emissions or concentrations. The policy maker's toolkit includes emissions taxes, fuel taxes, performance standards, tradable emissions allowances, and mandated production technologies.

In ranking these alternatives, economists tend to compare the instruments in terms of their cost-effectiveness.[1] However, policy makers often are at least as much concerned with how these options may differ in terms of the distribution of policy costs, since such differences importantly affect political feasibility.

Distributional impacts can be measured along several different dimensions – across household income groups, generations, geographic regions, and industries. The distribution across industries can be especially important, since industry groups often constitute a powerful political force. To the extent that industrial stakeholders wield significant political power, designing policies that achieve environmental goals while avoiding serious adverse impacts on key industries can enhance political feasibility.

In this paper we examine how the costs of meeting given targets for pollution emissions change once one adds the requirement that the regulations cause no loss in profit in key pollution-related industries. In our investigation, this requirement is met by including, as part of the environmental policy, either tax credits or reductions in capital tax rates to certain affected industries.

Our analysis is in the spirit of a paper by Bovenberg, Goulder, and Gurney (2005), which examined how introducing a constraint on profit-losses affects the costs of emissions taxes and quotas. The present paper goes beyond the previous paper by considering a wider range of policy instruments, focusing not only on emissions taxes and quotas[2] but also on taxes on fuels (intermediate inputs associated with pollution) and two "command-and-control" policies – performance standards and mandated production technologies.

We apply both analytical and numerical equilibrium models in this investigation. Compared with the Bovenberg *et al.* paper, the present investigation requires consid-

[1] See, for example, Tietenberg (1990), Stavins (1996), Goulder *et al.* (1999) and Fischer *et al.* (2003).

[2] In this analysis a system of tradable emissions quotas is equivalent to an emissions tax with a tax exemption for some emissions.

erably more complex analytical modeling in order to capture the impacts of this wider range of instruments. The analytical and numerical models both show that the overall gross cost[3] of achieving a given reduction in emissions can be understood in terms of two components: an *intrinsic abatement cost* and a *lump-sum compensation cost*. The former cost depends on the efficiency with which the policy instrument in question makes use of the three major channels for emissions reductions: input substitution, end-of-pipe treatment, and output reduction. The second cost reflects inefficiencies associated with providing the compensation to meet the no-profit-loss constraint, when this compensation takes the form of lump-sum payments such as corporate tax credits.[4]

As in earlier studies, we find that in the absence of a profits constraint, emissions taxes are less costly than fuel taxes and the command-and-control policies because they most effectively employ the three major channels for emissions reductions. However, introducing the distributional constraint can reverse the overall cost rankings. In particular, when compensation takes the form of tax credits and the required amount of abatement is small or moderate, the command-and-control policies emerge as less costly than emissions taxes. The analytical and numerical models show that at low levels of abatement, emissions taxes (and fuel taxes) have a significant disadvantage in terms of the costs of compensation – the lump-sum compensation cost is significant. The higher compensation cost more than offsets the emissions tax's advantage in terms of the intrinsic abatement cost. In contrast, when environmental policy is more stringent (that is, requires greater abatement), the emissions tax's advantage by virtue of its lower intrinsic abatement cost becomes more important than its disadvantage in terms of the compensation cost. Thus, the relative costs of emissions taxes and the command-and-control instruments depend importantly on the extent of required abatement.

The rest of the paper is organized as follows. The next section presents the analytical model and derives and interprets its results. The analytical results stem from linear approximations; hence they are not necessarily valid for large policy changes. In addition, the analytical model assumes that the regulated pollution-supplying industries are very small relative to the economy as a whole. The linearity and small-industry assumptions are relaxed in the numerical model of Section 3, which provides quantitative results.

[3] By "gross cost" we mean the cost before netting out the benefits from policy-induced environmental improvements.

[4] As shown below, when compensation takes the form of reductions in marginal corporate tax rates, the compensation is costly because it implies less effective use of the three abatement channels. In formal terms, this compensation-related cost is in fact an increase in the intrinsic abatement cost relative to what that cost would be in the absence of a compensation requirement.

Section 4 offers conclusions.

2 An Analytical Model

Here we describe an analytically tractable equilibrium model designed to capture the efficiency and distributional effects of a range of environmental policy instruments. The model can assess how the efficiency impacts change when the policies include compensation to affected industries. In the model, pollution cuts can be accomplished through both input-substitution and "end-of-pipe" emissions treatment. The model recognizes the imperfect mobility of capital, which is critical for evaluating the profit impacts of various policies.

There are two primary factors of production, capital (K) and labor (L). Capital is treated as imperfectly mobile across industries, labor as perfectly mobile. The model distinguishes three industries: an upstream industry that produces an intermediate good X whose use is associated with pollution, a downstream industry that produces a final good Y and generates pollution emissions, and another final good industry that produces a clean, final good C without generating any pollution. Industry Y's emissions depend on the extent to which it employs the intermediate input X. Industry Y can reduce these emissions by changing its input mix (substituting labor or capital for X) and by engaging in end-of-pipe treatment. One can think of the intermediate input, X, as a fossil fuel and regard the downstream industry, Y, as an industry like electricity that burns the fuel and produces pollution.

2.1 Model structure

2.1.1 Production

The upstream industry produces the intermediate good X according to the following constant-returns-to-scale production function

$$X = f_x(L_x, K_x), \tag{1}$$

where L_x denotes employment in the upstream industry and K_x stands for the capital stock in that industry. Competitive maximizing behavior yields

$$P_x \frac{\partial f_x(.;.)}{\partial L_x} = W, \tag{2}$$

$$P_x \frac{\partial f_x(.;.)}{\partial K_x} = R_x - S_{kx}, \tag{3}$$

where P_x denotes the price of the intermediate good, W the wage rate, R_x the rental rate of capital in the upstream sector, and S_{kx} a sector-specific capital subsidy in that sector. Since capital is imperfectly mobile, the rental rate can differ across industries. The wage rate, in contrast, is the same in both industries, in keeping with the assumption of perfectly mobile labor.

The constant-returns-to-scale production function of the downstream industry Y is given by

$$Y = f_y(K_y, X, L_y) = h(v(K_y; X); L_y), \tag{4}$$

where L_y stands for employment engaged in production in the downstream industry and K_y is the capital stock in that industry. Industry Y is the only source of demand for the intermediate input X. The production function is weakly separable.[5] In particular, the marginal rate of substitution between the intermediate input X and capital K_y does not depend on industry-specific employment L_y; the intermediate input and capital first yield the composite $v(K_y; X)$, which in turn is combined with labor to yield output Y. We assume that capital is complementary to the intermediate input in the sense that a rise in price of the intermediate input reduces the demand for capital at a given level of output.

The use of the intermediate input by the downstream industry causes pollution. This pollution can be reduced, however, by devoting resources to end-of-pipe treatment. Pollution emissions, E, are given by

$$E = n(X, g(C_a; Y_a)), \tag{5}$$

with $\partial n/\partial X \geq 0$; $\partial n/\partial g \leq 0$;$\partial g/\partial C_a \geq 0; \partial g/\partial Y_a \geq 0$. The subfunction $g(.,.)$ is a composite of the two final goods Y_a and C_a; it is an index of resources devoted to end-of-pipe treatment.[6]

Pure profits in the downstream industry are given by $(P_y + S)Y - (P_x + T_x)X - T_eE - WL_y - P_cC_a - P_yY_a - (R_y - S_{ky})K_y$, where P_y represents the price of the final good produced by the downstream industry Y, S a subsidy on that good, T_x an input tax on the good produced by the upstream industry, P_c the price of the other, clean final

[5] These separability assumptions are consistent with empirical work (see, e.g., Jorgenson and Wilcoxen (1993a, b) suggesting that capital is a complement to energy (or fuel) inputs.

[6] The functions $n(.\,,.)$ and $g(.,.)$ exhibit constant returns to scale in their arguments. The function $g(.,.)$ aggregates the goods C and Y also in the utility function (see (7) below).

good C, R_y the rental rate of capital in the downstream industry, S_{ky} a sector-specific subsidy to capital in that sector, and T_e, the tax on emissions. As indicated below, the various environmental policies we explore below involve a combination of the taxes T_x and T_e and the subsidies S, S_{ky} and S_{kx}.

The industry producing the clean final good C employs the constant-returns-to-scale production function

$$C = f_c(L_c, K_c),$$

where L_c and K_c stand for labor and capital employed in that industry. All industries maximize profits, taking prices as given. Since the production and emission functions exhibit constant returns to scale, profits are zero in equilibrium.

2.1.2 Imperfect capital mobility

An important feature of the model is the imperfect mobility of capital across sectors. This implies that the profit impacts of an unanticipated policy shock will not be uniformly spread across capital owners in all industries, because capital cannot costlessly move toward the sectors with the highest returns after the shocks. To capture capital's imperfect mobility, we employ the following transformation function:[7]

$$k(K_x; K_y; K_c) = K, \tag{6}$$

where K represents the economy-wide stock of capital. We assume that the substitution elasticities between the three types of capital are less than infinite. Thus, when a unit of capital is shifted out of one industry, less than one unit is available for other industries. This loss of effective capital represents capital adjustment costs.

2.1.3 Household utility and the supply of primary factors

Households obtain utility from consumption of the two final goods Y and C. Aggregate emissions E, labor supply L, and capital supply K produce disutility.[8] Households

[7] This supply function can be interpreted as a multi-product firm that employs aggregate capital as an input to produce three outputs: namely, the three capital stocks K_i $(i = x, y, c)$.

[8] In a fully dynamic model, the cost of supplying capital is current consumption foregone when resources are devoted to investment instead of consumption. We include capital in the utility function to account for the cost of supplying capital in our static model, which does not deal with investment explicitly. An alternative interpretation of K is as highly specialized labor which, in contrast with other labor, is imperfectly mobile across sectors.

maximize the utility function

$$U = u[m(g(Y_h, C_h), z(K, L)), E], \tag{7}$$

with $\frac{\partial g}{\partial Y_h}, \frac{\partial g}{\partial C_h}, \frac{\partial m}{\partial g}, \frac{\partial m}{\partial z}, \frac{\partial u}{\partial m} > 0$, and $\frac{\partial u}{\partial E}, \frac{\partial z}{\partial L}, \frac{\partial z}{\partial K} < 0$. Y_h and C_h denote household consumption of, respectively, the dirty and clean final goods. Since the utility function is weakly separable in environmental quality, such quality does not directly affect household decisions.

Households earn labor and capital income. Both types of income are taxed at the same proportional rate T. Uniform tax rates on capital and labor income are optimal, given that capital and labor are weakly separable in utility from consumption.[9] The household budget constraint is given by

$$P_c C_h + P_y Y_h = (1 - T)(WL + RK + \Pi),$$

where R denotes the ideal price index associated with the transformation function (6) and Π represents lump-sum subsidies.

2.1.4 Government budget

The government faces the following budget constraint:

$$P_c \Lambda + \Pi + SY + S_{ky} K_y + S_{kx} K_x = T_e E + T_x X + T(\Pi + WL + RK), \tag{8}$$

where Λ denotes government spending (on the clean good C).

2.1.5 Market equilibrium

Equilibrium in the markets for the two final goods requires that

$$Y_h + Y_a = Y,$$

and

$$\Lambda + C_h + C_a = C.$$

[9] A more complex structure might incorporate a utility function with which uniformity of factor tax rates is not optimal, and/or a tax system that did not include uniform rates. Such complications would not be particularly useful in the present study, since they would not be expected to exert significant influences on the industry-distributional effects of pollution policies or the costs of compensation.

With perfectly mobile labor, labor market equilibrium is given by

$$L = L_x + L_y + L_c.$$

2.2 Policy experiments

We explore several policies that achieve given targets for pollution abatement. The emissions tax and fuel (intermediate input) tax policies involve T_e and T_x, respectively. In the absence of uncertainty, the two command-and-control policies are equivalent to combinations of taxes and subsidies.[10] In particular, the technology mandate can be modelled as a revenue-neutral combination of a subsidy to the intermediate input (i.e., a negative value for T_x) and a tax on emissions $T_e > 0$:

$$T_x X + T_e E = 0. \tag{9}$$

Similarly, we represent the performance standard as a revenue-neutral combination of an output subsidy $S > 0$ and an emissions tax $T_e > 0$:

$$SY - T_e E = 0.$$

In general, these policies affect tax bases and thus can have revenue impacts.[11] In order to keep a balanced budget, the government adjusts the factor tax T while leaving real government spending Λ constant.

For small policy shocks, the model can be solved analytically by log-linearizing it around its initial equilibrium.[12] Unless indicated otherwise, small letters will stand for relative (percentage) changes of the variables denoted by the corresponding capital letters. Greek letters will represent either elasticities or shares in the initial equilibrium. In solving the model, we assume that the upstream and downstream pollution-related industries X and Y are small compared to the rest of the economy. This enables us to ignore effects on the real wage rate W/P_c when solving for output and emissions in the upstream and downstream industries. We adopt P_c as the numeraire.

[10] Fullerton and Metcalf (2001) demonstrate this equivalence.

[11] Even the command-and-control policies affect aggregate public revenues because the revenue-neutrality between their tax and subsidy components applies only at the level of industry Y, the targeted industry. These policies can thus change overall revenues by affecting the tax base elsewhere in the economy.

[12] This initial equilibrium may involve either zero abatement or a strictly positive level of abatement.

2.3 Efficiency Impacts

Our measure for the overall efficiency impact is the compensating variation, which for ease of notation we express relative to the output of the downstream industry.

As shown in the appendix, the overall marginal efficiency cost ψ of a small change in environmental policy can be split into two components, with one representing an efficiency cost directly connected with abatement, and the other representing the efficiency cost related to lump-sum compensation:

$$\psi = -\lambda\Omega + \mu\pi(1 - T), \tag{10}$$

We refer to the first right-hand term in (10) as the *intrinsic abatement cost*. It is the cost of pollution abatement, apart from any effect directly related to lump-sum compensation. This term applies under all of the policies considered. We refer to the second right-hand term in (10) as the *lump-sum compensation cost*. This additional term applies only when compensation is provided in the form of lump-sum tax credits.[13] We elaborate on these two terms below.

2.3.1 Efficiency Costs for Policies without Compensation

Under policies with no profits constraint, the marginal efficiency cost involves only the intrinsic abatement cost, -$\lambda\Omega$. The λ component of this impact stands for the marginal cost of public funds – the marginal cost in terms of household income of raising one additional dollar of government revenue. The appendix shows that in this model λ equals $\frac{1}{1-\varepsilon_u(T/(1-T))}$, where ε_u denotes the uncompensated elasticity of factor supply with respect to factor income.

