RAND Journal of Economics
Vol. 36, No. 4, Winter 2005
pp. 951–971

Efficiency costs of meeting industry-distributional constraints under environmental permits and taxes

A. Lans Bovenberg*

Lawrence H. Goulder**

and

Derek J. Gurney***

Many pollution-related industries have political influence sufficient to block policies that would harm their profits. A politically realistic approach to environmental policy seems to require avoiding significant profit-losses to these industries. Using analytically and numerically solved equilibrium models, we examine how the efficiency costs of emissions permits and tax policies change when the policies are designed to insulate profits. The relative increase in efficiency cost associated with protecting profits is highly sensitive to the extent of pollution abatement. Expanded opportunities for end-of-pipe treatment of pollution reduce the absolute efficiency costs of abatement policies, but have little impact on the relative increase in efficiency costs attributable to the constraint on profits.

1. Introduction

■ In evaluating environmental policies, economists tend to emphasize efficiency and cost-effectiveness. Yet the distributional impacts of policies clearly are highly relevant to social welfare, and such impacts often critically influence political feasibility. Distributional effects can be measured along a number of dimensions—across household income groups, geographic regions, generations, and industries. An especially important dimension is the potential distribution of impacts across domestic industries, because industry groups constitute a powerful political force.[1]

---

* Tilburg University and CentER; a.l.bovenberg@uvt.nl.

** Stanford University, NBER, and Resources for the Future; goulder@stanford.edu.

*** Stanford University; dgurney@stanford.edu.

We are grateful to Dallas Burtraw, Ian Parry, Billy Pizer, Kerry Smith, two anonymous referees, and seminar participants at the NBER Summer Institute Workshop on Public Policy and the Environment for helpful comments. We also thank Mark Jacobsen for excellent research assistance and the William and Flora Hewlett Foundation and National Science Foundation (grant no. SES-0112102) for financial support.

[1] One important explanation for the significant political influence of industry groups is provided by Olsen (1965), who argued that the degree of political mobilization of interest groups depends on the concentration of the policy impact. Concentrated potential impacts alleviate free-rider problems in lobbying efforts. Thus, industries that face concentrated

The degree to which environmental policies impose burdens on given industries is closely related to the capacity of these policies to generate public revenues or private rents. Some policies generate considerable public revenue—they include emissions taxes, fuel taxes, and systems of tradable permits in which the government initially allocates the permits through an auction. These revenue-generating policies tend to impose a large share of the economy-wide burden of regulation on the polluting firms. Under these policies, firms not only incur abatement costs but also must pay for inframarginal pollution: they must either pay pollution taxes on such emissions or purchase pollution permits giving them the right to generate such emissions. In effect, these policies transfer property rights over emissions or air quality from firms to the public sector. This transfer of property rights can have substantial distributional impacts and can thus generate considerable political opposition from the adversely affected parties.

To the extent that industrial stakeholders wield substantial political power, designing policies that achieve environmental goals while avoiding serious adverse effects on key industries can enhance political feasibility.[2] One way to reduce the burden on the polluting industries is to allow firms to retain a portion of the potential revenues. For example, the government could introduce a system of tradable permits in which permits are not auctioned but instead are given out free (or "grandfathered") on the basis of historical presence in the affected industry. In this case, regulated firms retain as rents what otherwise would have become government revenue from the sale of permits. Firms pay only for whatever pollution they would produce beyond what is implied by their initial permit allotment. Likewise, the government could introduce an emissions tax policy with an exemption for some inframarginal emissions. Here firms retain as rent what would otherwise have been a tax payment for inframarginal emissions.

These policies suffer little or no disadvantage on environmental grounds. Firms continue to face higher costs for pollution at the margin—each additional unit of pollution requires either the purchase of an additional permit or an increase in the pollution tax payment—and thus they are encouraged to cut pollution. But insulating firms through grandfathering of permits or exemptions to emissions taxes carries an efficiency cost because the government forgoes permit revenue or emission-tax revenue and thus must rely more on ordinary distortionary taxes (such as income or sales taxes) to raise revenues. This reduces efficiency because the forgone revenue is inframarginal and therefore would have yielded revenue at lower efficiency cost than ordinary taxes.[3] Alleviating the adverse distributional impact on particular polluting firms thus comes at a cost in terms of efficiency.[4]

This article examines the efficiency costs of avoiding adverse industry-distributional effects under environmental taxes and quotas. We investigate these issues using a general framework that can consider a wide range of pollution-control settings. Earlier work by Bovenberg and Goulder (2001), Smith, Ross, and Montgomery (2002), and Burtraw et al. (2002) investigated these issues in the context of CO_2 emissions policy.[5] The present investigation generalizes the earlier work in several ways. First, we extend the analysis to make it applicable not only to CO_2 but to other forms of pollution as well. In the earlier studies, demanders of pollution-related (namely, fossil) fuels could reduce the emissions-output ratio only through input substitution (for example, switching from coal to natural gas). This restriction is appropriate when the focus is

---

costs may tend to have more political involvement and influence than groups (e.g., consumers) that face dispersed benefits and more serious free-rider problems.

[2] Shifting the burden in this way offers potential attractions beyond political feasibility. To the extent that the government avoids producing unexpected adverse distributional impacts in its environmental initiatives, it helps to ensure stable property rights and thereby cultivates a reputation as an impartial guardian of investors' rights. This can enhance the investment climate and dynamic efficiency.

[3] This efficiency issue has been explored in previous articles comparing the costs of policies that differ in terms of whether they charge for inframarginal emissions. See, for example, Goulder et al. (1999), Parry and Oates (2000), and Fullerton and Metcalf (2001).

[4] There would be little or no added efficiency cost if the government could obtain the forgone revenue through lump-sum taxes or some other tax which, if increased, would reduce overall distortions of the tax system.