The other element in the intrinsic abatement cost, Ω, reflects the erosion of the tax base resulting from the environmental policy. In the case of the emissions tax, the expression for Ω is:

$$\Omega = \alpha_e^y e, \tag{11a}$$

where $\alpha_e^y \equiv T_e E/(P_y + S)Y$ stands for the emissions tax payment relative to the value of output in the downstream (Y) industry. For a reduction in emissions (i.e., emissions abatement) Ω is negative, representing the loss of emission-tax revenue as a result of

[13] When compensation is in the form of reductions in marginal tax rates on capital, the efficiency cost of such compensation is captured within the intrinsic abatement cost, as explained below.

the emissions reduction. Multiplication of Ω by the efficiency cost of raising a dollar of revenue (λ) yields the efficiency impact of a unit change in emissions.

The loss of tax base, Ω, differs under the other policies. Under the fuel tax, Ω is given by:

$$\Omega = \frac{T_x}{P_x}\alpha_x^y x, \tag{11b}$$

where $\alpha_x^y \equiv (P_x X)/(P_y + S)Y$ is the share of payments to the upstream (X) industry relative to the value of the Y industry. The right-hand side then equals the change in fuel tax payments when the use of X is curtailed incrementally.

Under the technology mandate, the expression for Ω amounts to:

$$\Omega = \alpha_e^y e + \frac{T_x}{P_x}\alpha_x^y x, \tag{11c}$$

which combines the effects of an emissions tax and a fuel tax. $T_x < 0$ represents the subsidy component of the technology mandate.

Finally, the expression for Ω in the case of the performance standard is:

$$\Omega = \alpha_e^y e - \frac{S}{P_y + S} y, \tag{11d}$$

which combines the effect of an emissions tax with a revenue-neutral subsidy, S, to output of the downstream industry.

The intrinsic efficiency cost has two properties that apply under all four policy types. First, under all policies, at initial abatement (i.e., the first unit), Ω is zero and thus the intrinsic efficiency cost is zero as well. Under the emissions tax, Ω is zero at initial abatement because the cost share α_e^y is infinitesimal as T_e goes to zero. Under the fuel tax, the term $\frac{T_x}{P_x}\alpha_x^y x$ is arbitrarily close to zero at initial abatement because T_x goes to zero. Under the performance standard, the emissions-tax component (first right-hand-side term) and output-subsidy component (second right-hand-side term) of (11d) each go to zero when abatement is arbitrarily small. Similarly, under the technology mandate, the emissions-tax component and input-subsidy component (the T_x contained in the second right-hand-side term) each go to zero.

The intuition for the zero initial impact is that each channel for abatement – input-substitution, end-of-pipe treatment, and output-demand reduction – involves infinitesimal costs at the first unit of abatement. Firms enjoy private marginal benefits from being able to produce pollution in the form of less expensive fuel mixes, less extensive equipment, and (from lower output prices) higher output demand. A profit-maximizing firm equates its marginal benefits of additional emissions along any of these channels to the marginal cost of emissions. In the absence of regulation, the marginal cost of emissions is zero; hence, the marginal benefit from an increment to emissions along any one of these channels is zero as well. Thus, the first unit of emissions reduction along any of these channels involves a marginal net private cost (foregone private net marginal benefit) of zero.

A second common feature of the marginal intrinsic efficiency cost is that it rises with the extent of abatement. Greater abatement involves increased use of some combination of the the channels of input substitution, output-demand reductions, and end-of-pipe-treatment. If production functions are concave, greater input-substitution involves increasing marginal costs. Furthermore, convex utility (downward sloping demand curves) implies that greater output reduction entails increasing marginal welfare costs. Finally, our emissions function (see (23)) involves rising marginal costs of end-of-pipe treatment.[14]

Beyond incremental abatement, the intrinsic efficiency costs differ across policies. As indicated in prior studies[15], the emissions tax has an advantage over other policies in terms of these costs because it yields appropriate incentives for end-of-pipe treatment, input substitution, and output-demand reduction (from higher output prices). The tax on the intermediate (fuel) input exploits only the channels of input substitution and output cuts. The command and control policies also exploit a subset of channels, with the technology mandate primarily engaging the end-of-pipe treatment channel and the performance standard including both end-of-pipe treatment and input substitution. The rankings of the fuel tax, technology mandate, and performance standards in terms of the intrinsic efficiency cost thus depend on the relative ease of input substitution, end-of-pipe treatment, and output-demand reduction. This determines the relative opportunity cost of neglecting one or more of these channels. We explore this issue numerically in Section 3 below.

[14] Constant or even declining marginal costs for end-of-pipe treatment are a possibility, but rising marginal costs seem most consistent with empirical cases such as the use of electrostatic scrubbers for reducing smokestack emissions of sulfur dioxide.

[15] See, for example, Goulder, Parry, Williams and Burtraw (1999).

2.3.2 Efficiency Costs of Policies Involving Compensation

Compensation via Tax Credits

Compensation is required to maintain capital income or equity value to owners of the pollution-related industries. We shall often refer to the profits constraint as the equity value neutrality (EVN) requirement. When policies include compensation that takes the form of lump-sum tax credits, the second term in (10), namely $\mu\pi(1-T)$, usually is non-zero. This term represents the lump-sum compensation cost. In this term, π stands for the value of the lump-sum credit needed to compensate capital owners in the polluting industries (again expressed relative to output in the downstream sector). μ represents the marginal excess burden from the additional factor taxation needed to provide the compensating tax credit. As shown in the appendix, μ can be written as $\frac{\varepsilon_c[T/(1-T)]}{1-\varepsilon_u[T/(1-T)]}$, where ε_c is the compensated factor supply elasticity.

Under the emissions tax and fuel tax policies, firms ordinarily suffer losses of profit and positive compensation is required to achieve equity value neutrality. In these cases, compensation via lump-sum tax credits introduces an extra efficiency cost relative to the case without compensation. The reason is that when emissions reductions are achieved through taxes, firms are required to pay the tax for whatever emissions they continue to generate (under the emissions tax) or for whatever amount of fuel they continue to utilize (under the fuel tax). Since this revenue transfer to the government is non-incremental, the magnitude of the required tax credit is significant as well. This produces a first-order efficiency cost, given by the product of the required credit ($\pi(1-T)$) and the marginal excess burden (μ).

Under command-and-control policies, the lump-sum compensation cost differs from this cost under tax policies. This reflects differences in the incidence and associated differences in required levels of compensation. The polluting industries tend to bear a smaller burden under the command-and-control policies (performance standard and technology mandate) than under the tax policies. This occurs because the command-and-control policies effectively include subsidies to the use of the intermediate input or to output of the final good Y.[16] Indeed, under these policies the polluting industries do not transfer fiscal resources to the government. Hence, they require little or no compensation.[17]

[16] See Fullerton and Heutel (2006) for an analysis comparing the long-run incidence of various command-and-control policies.

[17] Indeed, in some cases, certain firms can enjoy higher profits under a performance standard than

To illustrate, for initial abatement, the required lump-sum compensations for the owners of the pollution-related industries under the technology mandate, the performance standard and the emission tax, respectively, are given by

$$\pi = 0, \tag{12}$$

$$\pi = -\Sigma_p e, \tag{13}$$

$$\pi = -\Sigma_e e, \tag{14}$$

where $\Sigma_p \geq \Sigma_e > 0$. At initial abatement, the technology mandate does not require any compensation at all. Whereas the performance standard requires a non-marginal amount of compensation, the required compensation is less than with an emission tax.

Compensation via Cuts in Marginal Tax Rates on Sector-Specific Capital

We also explore compensation in the form of reductions in marginal tax rates on capital employed in the polluting industries. In this case, only the intrinsic abatement cost applies, though for a given environmental policy instrument this cost generally will be greater than if the policy involved no compensation. Compensation in the form of reduced capital tax rates raises the marginal intrinsic abatement cost by increasing the marginal costs of the output-reduction and input-substitution channels. Reduced marginal capital taxes lower the marginal costs of production, thereby working toward lower output prices and higher demand. Since total output is higher, greater abatement effort is needed to achieve a given reduction in emissions relative to the situation without compensation. Similarly, lower capital tax rates work toward greater demand for the fuel input (insofar as fuel and capital are complements in production). To the extent that producers aim to reduce emissions by lowering the fuel input, they must counter this positive impact on fuel use, and thus the opportunity cost of reducing emissions is higher. Indeed, the policies necessitate greater use of the output-reduction and input-substitution channels, which involve rising marginal costs. The rising marginal costs induce firms to make greater use of end-of-pipe treatment as well, to the point where the marginal costs of each channel are equal.

Relative Efficiency Cost of Alternative Compensation Mechanisms

in the absence of compensation. The numerical model obtains this result for a performance standard, when relatively little abatement is required (see Section 3).

One might expect that compensation through sector-specific cuts in marginal tax rates would always involve lower efficiency costs than compensation through lump-sum transfers, since such compensation does not require the government to raise factor taxes to finance lump-sum transfers. However, this is not the case. The relative efficiency cost of achieving compensation through lump-sum transfers versus sector-specific cuts in marginal tax rates depends on the extent of abatement. At initial (low) levels of abatement, sector-specific marginal rate cuts have a cost advantage. As discussed above, lump-sum compensation initially has a first-order efficiency cost, while marginal rate cuts initially involve no such cost. However, at higher levels of abatement, the efficiency advantage of marginal rate cuts declines. As mentioned, the intrinsic abatement cost associated with achieving a given level of abatement impact (the first term on the right-hand side of (10)) is larger under recycling through sector-specific marginal tax cuts than under lump-sum credits. As the required amount of abatement becomes large, this intrinsic cost component becomes more important compared to the lump-sum compensation cost. The cost of output reduction, input substitution, and end-of-pipe treatment rise with abatement on account of convex utility functions, concave production functions and convex end-of-pipe abatement. As a result, when required abatement is extensive, marginal abatement costs are large and the efficiency with which abatement occurs becomes relatively more important. At sufficiently high levels of abatement, the marginal instrinsic abatement cost (i.e. the first right-hand term in (10)) therefore dominates the lump-sum compensation cost (i.e. the second right-hand term in (10)). Correspondingly, at high levels of abatement, recycling through sector-specific tax cuts generates larger overall efficiency costs: the higher intrinsic abatement costs from such recycling dominate its initial efficiency advantage relative to lump-sum compensation.

With compensation through sector-specific cuts in marginal tax rates, the marginal efficiency costs of further abatement through emission taxes are given by

$$\psi = -\lambda \alpha_e^y e, \tag{15}$$

If lump-sum transfers are employed for compensation, we find

$$\psi = -\lambda \alpha_e^y e - r_x[(1-T)\mu - \lambda S_{kx}\sigma_k^x \Phi_x] - r_y[(1-T)\mu - \lambda S_{ky}\sigma_k^y \Phi_y], \tag{16}$$

where σ_k^x (σ_k^y) stands for the substitution elasticity between the industry-specific capital services in the upstream (downstream) industry and the capital services in the rest of the economy, while $\Phi_i > 0,\ \ i = x, y$ denotes a positive coefficient and $r_i < 0$ represents the rental losses in sector $i = x, y$. The terms between square brackets associated with the rental losses indicate that a loss in capital income in a sector requires lump-sum compensation (the term with $(1 - T)\mu$) but also induces capital to migrate away from the subsidized sector (if $S_{ki} > 0;\ \ i = x, y$), thereby reducing public spending on capital subsidies and enhancing efficiency.

At intial abatement (i.e. $\alpha_e^y = S_{kx} = S_{ky} = 0$), abatement with compensation through sector-specific tax cuts yields no first-order costs. With lump-sum compensation, in contrast, there are first-order costs $-(r_x + r_y)(1 - T)\mu > 0$. Intuitively, the tax payments on remaining emissions induce redistribution away from the polluting industries to the rest of the economy. This redistribution needs to be compensated through lump-sum subsidies financed by distortionary taxation. At higher levels of abatement (i.e. $\alpha_e^y > 0$ and $S_{kx}, S_{ky} > 0$ because the government uses sector-specific subsidies subsidies to compensate the polluting sectors), also abatement with compensation through sector-specific tax cuts yields first-order welfare losses. Moreover, if sector-specific cuts have become large enough (i.e. S_{kx} and S_{ky}), compensation through lump-sum subsidies becomes more efficient because lump-sum compensation does not attract additional capital to the subsidized sector thereby enhancing the efficiency with which capital is allocated across the sectors. To illustrate, if the sector-specific subsidy in the upstream industry has become $S_{kx} = (1 - T)\mu/(\lambda\sigma_k^x\Phi_x)$, compensation through lump-sum sum taxes is most efficient. Intuitively, the additional costs in terms of aggregate factor supply $-r_x(1 - T)\mu$ are exactly offset by smaller distortions in terms of the intersectoral allocation of capital $-r_x\lambda S_{kx}\sigma_k^x\Phi_x$.

2.3.3 Policy Rankings in Terms of Overall Efficiency Cost

How does the equity value neutrality (EVN) constraint affect the relative efficiency costs of the various environmental policies? As discussed earlier, emissions taxes have a cost advantage in the absence of a profits constraint. Once one introduces this constraint, however, the emissions tax's advantage can disappear. As with the relative efficiency cost of lump-sum compensation compared to compensation through sector-specific tax cuts, the relative efficiency cost of emission taxes compared to command-and-control policies depends on the level of abatement.

Consider first the case where compensation is provided through lump-sum transfers. At incremental abatement, the intrinsic abatement cost component is infinitesimal (under all policy instruments); hence, differences in policy costs reflect differences in the lump-sum compensation component. Since the emissions tax requires the most compensation, it involves the highest lump-sum compensation cost, and thus the highest overall cost (compare (14) with (12) and (13)).[18]

As abatement becomes more extensive, however, the intrinsic abatement cost component gains relative importance. Intuitively, at high levels of abatement, marginal costs of abatement are high, so that the efficiency with which abatement occurs becomes important. Since the command-and-control policies have a disadvantage in intrinsic abatement efficiency (fewer channels for abatement are employed), this disadvantage becomes magnified relative to their advantage in terms of the compensation-related efficiency cost. An emissions tax may thus have higher overall costs than the other policies when the abatement target is lax, and lower overall costs when the abatement target is stringent.

We can illustrate this with the efficiency losses associated with additional abatement due to a technology mandate:

$$\psi = -\lambda(\alpha_e^y + \frac{T_x}{P_x}(\alpha_x^y + \Gamma_m))e - (1-T)\mu\alpha_e^y e\bar{\Phi}_m, \tag{17}$$

where $\Gamma_m > 0$ and $\bar{\Phi}_m > 0$ are positive constants. The two right-hand terms represent the intrinsic abatement cost and the lump-sum compensation cost respectively (see (10)) for this case. These two cost components are infinitesimal at initial abatement (i.e. $\alpha_e^y = T_x = 0$) but become positive at non-marginal abatement (i.e. $\alpha_e^y > 0, T_x < 0$).