[5] For an excellent review of compensation issues in the context of U.S. CO_2 policy, see Dinan (2003).

on CO_2 emission reductions, since at present input substitution appears to be the only significant channel for reducing the CO_2 emissions-output ratio.[6] However, "end-of-pipe" treatment—the installation of equipment to filter or treat emissions as they move through the smokestack—is an important channel through which other pollutants can be reduced. We consider this additional channel as well, and thus we are able to apply our model to policies aimed at other pollutants besides CO_2.

A second contribution is that we employ both analytical and numerical models to generate our results: the previous studies applied only numerical models. Our analytical model enables us to obtain general results regarding the determinants of efficiency impacts and the distribution of policy costs. These results are then evaluated quantitatively with the numerical model.

A third extension is the integrated focus on downstream and upstream pollution-generating industries. While Bovenberg and Goulder (2001) concentrated on the problem of avoiding adverse impacts on "upstream" industries—the industries that supply fossil fuels—here we consider in addition the downstream industries, that is, the industries that utilize the fuels or other inputs associated with pollution. "Downstream policies" are a central feature of several recent legislative proposals.[7]

We find, in both models, that the efficiency cost from the compensation constraint rises with the extent of required pollution abatement. However, as the abatement requirement becomes more extensive, the cost of this constraint diminishes relative to the other efficiency costs of pollution control (i.e., the efficiency costs that apply even when profits are not protected). Under a wide range of parameter values in the numerical model, the relative cost increase exceeds 100% when the required amount of pollution abatement is modest, but falls below 10% when the abatement requirement is extensive. The degree of availability of end-of-pipe treatment can significantly reduce overall policy costs in absolute terms. At the same time, the availability of such treatment exerts little impact on the relative increase in efficiency cost imposed by the compensation constraint.

We focus on the free allocation of emissions permits as the instrument for avoiding profit losses. Both models show that the added efficiency cost is positively related to the share of permits that must be freely allocated (rather than auctioned) in order to preserve profits in the industries in question. Under a wide range of parameter values, profits can be maintained in both "upstream" (fossil-fuel-supplying) and "downstream" (fossil-fuel-using) industries by freely allocating less (and sometimes considerably less) than 50% of pollution permits.

The rest of the article is organized as follows. In Section 2 we present the analytical model and derive and interpret 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 compared to the economy as a whole. Section 3 describes and applies a numerical model, whose results extend and quantify those of the analytical model. Section 4 offers conclusions.

2. An analytical model

■ Here we describe an analytically tractable equilibrium model aimed at capturing the distributional and efficiency impacts of emissions taxes and permits on various industries and the consequences of shielding the production factors in these industries from income loss. Key features of the model include (i) attention to equilibrium relationships among upstream producers

---

[6] Scientists currently are investigating possibilities for "end-of-pipe" treatment of carbon dioxide emissions through carbon separation and geological sequestration. Eventually this may emerge as a significant channel for CO_2 emissions reduction. At present, however, this approach is very costly and has been applied only on a very limited basis. See Anderson and Newell (2003).

[7] The Bush Administration, Senator James Jeffords, and Senator Thomas Carper have each introduced bills to "cap and trade" emissions of various pollutants from U.S. electric power plants. The administration bill applies to sulfur dioxide, nitrogen oxides, and mercury; the other two bills target these emissions and carbon dioxide as well. In addition, the European Union is committed to introducing, on a Europe-wide basis, a system of tradable permits applied to several downstream industries, including electric power, steel, cement, and aluminum manufacturing.

of pollution-generating fuels and downstream users of such fuels; (ii) allowance for pollution reduction through both input substitution and end-of-pipe emissions treatment; and (iii) recognition of the imperfect mobility of capital and the associated implications for the impacts of policies on profits. A web Appendix, available at www.stanford.edu/~goulder, provides the full solution to the log-linearized model and derives expressions for important variables such as the marginal cost of public funds and the marginal excess burden.

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.

☐ **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

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

$$P_x \frac{\partial f_x(\cdot;\cdot)}{\partial K_x} = R_x, \tag{3}$$

where P_x denotes the price of the intermediate good, W the wage rate, and R_x the rental rate of capital in the upstream 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.[8] In particular, the substitution elasticity 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.

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. 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 $g(\cdot,\cdot)$ is a composite of the two final goods C_a and Y_a; it is an index of resources devoted to end-of-pipe treatment.[9]

---

[8] These separability assumptions are consistent with empirical work (see, e.g., Jorgenson and Wilcoxen (1993a, 1993b) suggesting that capital is a complement to energy (or fuel) inputs. The numerical model of Section 3 incorporates these assumptions as well, under which capital demand rather than labor demand is negatively affected if X is taxed.

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

Pure profits in the downstream industry are given by $P_yY - P_xX - T_eE - WL_y - P_cC_a - P_yY_a - R_yK_y$, where P_y represents the price of the final good produced by the downstream industry Y, P_c the price of the other, clean final good C, R_y the rental rate of capital in the downstream industry, and T_e the shadow cost of emissions. The shadow cost can be interpreted as the tax rate on emissions.

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.

□ **Household utility and the supply of primary factors.** 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:[10]

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

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.

Households obtain utility from consumption of the two final goods. Aggregate emissions E, labor supply L, and capital supply K produce disutility.[11] Households 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.[12]

Households earn labor and capital income. Both types of income are taxed at the same

---

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

[11] In a fully dynamic model, the cost of supplying capital is current consumption forgone when resources are devoted to investment instead of consumption. We include capital in the utility function to account for the cost of capital supply in our static model, which does not deal with investment explicitly. An alternative interpretation of K is as a production factor (like labor or entrepreneurship) that is imperfectly mobile across sectors. In this interpretation, L is the mobile factor and K is the imperfectly mobile factor.

[12] A more general formulation would relax the assumption of separability between environmental quality and other goods in utility. Empirical work exploits nonseparabilities to gauge the value of environmental quality based on demands for marketed goods (see, for example, Freeman (1993) and Smith (2000)). It is not clear in which direction the assumption of separability might bias the results. The efficiency cost estimates of environmental policy presented below are biased upward (downward) to the extent that environmental quality reduces (raises) the marginal disutility of factor supply compared to the marginal utility of final consumption of produced commodities.