At a negative input tax $T_x < 0$ on the good produced by the upstream industry (due to the technology mandate), the costs of additional abatement through the emission tax is given by

$$\psi = -\lambda(\alpha_e^y + \frac{T_x}{P_x}(\alpha_x^y + \Gamma_e))e - (1-T)\mu e\bar{\Phi}_t,$$

where $0 < \Gamma_e < \Gamma_m$ and $\bar{\Phi}_t > 0$ are positive constants. At initial abatement (i.e. $\alpha_e^y = T_x = 0$), the emission tax involves a positive first-order lump-sum compensation cost $(1-T)\mu e\bar{\Phi}_t > 0$ and is thus less efficient than the technology mandate, which involves only infinitesimal compensation cost. However, if the subsidy $-T_x > 0$ has become large

[18] In the present study, the higher cost of emissions taxes arises when compensation is lump-sum in nature. This result is reminiscent of earlier studies that have shown how emissions taxes can be more costly than other instruments when government budget balance must be achieved through lump-sum transfers. (See Parry and Oates (2000), Goulder et al. (1999) and Fullerton and Metcalf (2001)). In all of these studies, the use of lump-sum payments (and the associated need to finance such payments through distortionary taxes) lies behind the higher cost of the emissions tax.

enough, the fact that the emission tax results in less use of the subsidized fuel input (so that $\Gamma_e < \Gamma_m$) and thus achieves the required cut in emissions in a more efficient way makes the emission tax more efficient than the technology mandate. This effect of smaller intrinsic abatement costs of the emission tax is strengthened through larger lump-sum compensation cost of the technology mandate at non-marginal abatement. In particular, at non-marginal abatement (i.e.$\alpha_e^y > 0$),not only the emission tax but also the technology mandate involves non-marginal lump-sum compensation (see the last term at the right-hand side of (17)). The reason is that under the technology mandate the abatement costs $-\alpha_e^y e$ are born by the sector concerned rather than the government budget. Hence, at larger levels of abatement, the technology mandate losses its advantage in terms of smaller lump-sum compensation cost while its disadvantage in terms of larger intrinsic abatement cost becomes more important.

For similar reasons, the cost rankings of the two command-and-control policies can change as well as abatement becomes more extensive. The technology mandate employs only the input-substitution channel, while the performance standard engages both input substitution and output reduction. As a result, the technology mandate is at a disadvantage in terms of the intrinsic abatement cost. However, compared to the performance standard, it is more effective in protecting the upstream industry since it contains the drop in demand for the intermediate (fuel) input. Thus, it involves lower lump-sum compensation costs (compare (12) and (13) for inital abatement). This latter factor counts most heavily at low levels of pollution abatement, when the intrinsic abatement cost is less important. At these abatement levels, therefore, the technology mandate is less costly than the performance standard. However, the cost ranking is reversed at higher abatement levels, when differences in intrinsic abatement costs become larger.

Now consider the case where compensation is provided through lower sector-specific marginal tax rates. In this case, only the first right-hand term in (10) applies (the intrinsic abatement cost), although compensation affects the magnitude of this term. At initial (infinitesimal) abatement, all policies have infinitesimal intrinsic abatement costs. As abatement requirements become larger, the intrinsic abatement costs differ. As in policies without compensation, the rankings depend on the relative effectiveness with which the various abatement channels are exploited.[19]

[19] Compensation in the form of sector-specific reductions in marginal tax rates can influence the relative costs of the various abatement channels, and thereby influence the relative costs of the different policies. In our simulation experiments this impact on relative costs appears to be negligible.

3 A Numerical Model

Here we develop and apply a numerical model in order to obtain quantitative results. We briefly describe the model here; a complete description is in a technical appendix, available from www.stanford.edu/~goulder.

The formal structure of this numerical model is the same as that of the analytical model of Section 2, except that the numerical model does not assume that the polluting industries are infinitely small compared to the rest of the economy. Moreover, since this model is solved numerically, its solution does not rely on linearization techniques. Thus we can consider the impacts of large policy changes.[20]

3.1 Structure

3.1.1 Production and Factor Mobility

We adopt constant-elasticity-of-substitution (CES) functional forms for the production functions for the intermediate input X and the final goods Y and C. Each industry employs labor and capital as inputs, and industry Y employs the intermediate input X as well. Specifically:

$$Y = \gamma_y \left[\alpha_y v^{\frac{\sigma_y - 1}{\sigma_y}} + (1 - \alpha_y) L_y^{\frac{\sigma_y - 1}{\sigma_y}} \right]^{\frac{\sigma_y}{\sigma_y - 1}}, \tag{18}$$

$$X = \gamma_x \left[\alpha_x K_x^{\frac{\sigma_x - 1}{\sigma_x}} + (1 - \alpha_x) L_x^{\frac{\sigma_x - 1}{\sigma_x}} \right]^{\frac{\sigma_x}{\sigma_x - 1}}, \tag{19}$$

$$C = \gamma_c \left[\alpha_c K_c^{\frac{\sigma_c - 1}{\sigma_c}} + (1 - \alpha_c) L_c^{\frac{\sigma_c - 1}{\sigma_c}} \right]^{\frac{\sigma_c}{\sigma_c - 1}}, \tag{20}$$

with

$$v = \gamma_v \left[\alpha_v K_y^{\frac{\sigma_v - 1}{\sigma_v}} + (1 - \alpha_v) X^{\frac{\sigma_v - 1}{\sigma_v}} \right]^{\frac{\sigma_v}{\sigma_v - 1}}. \tag{21}$$

To capture the imperfect mobility of capital across industries, we apply a CES capital transformation function:

$$K = \gamma_k \left[\alpha_k K_x^{\frac{\sigma_k - 1}{\sigma_k}} + \beta_k K_y^{\frac{\sigma_k - 1}{\sigma_k}} + (1 - \alpha_k - \beta_k) K_c^{\frac{\sigma_k - 1}{\sigma_k}} \right]^{\frac{\sigma_k}{\sigma_k - 1}}, \tag{22}$$

[20] We also now consider total welfare impacts, as opposed to the marginal analysis of the previous section.

The parameter σ_k controls the curvature of this function. We employ negative values for σ_k so that the transformation function is bowed out from the origin. Successive increments to the supply of any given type of capital thus require ever-larger sacrifices of other types of capital, in keeping with increasing marginal adjustment costs. In contrast to capital, labor is perfectly mobile across industries.

3.1.2 Emissions

Emissions are generated by the downstream industry Y. These are a function of that industry's use of fuel (X) and the resources devoted by that industry to end-of-pipe treatment. We adopt the following emissions function:

$$\frac{E}{X} = \gamma_e \left[1 + \beta_e \left(\frac{g(Y_a, C_a)}{X}\right)^{\rho_e}\right]^{\frac{-1}{\rho_e}} \quad \beta_e > 0; \quad 0 < \rho_e < 1 \tag{23}$$

where the function $g(Y_a, C_a)$, representing resources devoted to end-of-pipe treatment, is a CES composite of the two final goods. The emissions ratio E/X above can be represented as $\gamma_e f(g/X)$. The function $f(.)$ has the following desirable properties:

- $f'(0) \Rightarrow -\infty$. This first unit of end-of-pipe treatment is very productive in cutting emissions. Accordingly, end-of-pipe treatment is positive if emissions are constrained (implying a positive shadow price of pollution permits)
- $f(\infty) = 0$. Pollution is eliminated completely if end-of-pipe treatment is very large.
- $f(0) = 1$. Without any end-of-pipe treatment, pollution remains finite.

3.1.3 Household Utility (Goods Demand and Factor Supply)

The household utility function is CES:

$$U = \left(\alpha_g G^{\frac{\sigma_u - 1}{\sigma_u}} + \alpha_z Z^{\frac{\sigma_u - 1}{\sigma_u}}\right)^{\frac{\sigma_u}{\sigma_u - 1}}, \tag{24}$$

where G is a CES composite of Y_h and C_h (the quantities of goods Y and C devoted to household consumption[21]):

$$G = \left(\alpha_{gy} Y_h^{\frac{\sigma_g - 1}{\sigma_g}} + \alpha_{gc} C_h^{\frac{\sigma_g - 1}{\sigma_g}} \right)^{\frac{\sigma_g}{\sigma_g - 1}}, \tag{25}$$

and Z is a CES composite of labor supply and aggregate capital supply:

$$Z = \left(\alpha_{zl} (\overline{L} - L)^{\frac{\sigma_z - 1}{\sigma_z}} + \alpha_{zk} (\overline{K} - K)^{\frac{\sigma_z - 1}{\sigma_z}} \right)^{\frac{\sigma_z}{\sigma_z - 1}}, \tag{26}$$

and where $\overline{L}$ and $\overline{K}$ represent the maximum potential labor supply (endowment of labor time) and capital supply, respectively. Note that this utility function does not account for the welfare impact of changes in environmental quality. All of the policy costs described in the results below should therefore be regarded as gross costs: they do not net out the benefits associated with policy-induced environmental improvements.

3.1.4 The Government

The government levies factor taxes and introduces the various environmental policies discussed above. All revenues are returned to the private sector through marginal or lump-sum cuts in factor taxes. The government's budget constraint is:

$$\begin{aligned} P_g \Lambda + \Pi(1 - T) + S_{kx} K_x + S_{ky} K_y \quad &= \quad \underbrace{T[WL + R_x K_x + R_y K_y + R_c K_c]}_{\text{factor tax revenue}} \\ &\quad + \underbrace{T_E E + T_x P_x X - SY}_{\text{environmental tax revenue}} \end{aligned}$$

where, as before, $P_g \Lambda$ is a fixed real government transfer to the households, Π is the amount of tax credit given to the X and Y industries, and T, T_e, and T_x are the tax rates on factors (labor, capital in industries X, Y, and C), emissions, and output from industry X, respectively. Total government revenue, shown on the right-hand side, comes from these taxes net of the subsidies used to model the command-and-control policies.[22]

[21] The parameters of the function G are the same as those in the end-of-pipe-treatment function g in (23) above.

[22] Households' revenues from the tax credit are also subject to tax at the marginal capital tax rate.

3.2 Equilibrium Conditions

For the emissions tax, emissions permits, and fuel tax policies, the requirements of the general equilibrium are that (1) household supply of labor must equal aggregate labor demand by firms, (2) demand for capital by each industry i ($i = x, y, c$) must equal the quantity supplied to that industry, (3) pollution emissions must equal the pollution level stipulated by environmental policy, and (4) government revenue must equal real transfers to households. The before-tax wage is the numeraire. The model identifies the primary "prices" that cause these four types of equilibrium conditions to be met. These are the equilibrium rental prices for capital, the emissions tax rate (or price of emissions permits), and the marginal factor tax rate T. These prices determine output prices and the real wage. Walras's law implies that the labor market clears when all the other markets clear.

For the technology mandate and performance standard, a further condition is introduced. As mentioned in the previous section, a technology mandate imposed on industry Y is equivalent to a revenue-neutral combination of an emissions tax and a subsidy to the polluting input X, while the performance standard imposed on that industry is a revenue-neutral combination of emissions tax and subsidy to Y. We simulate these two command-and-control policies as combinations of this sort. For these policies, the model adds the condition that the combination of the emissions tax and a subsidy to either X or Y is revenue-neutral.

Table 1 lists the policies considered and summarizes how they are implemented in the model.

3.3 Data

We apply the numerical model to the U.S., letting Y represent the electricity industry and C the other U.S. final goods industries. X refers to the industry producing (extracting) fossil fuels – coal, crude petroleum and natural gas. The use of these fuels by the electricity (Y) industry leads to emissions. We focus on control of sulfur dioxide (SO_2) emissions.

Table 2 indicates the inter-industry flows in our data set. These flows derive from the U.S. Commerce Department Bureau of Economic Analysis's *Benchmark Input & Output Tables for 1992.* The emissions data come from the 1992 column of Table 12.6 of the Energy Information Agency's *Annual Energy Review 1999.*

Table 3 displays the model's parameters. The elasticities of substitution in production are taken from the disaggregated general equilibrium data set developed by Barreto, Gurney, Xie, and Goulder (2002). For the Y industry, we calibrate the model to generate production and abatement elasticities consistent with those from the detailed "HAIKU" model of the U.S. electricity industry developed at Resources for the Future. The substitution elasticities σ_y and σ_v imply that, compared to capital, labor is a much better substitute for X.

The capital adjustment parameter σ_k is chosen so as to yield capital responses roughly consistent with findings from a survey by Chirinko, Fazzari, and Meyer (2002) indicating that the elasticity of investment with respect to the cost of capital is in the range of .25-.4.

We calibrate the model to generate uncompensated and compensated labor supply elasticities of 0.15 and 0.4, respectively.[23] This is consistent with the survey by Russek (1996). Together, these two elasticity targets yield the values for the elasticity of substitution between leisure and capital and the benchmark ratio of total (labor plus leisure) time to labor time. These values imply a marginal excess burden of 0.24 for labor taxes. As in the analytical model, capital supply elasticities are set equal to labor supply elasticities.[24] In this model, employing the same tax rate on both capital and labor income implies that the marginal excess burden for capital taxes is thus the same as that for labor taxes.

3.4 Simulation Results

3.4.1 Cost Effectiveness and Incidence – No EVN Constraint

We apply the model to examine the impacts of emissions taxes, performance standards, technology mandates, and fuel taxes.[25] Our first experiments assess the efficiency and incidence impacts of these instruments in the absence of compensation to achieve equity

[23] To calibrate the model to these labor supply parameters, we numerically solve the household's utility maximization problem with given prices and observe the change in labor supply resulting from a change in the after-tax wage. We solve this as a constrained optimization problem, where the amount of capital supplied is fixed. To calculate the compensated elasticity, we also alter the household's income so that utility remains unchanged despite the change in the after-tax wage.

[24] This is accomplished in calibration by setting the ratio $\overline{K}/K$ equal to the ratio $\overline{L}/L$.

[25] Because there is no uncertainty in this model, policies involving tradable emissions permits are equivalent to various emissions tax policies. If permits are initially allocated through an auction, an emissions tax of T_e is equivalent to a system involving auctioned permits that yields a permit price equal to T_e. Both policies will lead to the same economic outcomes, including the extent of abatement. A system of tradable permits in which the permits are initially allocated free is equivalent to an emissions tax with a lump-sum rebate equal to the total tax revenues. This latter system would in fact cause profits in the Y industry to be higher than in the unregulated status quo (see Bovenberg and Goulder, 2001).

value neutrality (EVN).

Figure 1 compares the policy costs, as measured by the negative of the equivalent variation.[26] The emissions tax is the most cost effective, followed by the two "command-and-control" policies (the technology mandate and performance standard). The fuel tax is the least cost effective and is omitted from the figure for scale – its costs may be found in Table 4. As indicated in Section 2, the emissions tax is most cost effective because it efficiently exploits all three channels for abatement: input substitution, end-of-pipe treatment, and output reduction. The other policies fail to exploit at least one of these channels. The performance standard – equivalent to the combination of emissions tax and subsidy to output – leads to inefficiently low output prices and thus makes relatively little use of the output-reduction channel. Similarly, the technology mandate – equivalent to the combination of an emissions tax and a subsidy to the fuel input – yields inefficiently low incentives for substitution away from the pollution-generating fuel, as well as for output reduction (the subsidy to the input leads to output prices that are lower than those under the emissions tax). The fuel tax provides no incentive for end-of-pipe treatment. The exceptionally high cost of the fuel tax in our model indicates that, under central values for parameters, the absence of the end-of-pipe channel is especially important.[27]

Table 4 indicates the price impacts of each policy, for abatement of 10, 25, and 75 percent. The performance standard leads to the smallest change in the demand (consumer) price of the downstream good Y because it is equivalent to an emissions tax and output subsidy. Indeed, the price of that good falls (slightly) in the case of 10 percent abatement. The technology mandate (which effectively subsidizes the fuel input to the downstream good industry) also has a relatively small impact on the price of the downstream good. The emissions tax and fuel tax yield the largest impacts on the price of the downstream good Y. The impact is especially large in the case of the fuel tax. Because this policy does not exploit the channel of end-of-pipe treatment, a very high fuel tax is needed to induce sufficient input-substitution to meet a given abatement target. This high tax leads to a large increase in cost of the fuel input and the price of the output Y.

Table 4 also displays the incidence (i.e., profit and wage) impacts of the different

[26] Note that the equivalent variation does not account for welfare impacts associated with improved environmental quality. Thus, the negative of our equivalent variation indicates *gross* policy costs.

[27] In the central case, the parameter ρ_e (calibrated from the HAIKU model) implies fairly elastic response of end-of-pipe treatment to the price of emissions. Hence, the fuel tax's failure to engage the channel of end-of-pipe treatment is a significant disadvantage in the model's central case.

policies. Because of their subsidy components, the technology mandate and performance standard have the smallest adverse profit impacts on the downstream industry Y. They also exert the smallest adverse impacts on profits to the upstream industry, reflecting the fact that these policies reduce only slightly the demand for the upstream good. The impacts of these two command-and-control policies differ in that the technology mandate protects especially the upstream industry, while the performance standard offers special protection to the downtream industry, in keeping with the different subsidy components of the two policies. The fuel tax imposes the largest burden on the upstream- and downsteam industries, reflecting the need to impose a relatively high tax rate to reach given levels of abatement when the channel of end-of-pipe treatment is not employed.

3.4.2 Cost-Effectiveness in the Presence of the EVN Constraint

Compensation via Tax Credits

We now examine the relative costs when the policies must include compensation to the pollution-related industries. These costs depend on the way that compensation is provided. We first investigate the costs when compensation is provided in the form of lump-sum tax payments or credits to both of the pollution-related industries, that is, to both X and Y.

Table 5 compares, for each policy, the aggregate policy costs in the presence and absence of the EVN constraint. The additional costs implied by the constraint are largest for the emissions tax and (especially) the fuel tax because these policies require the most compensation (in the form of tax credits). To preserve budget balance, the government must finance the tax credits by significantly increasing tax rates on factors of production. This raises the costs of the emissions tax and fuel tax considerably relative to the case without EVN. In contrast, under the command-and-control policies, much less compensation is needed, so for these policies the marginal factor tax rates in the cases with and without EVN are not much different. Hence, the added efficiency cost of the EVN constraint is smaller under command and control.

In fact, in keeping with the analysis of Section 2, the EVN requirement reverses the rankings of the various instruments in terms of overall costs (including the lump-sum compensation cost). As shown in Figure 2, the EVN constraint makes the costs of the emissions tax higher than those of the command-and-control policies, for all except very high amounts of abatement. The emissions tax's need for higher compensation (at any level of abatement) implies large compensation-related costs relative to those of the other policies. The relatively high compensation costs work against the emissions tax's advantage in terms of the intrinsic abatement cost. Figure 2 shows that, at low and moderate levels of abatement, the emissions tax's disadvantage in terms of compensation costs overwhelms its advantage in terms of intrinsic abatement costs. Only at very high levels of abatement does the intrinsic abatement advantage dominate. When very high levels of abatement are called for, the other policies' neglect of at least one important abatement channel ultimately leads to very high costs that offset their advantages related to compensation. Economists have long considered emissions taxes as a more cost-effective instrument than command-and-control policies. These results indicate that the need for compensation can reverse the rankings in terms of cost effectiveness.

At low levels of abatement, the compensation requirement also reverses the rankings between the two command-and-control policies. At less than 25 percent abatement, the performance standard now emerges as more costly than the technology mandate. This reflects the need for greater compensation under the performance standard, as analyzed in Section 2. Thus, at low levels of abatement the rankings between the emissions tax, performance standard and technology mandate are completely reversed when the EVN contraint is imposed.

Compensation via Industry-specific Cuts in Capital Tax Rates

We now examine the relative costs when compensation is achieved through reductions in the marginal rates on capital income in the X and Y industries. The bottom set of rows in Table 5 shows the results from these experiments.

The required levels of compensation under the various environmental policies are very similar to those in the case where industries were offered tax credits. In terms of overall policy cost, the choice of compensation method is more important for the emissions tax than for the command-and-control policies. Under the emissions tax, it is somewhat more efficient to compensate through marginal rate cuts in capital taxes than through lump-sum credits. When compensation is provided through marginal rate cuts, capital tax rates can be lower than would be the case under lump-sum tax credits (particularly in industries X and Y). This reduces the efficiency costs. For the command-and-control policies, in contrast, the choice of compensation method has relatively little impact on the efficiency cost, since the compensation requirements of these policies are relatively small.

Figure 3 compares the costs of different policies in the case where EVN is accomplished through marginal rate cuts. A comparison with Figure 1 indicates that each policy's costs are higher than in the case without compensation, while policy rankings are unchanged.[28]

We also consider the relative costs of the two different compensation methods, holding fixed the choice of environmental policy instrument. Marginal rate cuts are in general better at low levels of abatement, but worse at high levels.[29] As discussed in Section 2, capital tax cuts reduce the effectiveness of the input-substitution and output-demand channels and thus result in less efficient pollution abatement. Inefficient abatement is especially important when the abatement target is stringent. For example, under a fuel tax, the cost of compensation through marginal rate cuts is lower than the cost through tax credits if the required abatement is less than 10 percent, but becomes higher if greater abatement is called for. Similarly, under the emissions tax, the cost with compensation through marginal rate cuts overtakes the cost through lump-sum compensation once the abatement requirement exceeds 71 percent.

3.5 Sensitivity Analysis

Tables 6 and 7 display the sensitivity of our results to changes in key parameters. In Table 6, which focuses on abatement levels of 25 percent, the first column of numbers gives the efficiency cost of the emissions tax in the absence of compensation. The remaining columns indicate the ratio of efficiency costs for the policy in question to the cost in the first column. For each of the four policy instruments considered, we show these ratios both for the no-compensation case and for the case with compensation via corporate tax credits. Table 7 indicates the critical levels of abatement at which the efficiency rankings of policies change.

End-of-pipe treatment

Higher values for the parameter β_e imply greater ease of end-of-pipe treatment; when β_e is zero, end-of-pipe treatment is not possible (the ratio of emissions to fuel use is fixed). Table 6 shows that the cost of abatement rises and the relative cost of command-and-control policies increases as end-of-pipe treatment is made more difficult.

[28] As mentioned in Section 2, sector-specific tax cuts could affect relative policy costs by influencing the relative costs of the abatement channels. However, this effect is negligible in our simulations.

[29] This implies that for intermediate levels of abatement some combination of lump-sum compensation and marginal compensation will be more efficient than either instrument alone.

In the case without end-of-pipe treatment, where β_e equals zero, the technology mandate is no longer defined, and the fuel tax becomes equivalent to the emissions tax. For low values of β_e, the high relative cost of the performance standard means that the output-demand channel is important in reducing emissions. Since the performance standard omits this channel, its compensation-related advantage becomes small relative to its efficiency disadvantage. Hence, the critical abatement percentage beyond which the emissions tax becomes more efficient is lower, as indicated in Table 7. Even in the extreme case where β_e equals zero, however, the performance standard still outperforms the emissions tax for low enough abatement targets.

Capital adjustment costs

The parameter σ_k controls the adjustment costs in moving capital across sectors: higher values of σ_k imply less mobile capital. With lower capital mobility, owners of capital in the X or Y industries require greater compensation. The capital adjustment costs have relatively little effect on the intrinsic efficiency costs of abatement in the first column of Table 6, but have a large effect on compensation-related costs, as indicated by the ratio of costs with and without EVN for the various policies. Since this parameter directly controls how much industry compensation is needed for environmental policy, it has a large impact in Table 7. The compensation-related advantage of the command-and-control policies becomes more and more important as capital adjustment costs rise. Indeed, in the high-cost case, the performance standard is more efficient than the emissions tax until 90 percent abatement.

Elasticity of demand for output from industry Y

Easier substitution between C and Y in demand increases the importance of the output-demand effect. This slightly lowers overall abatement costs and increases the relative cost of the command-and-control policies (because they make less use of the output-demand channel). The higher elasticity also increases somewhat the need for compensation, since the Y sector shrinks more under environmental policy. These two effects (higher intrinsic cost of command-and-control policies as well as greater need for compensation) compete in their impact in Table 7. They almost exactly offset each other for the performance standard with the crossover remaining at 79 percent abatement.

Factor supply elasticity

The elasticity in the outer nest of the utility function, σ_u, controls the elasticity with which the household supplies labor and capital. Higher values for this elasticity mean that existing factor taxes lead to larger distortions in factor markets, and a higher marginal cost of public funds. A higher factor-supply elasticity raises the efficiency cost of providing compensation through corporate tax credits, since this compensation must be financed through higher factor taxes (which now have a higher efficiency cost). Thus, when the EVN constraint is imposed, the relative advantage of the command-and-control policies increases with the size of the factor supply elasticity. For example, the first row of Table 6 shows that under central values for parameters the cost of the emissions tax with EVN is about 24 percent higher than the cost of the technology mandate with EVN (1.439/1.156). With the high factor-supply elasticity, in contrast, the emissions tax's cost is about 53 percent higher (1.889/1.232). Higher factor-supply elasticities likewise imply higher crossover points in Table 7.

Input substitution between capital and fuel

The parameter σ_v controls the ease of subsitution between the intermediate input (fuel) and capital in the Y industry. A higher value for this parameter thus reduces the relative cost of policies that rely heavily on the fuel-capital substitution channel. Hence, the relative cost of the fuel tax and performance standard fall when σ_v takes a higher value. A high value for σ_v is especially disadvantageous for the technology mandate, since this policy does not exploit the fuel-capital substitution channel. Easier fuel substitution implies greater need for compensation to the upstream industry but less need for the downstream industry. The change in overall compensation requirements is nearly neutral, so the effects in Table 7 are driven primarily by the changes in relative intrinsic efficiency. With a higher substitution elasticity, the performance standard is more efficient than the emission tax over a wider range of abatement (because of the former policy's heavier reliance on fuel switching), while the technology mandate becomes less efficient more quickly than the emissions tax does.

Industries compensated

Here we explore how results change when only the downstream industry receives compensation instead of both the upstream and downstream industries. Narrowing the compensation net lowers the cost ratios for all policies, since less compensation is needed. The effect is particularly strong for the performance standard, which tends to hurt the upstream industry while preserving profits in the downstream industry. The results in Table 7 are as expected, with the compensation-related efficiency advantage of the command-and-control policies becoming somewhat less important when only one industry is compensated.

4 Conclusions

The political viability of a proposed environmental policy instrument can depend on whether it is likely to avoid significant profit losses to major industrial stakeholders. Using analytically and numerically solved models, we investigate the incidence of various environmental policy instruments and then explore how the aggregate costs of these instruments change with the requirement that major pollution-related industries be compensated for potential profit losses.

We show that the added cost from the compensation requirement can be decomposed into two components: (1) an increase in intrinsic abatement cost (the cost of utilizing the channels of inputsubstitution, end-of-pipe treatment, and output cuts in order to achieve pollution reductions), and (2) a cost directly associated with lump-sum compensation. We explore how these cost components are affected when compensation is provided either through sector-specific tax credits or by way of sector-specific reductions in capital tax rates. For each policy instrument, achieving compensation through tax credits raises both cost components, while achieving compensation through reductions in capital tax cuts raises only the intrinsic abatement cost.

Importantly, introducing the compensation requirement has very different impacts on the costs of different policy instruments. Restoring profits through tax credits, in particular, raises the costs of emissions taxes considerably more than it raises the costs of command-and-control policies such as performance standards and mandated technologies. This reflects the greater need for compensation under the emissions tax and the associated larger increase in the second cost component, the lump-sum compensation cost. Thus, while emissions taxes generally are more cost effective in the absence of a compensation requirement, imposing this requirement can make the emissions tax more costly than command-and-control policies. This result occurs when a small or moderate amount of pollution abatement is required. When the abatement requirement is very extensive, the emissions tax regains its status as the most cost-effective instrument; with extensive abatement, other policies suffer significant increases in intrinsic abatement costs, which causes overall costs to exceed those of the emissions tax, despite lower compensation requirements.

The potential advantage (at low or modest levels of abatement) of command-and-control policies reflects the fact that these policies effectively include subsidy components: a performance standard is equivalent to an emissions tax and output subsidy, while a technology mandate is equivalent to an emissions tax and input subsidy. The implicit subsidies limit the adverse profit impacts of these policies, thereby reducing the need for compensation. When equity value neutrality must be achieved through tax credits, the command-and-control policies therefore have an advantage, since they require less compensation through tax credits, which entail significant efficiency costs.

The introduction of a compensation requirement can thus significantly alter the cost-rankings of alternative environmental policy instruments. The extent to which the rankings are changed depends on the degree of stringency of the abatement requirement.

Some limitations in this study deserve mention. The two models do not incorporate uncertainty, nor do they capture heterogeneity among producers within given industries. These elements can influence the cost rankings of policy instruments. Uncertainty is associated with costs of monitoring and enforcement, and such costs generally differ across policies. In addition, when polluting firms have heterogeneous abatement costs and regulators have imperfect information about such costs, incentive-based policies like emissions taxes and fuel taxes may have an advantage over command-and-control policies in producing a cost-effective allocation of pollution-reduction efforts across firms.[30] Despite these limitations, the present analysis reveals how the compensation requirement affects the absolute and relative costs of major environmental policy instruments.

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[30] See, for example, Tietenberg (1990) and Stavins *et al.* (1998).

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Appendix: The Analytical Model

This appendix provides the details and derivation of the analytical results discussed in Section 2. Part 1 derives expressions for supply and demand in the goods markets and then solves for the equilibrium price changes resulting from environmental policy. Part 2 employs these equilibrium values to derive, for each of the four policy instruments considered above, the overall efficiency costs (both abatement efficiency cost and lump-sum compensation-related costs) that were presented in equations (10) through (11d) of the main text. Finally, Part 3 decomposes the overall welfare effect into the incidence on the upstream- and downstream industries.