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.[13] 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 transfers provided by the government.

☐ **Government budget.** The government faces the following budget constraint:

$$P_c \Lambda + \Pi = T_e E + T(\Pi + WL + RK), \tag{8}$$

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

☐ **Market equilibrium.** Equilibrium in the markets for the two final goods requires that

$$Y_h + Y_a = Y$$

and

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

With perfectly mobile labor, labor market equilibrium is given by

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

☐ **Policy experiments.** We explore several policies that achieve given targets for pollution abatement. Some policies include, in addition to the abatement target, the requirement of equity value neutrality (EVN). A policy achieves this neutrality for an industry if it provides compensation just sufficient to offset what otherwise would be the loss of income for the imperfectly mobile factor (i.e., capital) employed in that industry. The government provides this compensation through lump-sum transfers to capital owners of the affected industries. This is equivalent to the free allocation of pollution permits on the basis of the capital stock in the industry before the environmental policy is implemented. The government balances its budget by adjusting 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 in which initial abatement may be positive. 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 industries are small compared to the rest of the economy.[14] 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.

☐ **Efficiency costs.** *Two cost concepts.* We apply two key concepts for measuring the efficiency costs of distortionary taxation. The first, the marginal cost of public funds, is denoted by λ and is given by

$$\lambda = \left(\frac{1}{1 - \varepsilon_u[T/(1 - T)]}\right), \tag{9}$$

---

[13] 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.

[14] We relax this assumption in the numerical model below. When computing aggregate welfare effects, the analytical model accounts for the impact of changes in net factor prices on taxed factor supplies. Although the relative changes in net factor prices and thus factor supplies are infinitesimal, they apply to a very large tax base (in comparison with the base of the environmental tax). Hence, they generate first-order welfare effects, which are included in the analytical model.

where ε_u denotes the uncompensated wage elasticity of labor supply.[15] The marginal cost of public funds 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 (so that public expenditure does not affect marginal rates of substitution in utility).

A related cost concept, the marginal excess burden, applies in cases where the revenue is not spent on public goods but rather is returned to households as lump-sum transfers. The expression for the marginal excess burden of the labor tax, μ, is

$$\mu = \left(\frac{\varepsilon_c[T/(1-T)]}{1-\varepsilon_u[T/(1-T)]} \right), \tag{10}$$

where ε_c stands for the compensated wage elasticity of labor supply. As mentioned above, we assume that the initial tax system is optimal from a nonenvironmental point of view so that marginal excess burden of the capital tax is the same as that of the labor tax.[16]

Compensating the downstream industry. We define the nonenvironmental welfare impact ψ as the efficiency impact from the policy change, excluding the welfare effects from changes in environmental quality, but including, where applicable, the efficiency cost of compensating capital owners. Consider first the case where the EVN constraint applies only to capital owners in the downstream industry. In this case, the nonenvironmental welfare impact ψ_y (i.e., the compensating variation expressed relative to output in the downstream industry) can be written as

$$\psi_y/a \left(\equiv \frac{dU}{P_y Y \frac{\partial U}{\partial C}}/a \right) = -\lambda \alpha_e^y - \mu(1-T) \left[\left(\frac{\varepsilon_s^x}{\varepsilon_d^x + \varepsilon_s^x} \right) \left(\frac{\varepsilon_d^y}{\varepsilon_s^y + \varepsilon_d^y} \right) \right] \kappa, \tag{11}$$

where $a \equiv -e$ denotes the required proportional reduction in emissions, ε_s^i and ε_d^i $(i = x, y)$ represent the price elasticities of demand and supply in the two industries,[17] $\alpha e^y \equiv T_e E/(P_y Y)$ stands for the cost share of environmental taxes in the downstream sector, and κ is defined as the percentage increase in the production costs of Y stemming from the increased shadow price for emissions T_E associated with each percentage reduction in emissions (i.e., $\kappa \equiv \alpha_e^y t_e/a$).

Absolute costs. Expression (11) indicates that the efficiency costs of the pollution policy can be separated into two components: the costs attributable to reducing pollution (the first right-hand term) and the costs attributable to compensating capital in the downstream industry (the second right-hand term). The former cost, which applies whether or not the EVN requirement is imposed, is the efficiency cost associated with the loss of tax base that results when emissions decline in response to an environmental tax (or equivalent permit system). This cost will exceed the direct cost α_e^y if the marginal cost of public funds (λ) exceeds unity (which will be the case if $\varepsilon_u T > 0$: see equation (9)). This excess reflects the fact that the environmental policy erodes the base not only of the pollution tax but of the factor tax as well. The erosion of the factor tax base necessitates an increase in the factor tax rate. Under positive uncompensated elasticities ε_u and factor taxes T, this depresses factor supply and yields efficiency losses in the factor market.[18] The efficiency

---

[15] This is the partial equilibrium concept of the marginal cost of public funds because it does not take into account the indirect effect of a higher labor tax on emissions and emissions tax revenue. This partial equilibrium concept is appropriate if (as assumed by the analytical model—see previous subsection) the pollution sectors are infinitely small compared to the rest of the economy.

[16] The expressions for λ and μ therefore do not distinguish between the supply elasticities of capital (the immobile factor) and labor (the mobile factor). Indeed, the elasticities of aggregate capital supply coincide with the corresponding labor supply elasticities.

[17] The Appendix expresses these elasticities in terms of the local features of the production and utility functions (including various substitution elasticities).

[18] The first term on the right-hand side of (11) can be rewritten as $[\lambda \cdot \Delta E \cdot T_e/(P_y Y)]/a$. $T_e/(P_y Y)$ is the wedge between the marginal benefit and pretax marginal cost of emissions to the firm (the latter is zero), expressed relative to the value of output. ΔE is the change in emissions tax base. The product of the two is the efficiency impact directly implied

costs stemming from the emissions constraint, captured in the first term on the right-hand side of (11), increase with the stringency of environmental policy. This occurs because a more ambitious policy implies a higher value for α_e^y, the cost share of taxed emissions in the downstream sector. Indeed, starting from an equilibrium without any environmental policy (i.e., starting at $T_e = 0$), α_e^y is zero and the efficiency cost of incremental abatement is zero.