A.1 Equilibrium

A.1.1 Supply in the downstream industry

Competitive profit-maximizing behavior by the downstream industry yields

$$(P_y + S)\frac{\delta h(.;.)}{\delta V}\frac{\delta v(.;.)}{\delta X} = P_x + T_x + T_e\frac{\delta n}{\delta X}, \tag{A.1}$$

$$(P_y + S)\frac{\delta h(.;.)}{\delta L_y} = W, \tag{A.2}$$

$$-T_e\frac{\delta n}{\delta g}\frac{\delta g}{\delta C_a} = P_c; \quad -T_e\frac{\delta n}{\delta g}\frac{\delta g}{\delta Y_a} = P_y, \tag{A.3}$$

$$(P_y + S)\frac{\delta h(.;.)}{\delta V}\frac{\delta v(.;.)}{\delta K_y} = R_y - S_{ky}. \tag{A.4}$$

Loglinearizing the production function of the downstream industry (4) and employing the first-order conditions (A.1), (A.2), (A.3), and (A.4) (and using the fact that the emission function (5) exhibits constant returns to scale), we find

$$y = k_y + (1-\alpha_v^y)(l_y - v) + (1-\alpha_k^y)(x - k_y), \tag{A.5}$$

where $\alpha_k^y \equiv (R_y - S_{ky})K_y/((R_y - S_{ky})K_y + (P_x + T_x)X + T_eE + P_cC_a + P_yY_a)$, $\alpha_v^y \equiv ((R_y - S_{ky})K_y + (P_x + T_x)X + T_eE + P_cC_a + P_yY_a)/(P_y + S)Y = 1 - (WL_y/(P_y + S)Y)$, and $v = \alpha_k^y k_y + (1-\alpha_k^y)x$.

With constant-returns-to-scale production and emissions functions, the relative change in the output price is a weighted average of the relative changes in the input prices[31]

$$\hat{p}_y + s = \hat{p}_x + \hat{t}_x + \hat{t}_e + \hat{r}_y - \hat{s}_{ky}, \tag{A.6}$$

where $\hat{p}_y \equiv \frac{P_y}{P_y+S}p_y$; $\hat{p}_x \equiv \frac{P_xX}{(P_y+S)Y}p_x$; $\hat{t}_x \equiv \frac{XdT_x}{(P_y+S)Y}$; $\hat{t}_e \equiv \alpha_e^y t_e$; $\hat{r}_y \equiv \alpha_v^y\alpha_k^y\frac{R_y}{R_y-S_{ky}}r_y$, $\hat{s}_{ky} \equiv$

[31] $p_c = 0$ because P_c is the numeraire. Also $w = 0$ since the downstream- and upstream sectors are too small to affect the prices on the labor market. $p_c = 0$ implies that the costs of abatement do not change because, in line with our assumption that the upstream- and downstream industries are small compared to the rest of the economy, the share of abatement produced by the downstream industry (i.e. Y_a) in aggregate abatement $g(C_a; Y_a)$ is only infinitely small.

$\frac{K_y dS_{ky}}{(P_y+S)Y}$, where $\alpha_e^y \equiv T_e E/(P_y + S)Y$ stands for the cost shares of the emissions tax in the final-goods industry.

Capital supply is given by[32]

$$k_y = \hat{\sigma}_k^y \hat{r}_y, \tag{A.7}$$

where $\hat{\sigma}_k^y \equiv \frac{\sigma_k^y}{\alpha_v^y \alpha_k^y} \frac{R_y - S_{ky}}{R_y}$ and σ_k^y stands for the substitution elasticity between the industry-specific capital services in the final-goods sector and the capital services in the rest of the economy.

Using (A.4), (A.2), and (A.1) to eliminate P_y, and log-linearizing the results, we arrive at the following two equations

$$x - k_y = \hat{\sigma}_v[\hat{r}_y - \hat{s}_{ky} - (\alpha_k^y/(1-\alpha_k^y))(\hat{p}_x + \hat{t}_x + \hat{t}_e)], \tag{A.8}$$

$$l_y - v = \hat{\sigma}_y \alpha_k^y [\hat{r}_y - \hat{s}_{ky} + \hat{p}_x + \hat{t}_x + \hat{t}_e], \tag{A.9}$$

where $\hat{\sigma}_v \equiv \frac{\sigma_v}{\alpha_v^y \alpha_k^y}$ and σ_v stands for the substitution elasticity between the intermediate input and capital in the composite $v(.;.)$. $\hat{\sigma}_y \equiv \frac{\sigma_y}{\alpha_v^y \alpha_k^y}$ and σ_y represents the substitution elasticity between labor and the nest $v(.;.)$ in the production function $h(.;.)$ (see (4)). Substituting (A.7), (A.8) and (A.9) into (A.5) to eliminate k_y, $x - k_y$, and $l_y - v$, and using (A.6) eliminate $\hat{r}_y$ from the result, we write the supply of the final good in terms of its price, the price of the intermediate good, and the various policy instruments:

$$y = \varepsilon_y^y \hat{p}_y + \varepsilon_y^y s - \varepsilon_x^y [\hat{p}_x + \hat{t}_x + \hat{t}_e] + \hat{\sigma}_k^y \hat{s}_{ky}, \tag{A.10}$$

where

$$\varepsilon_y^y \equiv \hat{\sigma}_k^y + \hat{\sigma}_v(1-\alpha_k^y) + (1-\alpha_v^y)\alpha_k^y \hat{\sigma}_y, \tag{A.11}$$

$$\varepsilon_x^y = \hat{\sigma}_k^y + \hat{\sigma}_v. \tag{A.12}$$

The assumption that capital is complementary to the intermediate input implies that $(1-\alpha_v^y)\hat{\sigma}_y \geq \hat{\sigma}_v$, so that $\varepsilon_y^y \geq \varepsilon_x^y$.

A.1.2 Demand for the downstream good

Maximization of the utility function (7) yields

$$\frac{\delta g}{\delta Y} \Big/ \frac{\delta g}{\delta C} = \frac{P_y}{P_c}.$$

Log-linearization of this equation gives rise to the demand function

$$y = -\bar{\sigma}_g \hat{p}_y, \tag{A.13}$$

[32] This assumes that all households are well diversified so that income effects can be ignored. Alternatively, one can assume that a share γ_y of capital owners in the downtream industry is completely specialized in this sector (i.e., only derives income from capital in this sector). In that case, the elasticity σ_k^y in the following equation is replaced by $(1-\gamma_y)\sigma_k^y + \gamma_y \varepsilon_u$, where ε_u stands for the uncompensated elasticity of aggregate capital supply with respect to the rate of return.

where $\bar{\sigma}_g \equiv \sigma_g \frac{P_y+S}{P_y}$ and σ_g represents the substitution elasticity between the final good Y and other consumption goods C in the household sub-utility function $g(.,.)$ (see (7)).

A.1.3 Supply in the upstream industry

Log-linearizing the production function of the upstream industry (1), we find

$$x^s = k_x + (1-\alpha_k^x)(l_x - k_x), \tag{A.14}$$

where $\alpha_k^x \equiv (R_x - S_{kx})K_x/P_xX$ stands for the share of capital in output of the upstream sector. With a constant-returns-to-scale production function, the relative change in the output price is a weighted average of the relative changes in the input prices (note that wages do not change)

$$\hat{p}_x = \hat{r}_x - \hat{s}_{kx}, \tag{A.15}$$

where $\hat{r}_x \equiv \alpha_k^x \alpha_x^y \frac{R_x}{R_x - S_{kx}} r_x$ and $\hat{s}_{kx} \equiv \frac{K_x dS_{kx}}{(P_y+S)Y}$ with $\alpha_x^y \equiv P_xX/((P_y+S)Y)$.

Capital supply is given by

$$k_x = \hat{\sigma}_k^x \hat{r}_x, \tag{A.16}$$

where $\sigma_k^x \equiv \sigma_k^x \frac{R_x - S_{kx}}{R_x}/(\alpha_k^x \alpha_x^y)$ and σ_k^x stands for the substitution elasticity between the industry-specific capital services in the intermediate-goods industry and the capital services in the rest of the economy.

Using (2) and (3) to eliminate P_x and log-linearizing the results, we arrive at

$$l_x - k_x = \hat{\sigma}_x(\hat{r}_x - \hat{s}_{kx}), \tag{A.17}$$

where $\hat{\sigma}_x \equiv \sigma_x/((\alpha_k^x \alpha_x^y))$ stands for the substitution elasticity between the two inputs in the production of the intermediate good.

Substituting (A.16), (A.17), and (A.15) into (A.14) to eliminate k_x, $(l_x - k_x)$, and r_x, we write the supply of the final good in terms of its price and the demand price of the intermediate good

$$x^s = \hat{\sigma}^x \hat{p}_x + \hat{\sigma}_k^x \hat{s}_{kx}, \tag{A.18}$$

where $\hat{\sigma}^x \equiv \hat{\sigma}_k^x + (1-\alpha_k^x)\hat{\sigma}_x$ denotes the supply elasticity.

A.1.4 Demand for the upstream good

By substituting (A.7) into (A.8) to eliminate k_y and using (A.6) to eliminate $\hat{r}_y$ from the resulting expression, we can derive the impact on the demand for the intermediate good as

$$x = \varepsilon_y^x \hat{p}_y - \varepsilon_x^x[\hat{p}_x + \hat{t}_x + \hat{t}_e] + \hat{\sigma}_k^y \hat{s}_{ky} + \varepsilon_y^x s, \tag{A.19}$$

where

$$\varepsilon_y^x \equiv \hat{\sigma}_k^y + \hat{\sigma}_v = \varepsilon_x^y,$$

$$\varepsilon_x^x = \hat{\sigma}_k^y + \frac{\hat{\sigma}_v}{(1-\alpha_k^y)},$$

so that $\varepsilon_x^x \geq \varepsilon_y^x$.

A.1.5 Emissions

In order to find emissions, we write the emission function (5) as $X = \phi(E, g(C_a; Y_a))$, where $\phi(.,.)$ is homogenous of the first degree in its arguments, and log-linearize to arrive at

$$x = e + \frac{\alpha_v^y(1-\alpha_k^y) - \alpha_x^y \frac{P_x+T_x}{P_x} - \alpha_e^y}{\alpha_v^y(1-\alpha_k^y) - \alpha_x^y \frac{P_x+T_x}{P_x}}(c_a - e), \tag{A.20}$$

where we have used the fact that Y_a accounts for an infinitely small share of $g(C_a, Y_a)$. Writing (A.3) in terms of $\phi(.,.)$ (i.e. $\frac{d\phi}{dg}/\frac{d\phi}{dE} = \frac{P_c C_a + P_y Y_a}{g P_e}$) and log-linearizing, we arrive at

$$c_a - e = \sigma_e t_e, \tag{A.21}$$

where σ_e represents the substitution elasticity between emissions and aggregate end-of-pipe treatment in $\phi(.,.)$. Employing (A.21) to eliminate $(c_a - e)$ from (A.20), we find emissions in terms of the emission tax and the demand for the intermediate input[33]

$$e = x - \bar{\sigma}_e \hat{t}_e, \tag{A.22}$$

where $\bar{\sigma}_e \equiv \frac{\alpha_v^y(1-\alpha_k^y) - \alpha_x^y \frac{P_x+T_x}{P_x} - \alpha_e^y}{(\alpha_v^y(1-\alpha_k^y) - \alpha_x^y \frac{P_x+T_x}{P_x})\alpha_e^y}\sigma_e$.

A.1.6 Solution of the model

We can solve the model for p_y, p_x, r_x, r_y, x, e, and y most easily by writing the equilibrium in the market for the final good (from (A.10) and A.13)) and in the market for the intermediate good (from (A.19) and (A.18)) as follows:

$$(\varepsilon_y^y + \bar{\sigma}_g)\hat{p}_y = \varepsilon_x^y \hat{p}_x + \varepsilon_x^y[\hat{t}_x + \hat{t}_e] - \hat{\sigma}_k^y \hat{s}_{ky} - \varepsilon_y^y s,$$

$$(\hat{\sigma}^x + \varepsilon_x^x)\hat{p}_x = \varepsilon_y^x \hat{p}_y - \varepsilon_x^x[\hat{t}_x + \hat{t}_e] + \hat{\sigma}_k^y \hat{s}_{ky} - \hat{\sigma}_k^x \hat{s}_{kx} + \varepsilon_y^x s.$$

These are two linear equations in two unknowns (i.e. $\hat{p}_y$ ad $\hat{p}_x$) and can be solved by Cramer's rule

$$\begin{pmatrix} \hat{p}_y \\ \hat{p}_x \end{pmatrix} = \frac{1}{\Sigma}\begin{pmatrix} \hat{\sigma}^x + \varepsilon_x^x & \varepsilon_x^y \\ \varepsilon_y^x & \varepsilon_y^y + \bar{\sigma}_g \end{pmatrix} \times \begin{pmatrix} \varepsilon_x^y[\hat{t}_x + \hat{t}_e] - \hat{\sigma}_k^y \hat{s}_{ky} - \varepsilon_y^y s \\ -\varepsilon_x^x[\hat{t}_x + \hat{t}_e] + \hat{\sigma}_k^y \hat{s}_{ky} - \hat{\sigma}_k^x \hat{s}_{kx} + \varepsilon_y^x s \end{pmatrix}. \tag{A.23}$$

where $\Sigma \equiv (\bar{\sigma}_g + \varepsilon_y^y)(\hat{\sigma}^x + \varepsilon_x^x) - \varepsilon_x^y \varepsilon_y^x > 0$ [since $\bar{\Sigma} \equiv \varepsilon_y^y \varepsilon_x^x - \varepsilon_x^y \varepsilon_y^x > 0$].

[33] Without an initial emission tax (i.e. $\alpha_e^y = 0$), the firm does not abate in the initial equilibrium (i.e. $C_a = Y_a = 0$) so that $\alpha_v^y(1-\alpha_k^y) - \alpha_x^y - \alpha_e^y = 0$. The elasticity $\bar{\sigma}_e$ remains finite in such an equilibrium. The same holds true for $\alpha_e^y t_e = \frac{EdT_e}{(P_y+S)Y}$ even though t_e goes to infinity if the initial emission tax is zero.

The changes in the key model variables are easily derived from the solutions for $\hat{p}_y$ and $\hat{p}_x$ (which represent the changes in equilibrium goods prices):

$$\hat{r}_x = \hat{p}_x + \hat{s}_{kx}, \tag{A.24}$$

$$\hat{r}_y = \hat{p}_y - \hat{p}_x - \hat{t}_x - \hat{t}_e + \hat{s}_{ky} + s, \tag{A.25}$$

$$x = \hat{\sigma}^x \hat{p}_x + \hat{\sigma}_k^x \hat{s}_{kx}, \tag{A.26}$$

$$e = x - \bar{\sigma}_e \hat{t}_e \tag{A.27}$$

$$y = -\bar{\sigma}_g \hat{p}_y. \tag{A.28}$$

$$k_x = \hat{\sigma}_k^x \hat{r}_x, \tag{A.29}$$

$$k_y = \hat{\sigma}_k^y \hat{r}_y. \tag{A.30}$$

A.2 Overall efficiency impacts

We now analyze the non-environmental efficiency impacts of the policies. The welfare impact is defined as the sum of the changes in the after-tax producer surplus in the upstream industry (PSX), the change in the after-tax producer surplus in the downstream industry (PSY), and the change in non-environmental (after-tax) consumer surplus (NCS). It will be convenient to express the welfare impacts relative to $(P_y + S)Y$, the initial before-tax value of the output of the downstream industry Y. In what follows, we include the relevant terms for all policies simultaneously. To calculate the effect for an emissions tax alone, for example in equation (11a) of the main text, the fuel tax and subsidy to output would drop out of the expressions. The three components can be written as

$$psx \equiv \frac{dPSX}{(P_y + S)Y} = (1 - T)(\hat{r}_x + \pi_x) = (1 - T)(\hat{p}_x + \hat{s}_{kx} + \pi_x), \tag{A.31}$$

$$psy \equiv \frac{dPSY}{P_y Y} = (1 - T)(\hat{r}_y + \pi_y) = (1 - T)(\hat{p}_y - \hat{p}_x - \hat{t}_x - \hat{t}_e + \hat{s}_{ky} + s + \pi_y), \tag{A.32}$$

$$ncs \equiv \frac{dNCS}{P_y Y} = -(1 - T)[\frac{P_y}{P_y + S} p_y + (t/\beta)], \tag{A.33}$$

where we assume that all factor income is taxed at the factor tax rate T. We define $\pi_x \equiv \frac{d\Pi_x}{(P_y+S)Y}$, $\pi_y \equiv \frac{d\Pi_y}{(P_y+S)Y}$, and $t \equiv dT/(1-T)$, where Π_i $(i = x, y)$ denotes lump-sum compensation to sector i. $\beta \equiv P_y Y/Q$, where Q is aggregate factor income (before tax). This share goes to zero in our model, in which the downstream and upstream sectors are very small compared to the rest of the economy.[34]

[34] Also the relative change in the factor tax, t, goes to zero. However, the ratio t/β in (A.33) is well defined.

The overall welfare effect, expressed as a cost, is then $\psi \equiv -(psx + psy + ncs)$:

$$\psi = -(1-T)[-(t/\beta) - \Delta + \pi], \tag{A.34}$$

where $\Delta \equiv \hat{t}_x + \hat{t}_e - \hat{s}_{ky} - \hat{s}_{kx} - s$ and $\pi \equiv \pi_x + \pi_y$.

To find a reduced form for ψ, we derive t/β from the government budget constraint. The log-linearized version of the government budget constraint is given by

$$(1-T)\Delta + \Omega + T(q/\beta) + (1-T)(t/\beta) - (1-T)\pi = 0, \tag{A.35}$$

where $q \equiv [\hat{\alpha}_k k + (1-\hat{\alpha}_k)l]$ is the change in aggregate factor supply ($\hat{\alpha}_k$ is the share of capital income in aggregate value added and k and l represent aggregate capital and labor supply, respectively), and

$$\Omega \equiv \alpha_e^y e + \frac{T_x}{P_x}\alpha_x^y x - \frac{S}{P_y + S}y - \frac{S_{ky}}{R_y - S_{ky}}\alpha_v^y \alpha_k^y k_y - \frac{S_{kx}}{R_x - S_{kx}}\alpha_x^y \alpha_k^x k_x \tag{A.36}$$

The factor $(1-T)$ in (A.35) follows from the non-profit constraint, which implies that a higher pollution tax implies lower factor income. Ω can be computed from the solutions for the sector-specific variables in the polluting sector. Aggregate factor supply can be written as

$$q = \varepsilon_u(-\beta\Delta - t) + \varepsilon_i \beta, \tag{A.37}$$

where ε_u and $\varepsilon_i < 0$ stand for, respectively, the uncompensated elasticity of factor supply with respect to factor rewards and the elasticity of factor supply with respect to income. Substituting (A.37) into (A.35) to eliminate Δ, we establish

$$q/\beta = \left(\frac{\varepsilon_u \Omega/(1-T) - \varepsilon_c \pi}{1 - \varepsilon_u[T/(1-T)]}\right), \tag{A.38}$$

where $\varepsilon_c = \varepsilon_u - \varepsilon_i > 0$ represents the compensated elasticity of factor supply with respect to factor rewards. Substitution of (A.38) into (A.34) yields

$$\psi = -\lambda\Omega + \mu\pi(1-T), \tag{A.39}$$

where $\lambda \equiv \left(\frac{1}{1-\varepsilon_u(T/(1-T))}\right)$ stands for the marginal cost of public funds, which represents the cost in terms of household income of raising one additional dollar of government revenue spent on public goods that are separable in utility from private goods, and $\mu \equiv \left(\frac{\varepsilon_c}{1-\varepsilon_u(T/(1-T))}\right)$. The reduced expressions for Ω for each of the individual policies explored are given in equations (11a)-(11d) of the text.

The expressions (15) and (16) are found from (A.39) and using $\pi = -(\hat{r}_x + \hat{r}_y)$ (with the definitions $\hat{r}_x \equiv \alpha_k^x \alpha_x^y \frac{R_x}{R_x - S_{kx}} r_x$ and $\hat{r}_y \equiv \alpha_v^y \alpha_k^y \frac{R_y}{R_y - S_{ky}} r_y$) and (A.36) (with (A.7) and (A.16) to eliminate k_y and k_x and $S = T_x = 0$)

A.3 Decomposition of welfare effects

The welfare costs captured above are for the economy as a whole, but for the purposes of compensation it is important to express the incidence on each industry individually. In the notation, we are interested in $\hat{r}_x$ and $\hat{r}_y$, the (normalized) changes in the rental price of dirty industry capital. This determines the size of the transfer needed for compensation. The results in this section are expressed in terms of "forward" and "backward" shifting. These are defined, respectively, as the amount of the total burden on the downstream industry Y that can be shifted forward to consumers or backward to the upstream industry. The initial burden of the policy, less the total amount that can be shifted forward or backward, is the burden that remains on the Y industry. The incidence on the X industry is simply defined as the amount of the total burden that is shifted backward onto it. We examine each of the four environmental policies in turn.

A.3.1 Emissions tax

We first consider the impact of $\hat{t}_e > 0$, omitting all other policy instruments. This incidence on the X and Y industries, given in (A.42) and (A.44), is shown to be first order and proportional to the amount of abatement.

Burden on the X industry

The downstream Y industry shifts part of the cost burden $\hat{t}_e$ backward in lower input prices. This represents the burden on the X industry. The first equality below follows from (A.24) and the second follows from (A.23):

$$\hat{r}_x = \hat{p}_x = -\left(\frac{\varepsilon_x^x(\bar{\sigma}_g + \varepsilon_y^y) - \varepsilon_x^y \varepsilon_y^x}{\Sigma}\right)\hat{t}_e = \frac{\varepsilon_x^x \bar{\sigma}_g + \bar{\Sigma}}{\Sigma}\hat{t}_e, \tag{A.40}$$

The share of the overall burden $0 \leq \frac{\varepsilon_x^x \bar{\sigma}_g + \bar{\Sigma}}{\Sigma} \leq 1$ that can be shifted backward depends on the composite demand elasticity for the intermediate input ε_x^x compared to the supply elasticity $\hat{\sigma}^x$. Backward shifting is important if supply of the intermediate good is inelastic compared to demand.

This expression for $\hat{r}_x$ can be simplified further by solving for the emissions tax, $\hat{t}_e$, required to achieve a certain abatement target $a = -e$ by substituting (A.40) into (A.26) and substituting the result into (A.27):

$$\hat{t}_e = \kappa_e a, \tag{A.41}$$

where

$$\kappa_e \equiv \left[\hat{\sigma}^x \left(\frac{\varepsilon_x^x \bar{\sigma}_g + \bar{\Sigma}}{\Sigma}\right) + \bar{\sigma}_e\right]^{-1}.$$

Finally, substitution of (A.41) into (A.40) yields:

$$\hat{r}_x = -\frac{\varepsilon_x^x \bar{\sigma}_g + \bar{\Sigma}}{\hat{\sigma}^x \left(\varepsilon_x^x \bar{\sigma}_g + \bar{\Sigma}\right) + \bar{\sigma}_e \Sigma} a, \tag{A.42}$$

With lump-sum compensation, we need to set $\pi_x = -\hat{r}_x$ (see (A.31)) to compensate the capital owners in the upstream industry for their decline in rents.

Burden on the Y industry

The downstream industry can also shift part of the cost burden $\hat{t}_e$ forward in higher output prices (from (A.23))

$$\hat{p}_y = \left(\frac{\hat{\sigma}^x \varepsilon_x^y}{\Sigma}\right)\hat{t}_e. \tag{A.43}$$

The overall effect on the owners of the downstream industry is as follows (the first equality follows from (A.25), while the second equality follows from substituting (A.40) and (A.43)):

$$\begin{aligned}\hat{r}_y &= \hat{p}_y - \hat{p}_x - \hat{t}_e = -\left(\frac{\hat{\sigma}^x(\bar{\sigma}_g + \varepsilon_y^y - \varepsilon_x^y)}{\Sigma}\right)\hat{t}_e = \\ &-\frac{\hat{\sigma}^x(\bar{\sigma}_g + \varepsilon_y^y - \varepsilon_x^y)}{\hat{\sigma}^x\left(\varepsilon_x^x\bar{\sigma}_g + \bar{\Sigma}\right) + \bar{\sigma}_e\Sigma}a.\end{aligned} \tag{A.44}$$

With lump-sum compensation, we need to set $\pi_y = -\hat{r}_y$ (see (A.32)) to compensate the capital owners in the upstream industry for their decline in rents.

A.3.2 Fuel tax

A tax on the demand for the intermediate input implies similar redistributional effects as a tax on emissions. The only difference is that such a fuel tax does not employ the end-of-pipe channel to reduce emissions. Hence, the cost increase that is required to achieve a given abatement target is larger. In particular, we have

$$\hat{t}_x \equiv \alpha_x^y t_x = \kappa_x a, \tag{A.45}$$

with

$$\kappa_x \equiv \left[\bar{\varepsilon}_x^x\left(\frac{\hat{\sigma}^x}{\hat{\sigma}^x + \bar{\varepsilon}_x^x}\right)\right]^{-1} = \frac{(\bar{\sigma}_g + \varepsilon_y^y)(\hat{\sigma}^x + \bar{\varepsilon}_x^x)}{\hat{\sigma}^x[(\bar{\sigma}_g + \varepsilon_y^y)\varepsilon_x^x - \varepsilon_y^x\varepsilon_x^y]}.$$

We find the following distributional effects:

$$\hat{r}_x = \hat{p}_x = -\left(\frac{\bar{\varepsilon}_x^x}{\hat{\sigma}^x + \bar{\varepsilon}_x^x}\right)\hat{t}_x = -\frac{a}{\hat{\sigma}^x}. \tag{A.46}$$

$$\hat{p}_y = \left(\frac{\hat{\sigma}^x}{\hat{\sigma}^x + \bar{\varepsilon}_x^x}\right)\left(\frac{\varepsilon_x^y}{\bar{\sigma}_g + \varepsilon_y^y}\right)\hat{t}_x = \left(\frac{\varepsilon_x^y}{\bar{\sigma}_g + \varepsilon_y^y}\right)\frac{a}{\bar{\varepsilon}_x^x}.$$

$$\begin{aligned}\hat{r}_y &= \hat{p}_y - \hat{p}_x - \hat{t}_x = -\left(\frac{\hat{\sigma}^x}{\hat{\sigma}^x + \bar{\varepsilon}^x_x}\right)\left(\frac{\bar{\sigma}_g + \varepsilon^y_y - \varepsilon^y_x}{\bar{\sigma}_g + \varepsilon^y_y}\right)\hat{t}_x = \\ & -\left(\frac{\bar{\sigma}_g + \alpha^y_k(1-\alpha^y_v)\hat{\sigma}_y - \alpha^y_k\hat{\sigma}_v}{\bar{\sigma}_g + \hat{\sigma}^y_k + (1-\alpha^y_k)\hat{\sigma}_v + (1-\alpha^y_v)\alpha^y_k\hat{\sigma}_y}\right)\frac{a}{\bar{\varepsilon}^x_x}.\end{aligned}$$

As with the emissions tax, the expressions derived for $\hat{r}_x$ and $\hat{r}_y$ are not functions of α^y_e or T_x, but rather are proportional to the amount of abatement, a. Hence, even at low levels of abatement, the dirty industries require compensation.

A.3.3 Technology mandate

The incidence of policy on the dirty industries under a technology mandate is in sharp contrast to the two tax policies considered above. The key analytical result is that incidence no longer depends in a first-order way on abatement, but rather goes to zero as initial abatement gets small. The costs of lump-sum compensation then also vanish, which can make this policy more attractive than the taxes from an overall efficiency point of view.

A technology mandate implies a higher implicit emissions tax (i.e. $t_e > 0$) and a higher implicit subsidy on the intermediate input (i.e. $t_x < 0$) such that the additional implicit tax revenue from this combination of instruments is exactly zero:

$$\hat{t}_e + \hat{t}_x + \alpha^y_e e + \bar{T}_x \alpha^y_x x = 0, \tag{A.47}$$

where $\bar{T}_x \equiv T_x/P_x$.