The additional efficiency costs associated with EVN, represented by the second right-hand term of (11), rise with μ, the marginal excess burden of factor taxation, and with κ, the increase in the production cost of Y attributable to additional emission abatement. This latter cost increase is negatively related to the ease with which producers can invoke three channels for cutting emissions: end-of-pipe treatment, input substitution (substitution of capital for the intermediate input in the downstream industry), and output substitution (substitution of C for Y by final consumers, implying a lower output of the final good Y).[19] With a smaller required cost increase, the adverse impacts on profits are smaller, and less compensation is required.

In addition to the marginal excess burden of taxation μ and the required cost increase κ, the added efficiency cost of imposing EVN is directly related to the compensation ratio: the share of potential revenues from an emissions permit program that must be left with the downstream industry to achieve EVN. The compensation ratio for the downstream sector θ_y is given by

$$\theta_y = \frac{\left(\dfrac{\varepsilon_s^x}{\varepsilon_d^x + \varepsilon_s^x}\right)\left(\dfrac{\varepsilon_d^y}{\varepsilon_s^y + \varepsilon_d^y}\right)\kappa}{(\kappa - \alpha_e^y)}. \tag{12}$$

This ratio is large to the extent that capital owners in the downstream industry—rather than the consumers of the final good Y or the capital owners in the upstream industry—bear a large share of the burden of the environmental policy. Expression (12) indicates that their burden share will be large when (i) the downstream industry cannot easily substitute between the intermediate input X and other inputs (so that ε_d^x and ε_s^y are small), (ii) the upstream industry can easily substitute between mobile labor and immobile capital (so that ε_s^x is large), or (iii) consumers can easily substitute between the two final goods (so that ε_d^y is large). Each of these conditions works toward larger reductions in the rental price of capital in industry Y following implementation of the environmental policy.

The level of pollution abatement also affects the compensation ratio. Higher abatement lowers the denominator of (12) by raising α_e^y. This reflects the fall in potential revenues stemming from the additional erosion of the emissions tax base. In contrast, the increment to required compensation (which is given by the numerator at the right-hand side of (12)) does not fall with abatement. Hence a larger share of potential revenue must be used to compensate the capital owners as required abatement expands.

Relative costs. Many policy makers are especially interested in the added efficiency cost of imposing EVN *relative* to the cost when no EVN requirement is imposed. Let χ_y denote the additional efficiency cost of achieving equity value neutrality, relative to the marginal efficiency cost of achieving environmental improvement in the absence of the EVN requirement. χ_y is in fact the ratio of the two terms on the right-hand side of (11):

$$\chi_y \equiv \frac{\mu(1-T)\left[\left(\dfrac{\varepsilon_s^x}{\varepsilon_d^x + \varepsilon_s^x}\right)\left(\dfrac{\varepsilon_d^y}{\varepsilon_s^y + \varepsilon_d^y}\right)\right]\kappa}{\lambda\alpha_e^y} = \varepsilon_c T\theta_y\frac{[1 - \alpha_e^y/\kappa]}{\alpha_e^y/\kappa}, \tag{13}$$

---

by the change in emissions tax base. Multiplying this product by λ yields the overall efficiency impact, which accounts also for induced changes in the factor tax base. All of these efficiency impacts abstract from the environmental benefits from the policy intervention—the focus is on the cost side of the ledger.

[19] The Appendix derives expressions that relate κ to features of the production technologies and preferences.

where the second equality follows from (9), (10), and (12). The additional efficiency losses are substantial if the compensated wage elasticity of labor supply ε_c and the distortionary tax T are large. When the government compensates capital owners (e.g., through free allocation of emissions permits), it forgoes government revenue. This obliges the government to rely more on ordinary (factor) taxes. Additional reliance on ordinary taxes implies a larger labor market distortion and thus is especially costly when ε_c and T are large. The additional efficiency losses are also substantial if the compensation ratio θ_y is large. This will be the case if the owners of capital in the downstream industry cannot shift the tax burden onto consumers of the final good or capital owners in the upstream industry (i.e., if ε_s^x and ε_d^y are large compared to ε_d^x and ε_s^y). Another key factor is the parameter κ: the larger the required cost increase faced by the downstream industry to arrive at a given emission cut a, the larger the additional efficiency losses of establishing equity value neutrality. This can be seen most directly from (11): the added efficiency costs increase with κ, while the other efficiency costs are independent of κ.

Expression (13) also indicates that the EVN cost ratio χ_y declines with the initial level of abatement (i.e., the level of abatement to which the marginal increase in abatement applies). This is the case because higher initial abatement tends to imply a higher emission tax share $\alpha_e^y \equiv T_e E/P_y Y$. In an initial equilibrium without any abatement, the implicit emission tax rate is zero, i.e., $T_e = \alpha_e^y = 0$. Starting from such an equilibrium, the efficiency cost of providing lump-sum compensation to industry is first order. In contrast, the other element of efficiency cost—the economy-wide cost of abatement (in terms of erosion of the environmental tax base)—is only second order, as discussed above. Thus, initially, χ_y is infinite: distributional effects dominate the efficiency costs of abatement. At higher levels of initial abatement, the marginal economy-wide costs of additional abatement become positive and typically rise faster than the marginal costs of lump-sum compensation. Indeed, in contrast to the economy-wide marginal efficiency costs of abatement, the marginal costs of compensation do not directly depend on the initial abatement level (for given demand and supply elasticities). Hence the marginal efficiency costs of additional compensation become smaller compared to marginal economy-wide costs as emissions reductions become more extensive. Thus at high levels of pollution abatement, pure efficiency costs of abatement, which are borne by the economy as a whole (and reflect the loss of the environmental and factor tax bases), tend to dominate the efficiency costs associated with compensation.