Substitution of (A.40) and (A.46) into (A.26) yields

$$x = -\tilde{\sigma}^x(\hat{t}_e + \hat{t}_x),$$

where $\tilde{\sigma}^x \equiv \frac{\hat{\sigma}^x\bar{\varepsilon}^x_x}{\hat{\sigma}^x + \bar{\varepsilon}^x_x}$. Substituting this expression into (A.47) to eliminate x, we find the required overall cost increase $\hat{t}_e + \hat{t}_x$ in terms of the abatement target $a = -e$:

$$\hat{t}_e + \hat{t}_x = \frac{\alpha^y_e a}{1 - \bar{T}^y_x \alpha^y_x \tilde{\sigma}^x}, \tag{A.48}$$

and the impact on the demand for the intermediate input

$$x = -\tilde{\sigma}^x(\hat{t}_e + \hat{t}_x) = \frac{-\tilde{\sigma}^x\alpha^y_e a}{1 - \bar{T}_x \alpha^y_x \tilde{\sigma}^x}.$$

Substitution of the latter expression in $a = -x + \bar{\sigma}_e\hat{t}_e$ to eliminate x yields the required increase in the price of emissions:

$$\hat{t}_e = \left(1 - \frac{\tilde{\sigma}^x\alpha^y_e}{1 - \bar{T}_x\alpha^y_x\tilde{\sigma}^x}\right)\frac{a}{\bar{\sigma}_e}. \tag{A.49}$$

The distributional effects are then given by (where we use (A.23))

$$\hat{r}_x = \hat{p}_x = -\left(\frac{\bar{\varepsilon}_x^x}{\hat{\sigma}^x + \bar{\varepsilon}_x^x}\right)(\hat{t}_e + \hat{t}_x) = -\left(\frac{\bar{\varepsilon}_x^x}{\hat{\sigma}^x + \bar{\varepsilon}_x^x}\right)\left(\frac{\alpha_e^y a}{1 - \bar{T}_x \alpha_x^y \tilde{\sigma}^x}\right). \tag{A.50}$$

$$\hat{p}_y = \left(\frac{\hat{\sigma}^x}{\hat{\sigma}^x + \bar{\varepsilon}_x^x}\right)\left(\frac{\varepsilon_x^y}{\bar{\sigma}_g + \varepsilon_y^y}\right)(\hat{t}_e + \hat{t}_x) = \left(\frac{\hat{\sigma}^x}{\hat{\sigma}^x + \bar{\varepsilon}_x^x}\right)\left(\frac{\varepsilon_x^y}{\bar{\sigma}_g + \varepsilon_y^y}\right)\left(\frac{\alpha_e^y a}{1 - \bar{T}_x \alpha_x^y \tilde{\sigma}^x}\right).$$

$$\begin{aligned}\hat{r}_y &= \hat{p}_y - \hat{p}_x - \hat{t}_e - \hat{t}_x = -\left(\frac{\hat{\sigma}^x}{\hat{\sigma}^x + \bar{\varepsilon}_x^x}\right)\left(\frac{\bar{\sigma}_g + \varepsilon_y^y - \varepsilon_x^y}{\bar{\sigma}_g + \varepsilon_y^y}\right)(\hat{t}_e + \hat{t}_x) \\ &= -\left(\frac{\hat{\sigma}^x}{\hat{\sigma}^x + \bar{\varepsilon}_x^x}\right)\left(\frac{\bar{\sigma}_g + \alpha_k^y(1-\alpha_v^y)\hat{\sigma}_y - \alpha_k^y \hat{\sigma}_v}{\bar{\sigma}_g + \hat{\sigma}_k^y + (1-\alpha_k^y)\hat{\sigma}_v + (1-\alpha_v^y)\alpha_k^y \hat{\sigma}_y}\right)\left(\frac{\alpha_e^y a}{1 - \bar{T}_x \alpha_x^y \tilde{\sigma}^x}\right).\end{aligned}$$

Without any initial environmental policy (i.e. $\alpha_e^y = 0$),environmental policy does not yield any first-order costs. Moreover, redistributional effects are completely absent. This environmental policy yields neither efficiency costs nor redistributional effects. This gives rise to (12).

A.3.4 Performance standard

At initial abatement, and like the technology mandate, the performance target does not impose any net burden when summing the effect across polluting sectors and consumers of the polluting final commodity. Specifically, we have (using (A.24) and (A.25))

$$\hat{p}_y - \hat{r}_x - \hat{r}_y = \hat{t}_e - s = 0. \tag{A.51}$$

In contrast to the technology mandate, however, the performance standard does redistribute across the three parties involved in pollution: the owners of the downstream sector, the owners of the upstream sector and the consumers of the polluting industry. In particular, consumers of the polluting final good gain at the expense of the owners of the upstream industry. The need for compensation can be written as

$$\pi = -\hat{r}_x - \hat{r}_y = -\hat{p}_y > 0 \tag{A.52}$$

Unlike the technology mandate, then, the performance standard requires compensation even at initial abatement, and so can involve a first-order cost of raising revenue for lump-sum compensation.

The performance standard is an intermediate case to the emissions tax and technology mandate, both in terms of overall efficiency costs and required compensation. It uses more abatement channels than the technology mandate, but fewer than the emissions tax, making the first-order abatement costs intermediate. In terms of the need for compensation, the performance standard involves some rent shifting at incremental abatement, which gives rise to some compensation need. We show now that the amount of compensation needed is less than under the emissions tax.

The performance standard implies a higher implicit emission tax (i.e. $t_e > 0$) and a higher implicit subsidy on the final output (i.e. $s > 0$) such that the additional implicit tax revenue from this combination of instruments is exactly zero:

$$\hat{t}_e - s + \alpha_e^y e - \bar{S}y = 0, \tag{A.53}$$

where $\bar{S} \equiv \frac{S}{P_y+S}$.We consider the case in which initial environmental policy is absent (i.e. $\alpha_e^y = S = 0$) so that there are no first-order efficiency effects. In this case, we have $\hat{t}_e = s$.

Incidence on X (shifted backward from Y)

The result for backward shifting is given by (use (A.23) with $\hat{t}_e = s$)

$$\hat{r}_x = \hat{p}_x = -\left(\frac{\bar{\sigma}_g(\varepsilon_x^x - \varepsilon_y^x) + \varepsilon_x^x\varepsilon_y^y - \varepsilon_x^y\varepsilon_y^x}{(\bar{\sigma}_g + \varepsilon_y^y)(\hat{\sigma}^x + \varepsilon_x^x) - \varepsilon_x^y\varepsilon_y^x}\right)\hat{t}_e = -\Phi_p\hat{t}_e. \tag{A.54}$$

This shifting share $\Phi_p = \frac{\bar{\sigma}_g(\varepsilon_x^x - \varepsilon_y^x) + \bar{\Sigma}}{\Sigma}$ lies between zero and unity. In contrast to the technology mandate, the performance standard hurts the upstream industry even if we introduce the policy from an initial situation without any environmental policy. Intuitively, the performance standard employs input substitution to cut pollution. This reduces the demand for intermediate input and thereby harms the upstream industry. Indeed, the abatement effect is given by (the third equality follows from (A.54))

$$a = -x + \bar{\sigma}_e\hat{t}_e = -\hat{\sigma}^x\hat{p}_x + \bar{\sigma}_e\hat{t}_e = [\hat{\sigma}^x\Phi_p + \bar{\sigma}_e]\hat{t}_e, \tag{A.55}$$

so that we have

$$\hat{t}_e = \kappa_p a, \tag{A.56}$$

where

$$\kappa_p \equiv [\hat{\sigma}^x\Phi_p + \bar{\sigma}_e]^{-1} = \frac{\Sigma}{\hat{\sigma}^x\left(\bar{\sigma}_g(\varepsilon_x^x - \varepsilon_y^x) + \bar{\Sigma}\right) + \bar{\sigma}_e\Sigma}. \tag{A.57}$$

The increase in the shadow price for emissions is thus larger than with an emission tax, but lower than with a technology mandate. The reason is that a performance standard employs more channels to cut emissions than a technology mandate (namely input substitution) but fewer channels than an emission tax (namely output cuts).

Note that the burden on the upstream industry is larger than under the technology mandate, but smaller than under the emission tax (note that we assume $\alpha_e^y = 0$ for now). The impact on the upstream industry can be written as

$$\hat{r}_x = \hat{p}_x = -\left(\frac{\Phi_i}{\hat{\sigma}^x\Phi_i + \bar{\sigma}_e}\right)a,\ \ i = p, e, \tag{A.58}$$

where the shifting share in case of the emission tax, $\Phi_e \equiv -(\hat{r}_x/\hat{t}_e)$ is given by

$$\Phi_e \equiv \left(\frac{\varepsilon_x^x\bar{\sigma}_g + \bar{\Sigma}}{\Sigma}\right) \geq \Phi_p = \left(\frac{\bar{\sigma}_g(\varepsilon_x^x - \varepsilon_y^x) + \bar{\Sigma}}{\Sigma}\right). \tag{A.59}$$

The inequality implies that the decline in r_x is larger under an emissions tax than under a performance target. Intuitively, the performance standard does not cut emissions through output substitution and thus relies more on the end-of-pipe channel, which does not reduce demand for the intermediate input.

Fraction of burden on Y shifted forward

Forward shifting amounts to (use (A.23) with $\hat{t}_e = s$)

$$\hat{p}_y = -\left(\frac{\hat{\sigma}^x(\varepsilon^y_y - \varepsilon^y_x) + \bar{\Sigma}}{(\bar{\sigma}_g + \varepsilon^y_y)(\hat{\sigma}^x + \varepsilon^x_x) - \varepsilon^y_x\varepsilon^x_y}\right)\hat{t}_e.$$

Consumers will benefit from the performance target (the change in price $\hat{p}_y$ is generally negative since $\varepsilon^y_y \geq \varepsilon^y_x$ and $\bar{\Sigma} \geq 0$). The effect on quantity of output is given by

$$y = -\frac{\hat{p}_y}{\bar{\sigma}_g}, \tag{A.60}$$

meaning that, since the change in price is negative, the output channel for abatement is not used.

Overall burden on Y

The effect on the rental price of capital in the downstream industry is the sum of backward and forward shifting. There is no net burden in this case since $\hat{t}_e - s = 0$:

$$\begin{aligned}\hat{r}_y \;&=\; \hat{p}_y - \hat{p}_x = \left(\frac{\bar{\sigma}_g(\varepsilon^x_x - \varepsilon^x_y) - \hat{\sigma}^x(\varepsilon^y_y - \varepsilon^y_x)}{(\bar{\sigma}_g + \varepsilon^y_y)(\hat{\sigma}^x + \varepsilon^x_x) - \varepsilon^y_x\varepsilon^x_y}\right)\hat{t}_e = \left(\frac{\bar{\sigma}_g(\varepsilon^x_x - \varepsilon^x_y) - \hat{\sigma}^x(\varepsilon^y_y - \varepsilon^y_x)}{\Sigma}\right)\hat{t}_e \\ &\left(\frac{\bar{\sigma}_g\hat{\sigma}_v\frac{\alpha^y_k}{1-\alpha^y_k} + \alpha^y_k\hat{\sigma}^x[\hat{\sigma}_v - (1-\alpha^y_v)\hat{\sigma}_y]}{(\bar{\sigma}_g + \varepsilon^y_y)(\hat{\sigma}^x + \varepsilon^x_x) - \varepsilon^y_x\varepsilon^x_y}\right)\hat{t}_e.\end{aligned} \tag{A.61}$$

A performance target thus benefits the downstream industry if $\hat{\sigma}_v$ and $\bar{\sigma}_g$ are large compared to $\hat{\sigma}_y$ and $\hat{\sigma}^x$. Intuitively, the implicit subsidy is shifted to the downstream industry (i.e. supply), while the implicit tax on intermediate input is shifted to the upstream industry. Moreover, the downstream industry finds it easy to shift away from the dearer input (to capital) while finding it difficult to shift to the cheaper input labor (as a consequence of the output subsidy).

We can write (substitute (A.56) and (A.57) into the third equality in (A.61) to eliminate $\hat{t}_e$ and κ_p)

$$\hat{r}_y = -\left(\frac{\hat{\sigma}^x(\varepsilon^y_y - \varepsilon^y_x) - \bar{\sigma}_g(\varepsilon^x_x - \varepsilon^x_y)}{\hat{\sigma}^x\left(\bar{\sigma}_g(\varepsilon^x_x - \varepsilon^x_y) + \bar{\Sigma}\right) + \bar{\sigma}_e\Sigma}\right)a. \tag{A.62}$$

When comparing this effect with the corresponding effect of the emission tax (i.e. (A.44), we find through algabraic manipulationms (and using $\varepsilon^x_x \geq \varepsilon^x_y$) that the loss in rentals in the downstream industry is larger under the emission tax than under the performance standard. Accordingly, both the upstream and the downstream industries are better off under the performance standard than under the emission tax. This implies that $\Sigma_p \geq \Sigma_e > 0$ in (13) and (14).

Table 1
Policies and Their Implementation in the Numerical Model

<table>
<tr><th>Policy</th><th></th><th colspan="3">Instrument for Achieving ...</th></tr>
<tr><td></td><td></td><td>Emissions Target</td><td>EVN Constraint</td><td>Government Budget Balance</td></tr>
<tr><td>Emissions Tax</td><td></td><td>tax on E</td><td rowspan="4">sector-specific lump-sum tax credit
or
sector-specific reductions in capital tax rates
(all policies)</td><td rowspan="4">economy-wide equi-proportionate cuts in capital and labor tax rates
(all policies)</td></tr>
<tr><td>Input (Fuel) Tax</td><td></td><td>tax on X</td></tr>
<tr><td>Technology Mandate (constraint on E/X)</td><td></td><td>revenue-neutral* combination of tax on E and subsidy to X.</td></tr>
<tr><td>Performance Standard (constraint on E/Y)</td><td></td><td>revenue-neutral* combination of tax on E and subsidy to Y</td></tr>
</table>

* Revenue-neutral at the industry level. This neutrality is gross of changes in revenues stemming from impacts on the bases of other taxes.

Table 2

Benchmark Input-Output flows for the Numerical Model[1]

	Use of Input by Industry ...				
	X	Y	C	Total Receipts to Each Input	Endowments[3]
Input[2]:					
X	0.0	27.1	0.0	27.1	
L	2.6	11.8	1765.3	1779.7	5249.8
K	13.7	44.0	712.4	770.1	2271.5
factor taxes	10.8	48.0	1651.8	1710.6	
Total Input Payments by Each Industry	27.1	130.9	4129.5		
SO_2 Emissions[4]		15.2			

[1] In billions of year-2000 dollars per year except where otherwise noted

[2] Inputs of labor and capital are net of factor taxes.

[3] Endowments correspond to $\bar{L}$ and $\bar{K}$ in equation (9) of text.

[4] Millions of tons per year

Sources: Except for the emissions data, these flows are based on the Department of Commerce Bureau of Economic Analysis=s *Benchmark Input & Output Tables for 1992.* The emissions data are from Table 12.6 of the Energy Information Agency=s *Annual Energy Review* 1999.