The effect of ease of end-of-pipe treatment on the EVN cost ratio χ_y is ambiguous. On the one hand, easier end-of-pipe abatement means that to achieve a given reduction in emissions, the emissions tax rate (or permit price) has to rise less (implying a smaller value for κ). The lower cost increase partially compensates the Y industry and thus alleviates the additional efficiency cost of imposing EVN. On the other hand, easier end-of-pipe abatement also reduces the efficiency cost of abatement in the absence of EVN. In particular, it reduces the level of T_e required to achieve a certain emission target E, thereby decreasing the cost share of environmental taxes α_e^y. Hence easier end-of-pipe treatment reduces the absolute efficiency costs by lowering both the costs of compensating capital and the costs of reducing pollution (i.e., both terms on the right-hand side of (11)). At the same time, the impact on the relative cost of imposing the EVN constraint—the ratio of the two terms—is ambiguous.

Compensating the upstream industry. If only the upstream industry receives compensation, the additional efficiency cost of achieving equity value neutrality χ_x can be written as

$$\chi_x = \varepsilon_c T \frac{\left(\dfrac{\varepsilon_d^x}{\varepsilon_d^x + \varepsilon_s^x}\right)\kappa}{\alpha_e^y}. \tag{14}$$

This expression indicates that the relative increase in efficiency cost from the EVN requirement is smaller, the larger the supply elasticity ε_s^x or the smaller (in absolute value) the demand elasticity ε_d^x. The supply elasticity will be large when immobile factors are relatively unimportant in the upstream industry. Under those conditions, profits account for only a small share of the value of that industry's output and not much compensation is needed to establish EVN in that sector.

The additional cost of compensating both the upstream and downstream industries is given by the sum of (14) and (13), which can be written as

$$\varepsilon_c T \frac{\left[1-\left(\frac{\varepsilon_s^x}{\varepsilon_d^x+\varepsilon_s^x}\right)\left(\frac{\varepsilon_s^y}{\varepsilon_s^y+\varepsilon_d^y}\right)\right]\kappa}{\alpha_e^y}.$$

The relative cost increase of compensating the capital owners in both these industries is therefore substantial if producers can shift only a small share of the additional costs of emissions to consumers, as indicated by a small share

$$\left(\frac{\varepsilon_s^x}{\varepsilon_d^x+\varepsilon_s^x}\right)\left(\frac{\varepsilon_s^y}{\varepsilon_s^y+\varepsilon_d^y}\right).$$

In this case, a large share of the economy-wide burden of emissions control falls on the sectors requiring compensation, and the cost of compensating these sectors is large relative to the economy-wide efficiency cost.

□ **A graphical illustration.** Figure 1 heuristically illustrates some of the main results from this section, with a focus on the downstream industry. Suppose that the government constrains emissions through pollution permits, and that all permits are auctioned. In this case, the cost of producing Y increases because the input X effectively becomes more costly: the purchase of each unit of X now also requires the purchase of permits for the emissions associated with X. Producers of Y can mitigate this cost increase through fuel substitution and expenditures on end-of-pipe treatment; indeed, they will do so until, at the margin, the cost increase from fuel substitution and from end-of-pipe treatment equals the savings from reduced emissions (and permit obligations). The new industry supply curve is S_1, and the equilibrium consumer price (or demand price) rises to p_{D1}. The dashed line S' indicates the marginal production costs exclusive of the permit-acquisition costs. This line is above S_0 because of the additional costs from fuel substitution and end-of-pipe treatment. This policy reduces producer surplus from its original value given by the area *efh* to the value given by the area *cdg*.

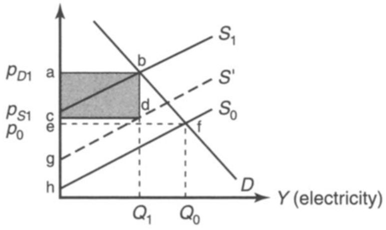
If instead the same number of permits is given out free rather than auctioned, much of the impact is similar. Firms have the same incentives to engage in fuel substitution and end-of-pipe treatment, since reducing emissions yields a benefit by reducing the required holdings of permits, which either allows more sales of permits or lowers required purchases of additional permits. Hence the marginal cost of production still includes the permit cost, and the policy again raises the supply curve to S_1. The equilibrium consumer price is again p_{D1}. However, the profit impacts are different in this case. Recipients of free permits enjoy higher prices yet do not have to pay for those permits. In addition to the gross producer surplus *cdg*, these producers collectively earn rents given by the rectangular area *abdc*. As drawn, these rents more than compensate for the gross loss of producer surplus; that is, the rectangular area exceeds the difference between triangular areas *efh* and *cdg*.

The rectangle *abdc* represents potential permit revenues: this is the amount of revenue generated if 100 percent of the permits are auctioned. To achieve equity value neutrality, the government would need to allow firms to retain as rents a large enough fraction of *abdc* to offset the gross loss of producer surplus. In the diagram, this share, which we have termed the compensation ratio, is roughly 40 percent. The reader can confirm from the diagram that this share is larger, the greater (in absolute value) the elasticity of demand and the smaller the elasticity of supply for Y.

The gross loss of producer surplus and compensation ratio will depend on the ease of end-of-pipe treatment. To the extent that such treatment is a low-cost option, firms' marginal costs

FIGURE 1

RENTS, COSTS, AND THE COMPENSATION RATIO



of achieving emissions reductions will be lower, and thus for any given abatement target (or number of permits in circulation), the permit price will be lower. Hence the upward shift in the supply curve will be smaller than when end-of-pipe treatment is more costly. The smaller rise in the supply curve influences the compensation ratio two ways. First, it implies that the gross loss of producer surplus will not be so large, which diminishes the numerator of the compensation ratio. In addition, the smaller upward shift affects the potential revenues from the policy change. Depending on supply and demand elasticities, the potential revenues may be larger or smaller than in the case where end-of-pipe treatment is more costly. Thus, the implication of the ease of end-of-pipe treatment for the compensation ratio is ambiguous.

3. A numerical model

■ Here we develop and apply a numerical model in order to obtain quantitative results and consider the impacts of large policy changes.

□ **Structure.** We briefly describe the model here; a complete description is in the web Appendix (available from www.stanford.edu/~goulder). The formal structure of the numerical model and its degree of aggregation match that of the analytical model described in the previous section. However, this model relaxes the assumption that the industries *X* and *Y* are "small," thus allowing the real wage to be endogenous. Moreover, since the model is solved numerically, its solution does not rely on linearization techniques. Hence this model can consider the impacts of large policy changes.

The model adopts constant-elasticity-of-substitution (CES) functional forms for the production functions of the intermediate input *X* and the final goods *Y* and *C*. As in the analytical model, each industry employs labor and capital as inputs, and industry *Y* employs the intermediate input *X* as well (with the same nesting as in the analytical model). Thus the production function for the *Y* industry is given by

$$Y = \gamma_y \left[\alpha_{yv} v^{\frac{\sigma_y - 1}{\sigma_y}} + (1 - \alpha_{yv}) L_y^{\frac{\sigma_y - 1}{\sigma_y}} \right]^{\frac{\sigma_y}{\sigma_y - 1}}, \tag{15}$$

with

$$v = \gamma_v \left[\alpha_v K_y^{\frac{\sigma_v - 1}{\sigma_v}} + (1 - \alpha_v) X^{\frac{\sigma_v - 1}{\sigma_v}} \right]^{\frac{\sigma_v}{\sigma_v - 1}}. \tag{16}$$

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

$$K = \gamma_k \left[\alpha_k K_x^{\frac{\sigma_k - 1}{\sigma_k}} + \beta_k K_y^{\frac{\sigma_k - 1}{\sigma_k}} + (1 - \alpha_k - \beta_k) K_c^{\frac{\sigma_k - 1}{\sigma_k}} \right]^{\frac{\sigma_k}{\sigma_k - 1}}, \tag{17}$$

where *K* represents the aggregate capital stock. 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. This implies increasing marginal adjustment costs: successive increments to the supply of any given type of capital require ever-larger sacrifices of other types of capital. In contrast to capital, labor is perfectly mobile across industries.

The household utility function is CES,

$$U = \left(\alpha_g G^{\frac{\sigma_u - 1}{\sigma_u}} + \alpha_z Z^{\frac{\sigma_u - 1}{\sigma_u}}\right)^{\frac{\sigma_u}{\sigma_u - 1}}, \tag{18}$$

where G is a CES composite of the final goods Y and C,

$$G = \left(\alpha_{gc} C^{\frac{\sigma_g - 1}{\sigma_g}} + \alpha_{gy} Y^{\frac{\sigma_g - 1}{\sigma_g}}\right)^{\frac{\sigma_g}{\sigma_g - 1}}, \tag{19}$$

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

$$Z = \left(\alpha_{zl}(\overline{L} - L)^{\frac{\sigma_z - 1}{\sigma_z}} + \alpha_{zk}(\overline{K} - K)^{\frac{\sigma_z - 1}{\sigma_z}}\right)^{\frac{\sigma_z}{\sigma_z - 1}}, \tag{20}$$

and $\overline{L}$ and $\overline{K}$ represent the maximum potential supplies of labor (the endowment of labor time) and of capital, respectively.

We adopt the emissions function

$$\frac{E}{X} = \gamma_e \left[1 + \beta_e \left(\frac{G_a}{X}\right)^{\rho_e}\right]^{\frac{-1}{\rho_e}} \qquad \beta_e > 0;\ 0 < \rho_e < 1, \tag{21}$$

where end-of-pipe abatement G_a is a CES composite of the two final goods C and Y, with the same parameters as in (19).

The emission function E/X can be represented as $\gamma_e f(G_a/X)$. The function $f(\cdot)$ features the following desirable properties:

(i) $f'(0) \Rightarrow -\infty$. 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).

(ii) $f(\infty) = 0$. Pollution is eliminated completely if end-of-pipe treatment is very large.

(iii) $f(0) = 1$. Without any end-of-pipe treatment, pollution remains finite.

□ **Equilibrium.** The requirements of the general equilibrium are that (a) household supply of labor must equal aggregate labor demand by firms, (b) demand for capital by each industry i ($i = x, y, c$) must equal the quantity supplied to that industry, (c) pollution emissions must equal the pollution level stipulated by environmental policy, and (d) government revenue must equal real transfers to households.

The nominal price of labor is the numeraire. The primary prices in the model (from which all other prices can be determined) are the rental prices of capital (R_{k_i}, $i = x, y, c$), the price of pollution permits, and the tax on factor income. To obtain the general equilibrium, the model identifies the vector of primary prices that meets the four requirements above. Walras's law implies that the labor market clears when all other markets clear.

The auctioning of pollution permits or the introduction of an emission tax generates new government revenue. To maintain overall government revenue just sufficient to finance the (fixed) real transfers to households (that is, to satisfy the fourth condition above), the model reduces the tax rate on factor income.

In policy experiments involving the EVN requirement, the model must also calculate the extent of grandfathering just sufficient to prevent a loss of profit rates for the owners of the initial

TABLE 1 **Benchmark Input-Output Flows for the Numerical Model**

	Use of Input by Industry			Total Receipts to Each Input	Endowments
	X	Y	C		
Input:					
X	.0	27.1	.0	27.1	
L	2.6	11.8	1,765.3	1,779.7	5,249.8
K	13.7	44.0	712.4	770.1	2,271.5
Factor taxes	10.8	48.0	1,651.8	1,710.6	
Total input payments by each industry	27.1	130.9	4,129.5		
SO_2 emissions (Mtons/year)		15.2			

Notes: 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 Administration's *Annual Energy Review 1999*.

In billions of year-2000 dollars per year except where otherwise noted. Inputs of labor and capital are net of factor taxes. Endowments correspond to $\overline{L}$ and $\overline{K}$ in equation (20) of text.