Table 3

Central Case Parameter Values

parameters for Y industry		
β_e	ease of end-of pipe treatment -- scale parameter	2.0
ρ_e	ease of end-of-pipe treatment -- curvature parameter	0.6
σ_y	elasticity of substitution between *v* and *L* in production of *Y*	0.75
σ_v	elasticity of substitution between *X* and *K* in production of *v*	0.15
parameters for X and C industries		
σ_x	elasticity of substitution between *K* and *L* in production of *X*	1.0
σ_c	elasticity of substitution between *K* and *L* in production of *C*	1.0
other production-related parameters		
σ_k	ease of capital movement	-1.0
utility function parameters		
σ_u	elasticity of substitution between *G* (*C*-*Y* composite) and *Z* (*L*-*K*) composite	0.66
σ_g	elasticity of substitution between *C* and *Y*	0.9
σ_z	elasticity of substitution between *L* and *K*	0.9

Table 4: Impacts of Alternative Policies
(No Industry Compensation Requirement)

Policy Experiment	Tax on Emissions			Tax on Fuel			Technology Mandate			Performance Standard		
Percent abatement	10	25	75	10	25	75	10	25	75	10	25	75
Tax on E or X[1]	0.10	0.26	3.87	0.54	1.93	42.52	0.11	0.29	4.99	0.10	0.27	4.44
Fraction abatement from EOP	0.88	0.89	0.76	0.00	0.00	0.00	0.99	0.98	0.89	0.93	0.93	0.83
Aggregate Cost *(as % of income)*	0.001	0.008	0.160	0.011	0.077	1.387	0.001	0.008	0.176	0.001	0.008	0.169
Price and Quantity Impacts												
% change in supply price of X	-0.89	-2.13	-13.58	-7.52	-19.15	-61.92	-0.06	-0.32	-6.39	-0.50	-1.26	-9.70
% change in demand price of X	-0.89	-2.13	-13.58	42.15	136.29	1417.83	-5.47	-12.46	-82.90	-0.50	-1.26	-9.70
% change in quantity of X	-1.19	-2.85	-17.89	-10.00	-25.00	-75.00	-0.08	-0.44	-8.52	-0.68	-1.71	-12.92
% change in supply price of Y	0.67	1.63	12.99	6.40	20.45	210.79	0.04	0.24	5.32	1.14	2.69	19.35
% change in demand price of Y	1.66	3.95	24.90	14.27	36.45	100.48	0.10	0.55	10.79	-0.06	0.16	7.25
% change in quantity of Y	-0.58	-1.42	-10.40	-5.32	-15.21	-64.37	-0.04	-0.22	-4.70	0.01	-0.11	-4.21
Incidence[2]												
Change in profit to X	-0.14	-0.34	-2.20	-1.20	-3.04	-9.70	-0.01	-0.05	-1.07	-0.08	-0.21	-1.59
As a % of EV	172%	71%	22%	183%	64%	11%	10%	10%	10%	93%	41%	15%
Change in profit to Y	-0.22	-0.54	-3.99	-2.00	-5.79	-25.81	-0.02	-0.09	-1.85	0.02	-0.02	-1.50
As a % of EV	265%	111%	40%	305%	121%	30%	17%	17%	17%	-20%	3%	14%
Change in profit to X and Y	-0.36	-0.88	-6.19	-3.20	-8.83	-35.50	-0.02	-0.14	-2.92	-0.06	-0.22	-3.09
As a % of EV	438%	182%	62%	487%	185%	41%	27%	27%	27%	73%	44%	30%
Change in profit to C	0.05	0.03	-1.68	0.42	0.22	-19.39	-0.02	-0.12	-2.55	-0.03	-0.13	-2.57
Change in wage income	0.23	0.36	-2.38	2.03	3.14	-41.06	-0.05	-0.26	-5.53	0.00	-0.15	-4.92

[1]Tax on emissions is in thousands of dollars per ton; Tax on fuel is in percent.
[2]Units in this panel are billions of dollars unless indicated otherwise.

Table 5: Effects of Policies with and without EVN Constraint
(Emissions reduced by 25 percent in all cases)

	Tax on Emissions	Tax on Fuel	Technology Mandate	Performance Standard
Aggregate Cost Without EVN[1]	0.0078	0.0767	0.0084	0.0081
Compensation Needed for EVN				
for X as % of profit	2.50	22.26	0.40	1.51
for Y as % of profit	1.22	13.17	0.20	0.04
total as % of profit	1.52	15.33	0.25	0.38
EVN Via Lump-Sum Tax Credits				
aggregate cost with EVN[1]	0.0112	0.1081	0.0090	0.0090
increase in cost[1]	0.0034	0.0313	0.0006	0.0009
EVN Via Cuts in Factor Tax Rates				
aggregate cost with EVN[1]	0.0083	0.1633	0.0086	0.0084
increase in cost[1]	0.0005	0.0866	0.0002	0.0003
tax rates used to achieve EVN				
capital tax rate for X[2]	34.86	-281.62	39.29	35.94
capital tax rate for Y[2]	38.78	-26.58	39.82	40.65

[1]Expressed as a percent of benchmark income.
[2]Net of the subsidy used for EVN. All capital taxes are set to 40% in the benchmark.

Table 6: Policy Costs under Alternative Parameter Values

	Equivalent Variation (EV) at 25% Abatement	Ratio of EV at 25% Abatement to EV in Left-Most Column							
	Emissions Tax	Emissions Tax		Fuel Tax		Technology Mandate		Performance Standard	
	No EVN	No EVN	With EVN	No EVN	With EVN	No EVN	With EVN	No EVN	With EVN
Central case	0.0078	1.000	1.439	9.885	13.924	1.084	1.156	1.043	1.154
β_e (end-of-pipe treatment ease)									
Very low (0.0)	0.0767	1.000	1.409	1.000	1.409	n/a	n/a	2.260	2.424
Low (1.0)	0.0202	1.000	1.425	3.791	5.341	1.243	1.325	1.118	1.231
High (4.0)	0.0026	1.000	1.447	29.139	41.047	1.028	1.096	1.014	1.125
σ_k (capital adjustment costs)									
Very low (-100.0)	0.0074	1.000	1.037	7.298	7.551	1.119	1.130	1.066	1.082
Low (-4.0)	0.0075	1.000	1.188	8.060	9.485	1.106	1.141	1.058	1.111
High (-0.25)	0.0080	1.000	1.705	13.462	22.120	1.059	1.168	1.026	1.187
σ_g (elasticity of demand for *Y*)									
Low (0.45)	0.0079	1.000	1.303	12.959	16.388	1.070	1.121	1.027	1.126
High (1.8)	0.0076	1.000	1.598	7.864	12.384	1.101	1.198	1.062	1.186
σ_u (factor supply elasticity)									
Low (0.33)	0.0069	1.000	1.219	9.889	11.907	1.085	1.120	1.043	1.098
High (1.32)	0.0102	1.000	1.889	9.864	17.996	1.084	1.232	1.042	1.270
σ_v (substitutability between capital and fuel inputs)									
Low (0.075)	0.0079	1.000	1.448	12.023	16.897	1.067	1.139	1.044	1.164
High (0.30)	0.0075	1.000	1.423	7.357	10.291	1.114	1.186	1.041	1.136
Industries compensated									
Y industry only	0.0078	1.000	1.267	9.885	12.561	1.084	1.128	1.043	1.051

* In the EVN cases, compensation is provided through lump-sum tax credits.

Table 7: Efficiency "Crossover Points" under Alternative Parameter Values

	Crossover Point[1]	
	Technology Mandate	Performance Standard
Central case	67	79
β_e (end-of-pipe treatment ease)		
Very low (0.0)	n/a	7
Low (1.0)	35	54
High (4.0)	86	91
σ_k (capital adjustment costs)		
Very low (-100.0)	3	6
Low (-4.0)	35	49
High (-0.25)	76	90
σ_g (elasticity of demand for Y)		
Low (0.45)	61	79
High (1.8)	70	79
σ_u (factor supply elasticity)		
Low (0.33)	47	63
High (1.32)	80	90
σ_v (substitutability between capital and fuel inputs)		
Low (0.075)	72	77
High (0.30)	57	83
Industries compensated		
Y industry only	54	75

[1]The value indicated is the percent abatement at which the emissions tax becomes more efficient than the policy shown when firms are compensated via a lump-sum tax credit.

Figure 1: Policy Costs relative to Emissions Tax Cost
--No Compensation--

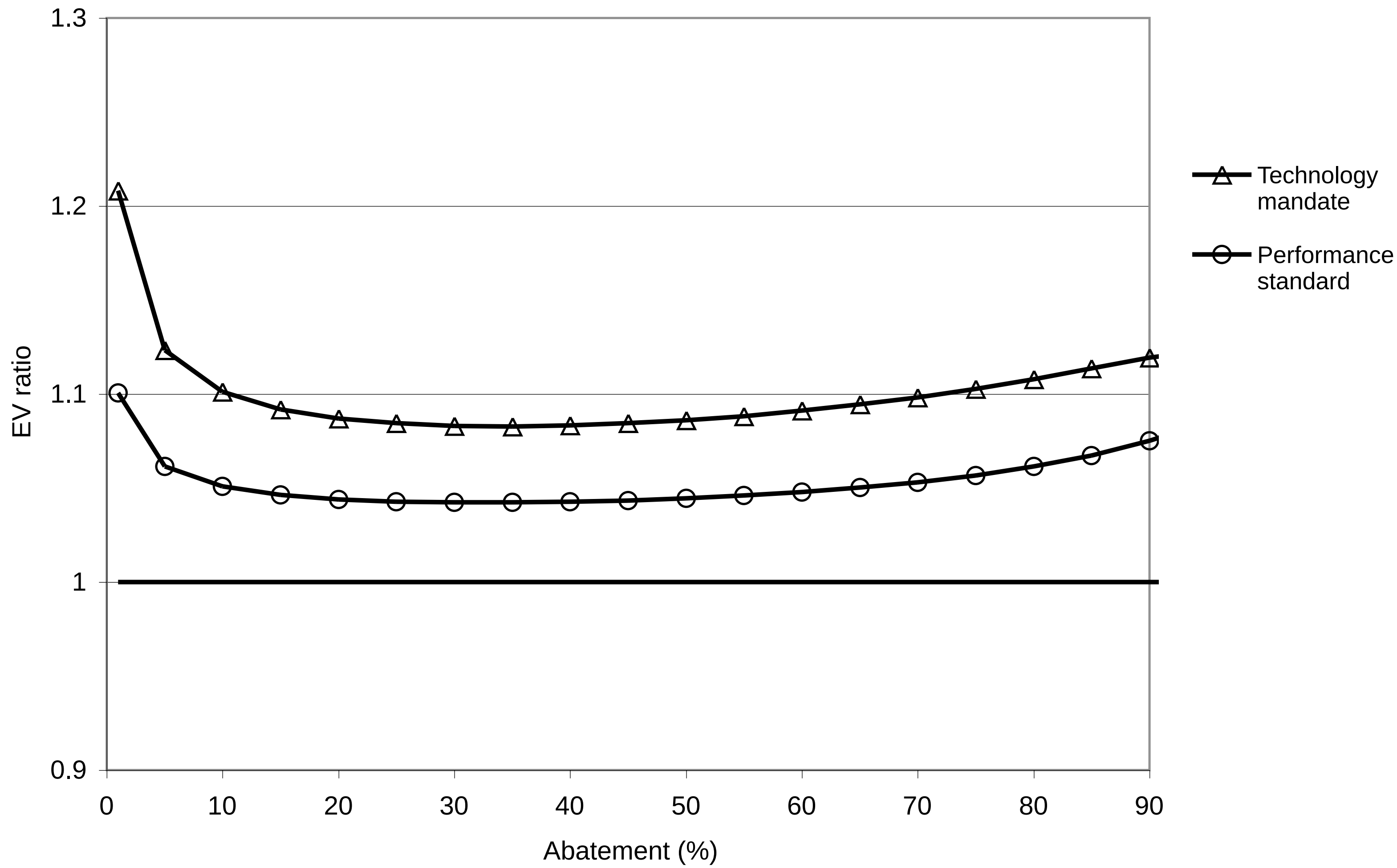

Figure 2: Policy Costs relative to Emissions Tax without Compensation
--Compensation via Lump-Sum Tax Credits--

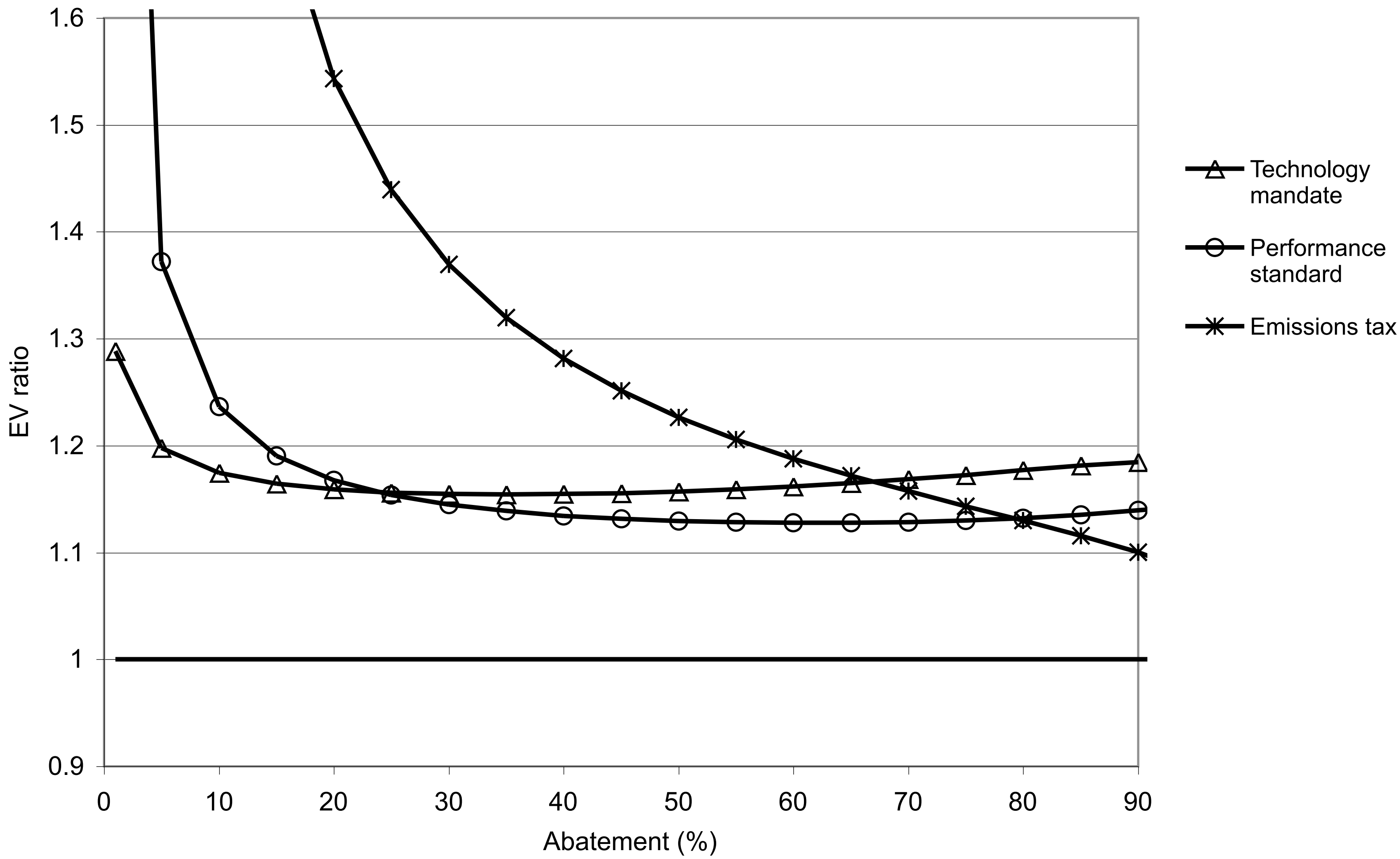

Figure 3: Policy Costs relative to Emissions Tax without Compensation
--Compensation via Marginal Capital Tax Rate Cuts--