(i.e., prepolicy-change) capital stock. It may be noted that the extent of grandfathering affects the revenue yield from the policy and thus influences the extent to which the tax rate on labor and capital can be cut.

□ **Data.** The numerical model is applied to the United States. We choose the electricity industry as the downstream industry and regard its suppliers of fossil fuels as the upstream industry. We focus on control of sulfur dioxide (SO_2) emissions.

Table 1 indicates the interindustry flows in our dataset. These flows derive from the U.S. Bureau of Economic Analysis (1998). The emissions data come from the U.S. Energy Information Administration (1999).

Table 2 displays the parameters used in the model. The elasticities of substitution in production are taken from the disaggregated general equilibrium dataset developed by Barreto et al. (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 recent 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 to .40.

TABLE 2 **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	.6
σ_y	elasticity of substitution between v and L in production of Y	.75
σ_v	elasticity of substitution between X and K in production of v	.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 v 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	.66
σ_g	elasticity of substitution between C and Y	.9
σ_z	elasticity of substitution between L and K	.9

We calibrate the model to generate uncompensated and compensated labor supply elasticities of .15 and .40, respectively.[20] 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 .24 for labor taxes. As in the analytical model, capital supply elasticities are set equal to labor supply elasticities. With the same factor tax rate on both capital and labor income, the marginal excess burden for capital taxes is thus the same as that for labor taxes.

□ **Policy experiments and results.** We employ the model to examine how much the introduction of the EVN constraint adds to the efficiency cost of pollution abatement and how this depends on the extent of pollution abatement and on technologies and preferences.

Under the assumptions of the numerical model (including, in particular, the absence of uncertainty), for any policy involving pollution permits there is an equivalent policy involving a pollution tax. For example, a policy involving 100% auctioning of pollution permits is equivalent to a pollution tax without any inframarginal exemption and whose tax rate equals the permit price. Similarly, a policy involving partial free allocation of permits can be made equivalent to a pollution tax with a partial inframarginal exemption and with a tax rate equal to the permit price.[21] In the following, we describe all the policy experiments as permits policies, although the results apply also to tax policies generating the same emissions reductions.

A reference case: no EVN requirement. Under policy 1, the EVN constraint is not imposed. This is a reference case. This policy involves 100% auctioning of emissions permits to industry Y. Net revenues from the policy are recycled to the private sector through cuts in the marginal rates of labor and capital taxes. Under this policy, we vary the amount of permits provided to consider cuts in SO_2 emissions ranging from zero to 75% of initial, unregulated emissions.

Table 3 displays the equilibrium outcomes under this policy. Permit prices and potential permit revenues rise with the extent of the required pollution reduction. The need to purchase permits and to abate pollution increases production costs in industry Y, leading to higher output prices and lower equilibrium output. This is accompanied by a reduced use of factors in this industry and lower rental rates on capital. Even though capital is imperfectly mobile and sector-specific rental rates fall substantially, sector Y reduces demand for capital more than demand for labor. The reason is that capital is a complement to the polluting intermediate input X. Hence labor rather than capital substitutes for the more expensive intermediate input X.

Input substitution and reduced output in industry Y curtail demand for the output X of the upstream industry, which in turn causes prices, profits, and factor use to fall in that industry as well. In this sector, labor use declines more than capital demand because, in contrast to capital, labor is perfectly mobile intersectorally.

Higher prices for the output of the downstream industry cause a shift in demand toward industry C, the other final good industry. The impacts on industry C are relatively small, however. The use of capital in this industry rises because profit rates in this industry are much less significantly reduced than in the pollution-related industries. The bottom panel of Table 3 displays the efficiency impact of this policy. Efficiency costs are measured by the negative of the equivalent variation, expressed as a percentage of benchmark income. This welfare measure indicates gross costs, not net benefits, since it does not account for the welfare impacts associated with policy-induced changes in environmental quality. Efficiency costs rise more than in proportion to the extent of pollution reduction.

Compensating the downstream industry. Policy 2 imposes the EVN constraint for the downstream industry, the industry that actually produces SO_2 emissions. EVN is achieved through the free

---

[20] 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.

[21] For a further discussion of equivalences between pollution permit and tax policies, see Farrow (1999) and Williams (2002).

TABLE 3 **Numerical Results Under Central Case Parameter Values**

	1			2			3			4		
	No Compensation			Compensation to Y			Compensation to X			Compensation to X & Y		
Percentage Abatement	10	25	75	10	25	75	10	25	75	10	25	75
Policy instruments												
Permit price ($ thousands/ton)	.10	.26	3.86	.10	.26	3.85	.10	.26	3.85	.10	.26	3.85
Potential permit revenues ($ billions)	1.33	2.94	14.66	1.33	2.94	14.64	1.33	2.94	14.65	1.33	2.94	14.63
Compensation ratio, industry Y	—	—	—	28.05	31.03	46.31	—	—	—	28.44	31.46	46.88
Compensation ratio, industry X	—	—	—	—	—	—	17.98	19.49	25.10	18.17	19.70	25.42
Industry X												
% change in output price	−.91	−2.17	−13.90	−.91	−2.17	−13.89	−.91	−2.17	−13.89	−.91	−2.17	−13.89
% change in K rental price	−1.07	−2.56	−16.22	−1.07	−2.56	−16.21	−1.07	−2.56	−16.22	−1.07	−2.56	−16.21
% change in K stocks	−1.03	−2.46	−15.60	−1.03	−2.46	−15.63	−1.03	−2.46	−15.62	−1.03	−2.47	−15.66
% change in employment	−2.08	−4.94	−29.18	−2.08	−4.94	−29.21	−2.08	−4.94	−29.20	−2.08	−4.95	−29.22
% change in output	−1.19	−2.85	−17.89	−1.20	−2.86	−17.93	−1.19	−2.86	−17.91	−1.20	−2.86	−17.95
Industry Y												
% change in output price	.65	1.59	12.67	.65	1.59	12.66	.65	1.59	12.67	.65	1.59	12.66
% change in K rental price	−.53	−1.28	−9.25	−.53	−1.28	−9.25	−.53	−1.28	−9.25	−.53	−1.28	−9.24
% change in K stocks	−.48	−1.18	−8.58	−.49	−1.18	−8.62	−.49	−1.18	−8.60	−.49	−1.19	−8.65
% change in employment	−.08	−.21	−1.60	−.09	−.21	−1.66	−.09	−.21	−1.63	−.09	−.22	−1.69
% change in output	−.58	−1.42	−10.40	−.59	−1.43	−10.44	−.58	−1.43	−10.42	−.59	−1.43	−10.47
Industry C												
% change in output price	−.02	−.05	−.35	−.02	−.05	−.35	−.02	−.05	−.35	−.02	−.05	−.35
% change in K rental price	−.02	−.06	−.42	−.02	−.06	−.42	−.02	−.06	−.42	−.02	−.06	−.42
% change in K stocks	.02	.05	.32	.02	.04	.26	.02	.05	.29	.02	.04	.23
% change in employment	.01	.04	.22	.01	.03	.16	.01	.03	.19	.01	.02	.13
% change in output	.02	.04	.25	.01	.03	.19	.01	.03	.22	.01	.03	.16
Aggregate factor supplies												
% change in labor	.01	.03	.17	.01	.02	.11	.01	.02	.13	.01	.01	.08
% change in capital	−.03	−.06	−.47	−.03	−.07	−.52	−.03	−.07	−.50	−.03	−.08	−.56
Efficiency cost												
−EV ($ billions)	.08	.48	9.92	.14	.61	10.88	.12	.56	10.44	.17	.70	11.42
% increase from policy 1	—	—	—	63.94	26.81	9.73	41.05	16.86	5.27	106.45	44.29	15.19
−EV as % of benchmark income	.00	.01	.16	.00	.01	.18	.00	.01	.17	.00	.01	.18

allocation of a share of the permits to the industry in question. The permits are grandfathered on the basis of the capital stock in the industry before the environmental policy is announced and implemented. Only the owners of existing capital are compensated: capital that moves into the industry afterward does not benefit from grandfathering. Free permit allocation implies a sacrifice of potential revenue. Thus, for any given pollution reduction, the reduction in factor tax rates will generally be less extensive under this policy than under policy 1. As indicated by the analytical model, this is the source of the added efficiency cost of the EVN requirement.

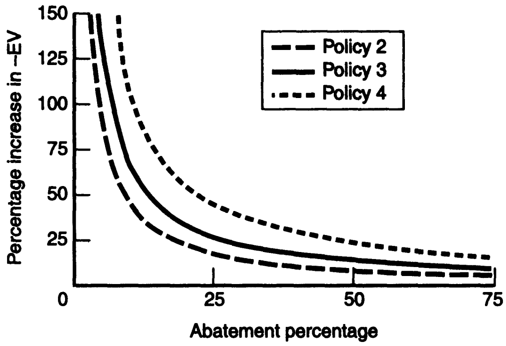
Relative and absolute increases in efficiency costs. Figure 2 shows the additional efficiency cost implied by the EVN requirement, as a percentage of the efficiency cost under Policy 1. These additional costs are closely related to the variable χ_y, introduced in Section 2.[22] The figure shows that the relative increase in efficiency cost declines with the extent of abatement. If the required

---

[22] The only difference is that Figure 2 provides the additional costs of EVN for the entire range of abatement (compared to no abatement at all), while χ_y represents the additional costs of EVN for a marginal increase in abatement beyond some initial amount.

FIGURE 2

ADDITIONAL COSTS (OVER POLICY 1) OF EQUITY VALUE NEUTRALITY



abatement is below 5%, achieving EVN for the downstream industry raises costs by over 100%. In contrast, when required emissions reductions exceed 50%, the relative increase is below 18%.

These results square with the findings of the analytical model, which indicated that, starting from an equilibrium without abatement, the first increment of abatement implies no first-order efficiency costs in the absence of a compensation requirement. In contrast, achieving EVN involves first-order efficiency costs, even at the first increment of abatement. Thus the additional efficiency cost of preventing adverse profit impacts (relative to the marginal efficiency costs under policy 1) is infinite for initial abatement. This ratio then falls with abatement, since the adverse profit impacts (and thus the required compensation for the affected industries) grow more slowly than the other efficiency costs, that is, the efficiency costs associated with abatement rather than compensation. Indeed, at higher amounts of abatement, these other costs become increasingly important relative to the costs that the environmental policies impose on the regulated industries.

Although the relative increases in efficiency costs become smaller as abatement becomes more extensive, the absolute increase becomes larger. This can be seen by comparing, at different levels of abatement, the efficiency costs of policies 2 and 1 in the third-to-last row of Table 3.

The compensation ratio as a function of abatement. The compensation ratio has been defined as the compensation necessary to achieve EVN as a fraction of the total gross revenue that would be collected if 100% of the emissions permits were auctioned. It corresponds to the share of permits that must be freely allocated in order to achieve EVN.[23] Figure 3 displays the compensation ratios for the downstream industry under policy 2, as a function of abatement. These ratios rise with the extent of abatement, consistent with the analytical model's results. Even at high levels of abatement, the ratios are below 50%. Although higher abatement implies larger losses of profit in the absence of compensation (the numerator of the ratio), it also implies larger potential revenues or rents (the denominator), which tempers the rate of increase in the compensation ratio.

☐ **Providing broader compensation.** Table 3 indicates that under the reference case (policy 1), the percentage reduction in the return to capital in the upstream industry is significant: it is about twice as large as that for owners of capital in the downstream industry. Thus it is useful to consider policies in which the EVN requirement applies to the upstream industry. Policy 3 imposes this requirement on the upstream industry alone. As before, the requirement is implemented through the free allocation of emissions permits.[24] In policy 4, the requirement is imposed on both the

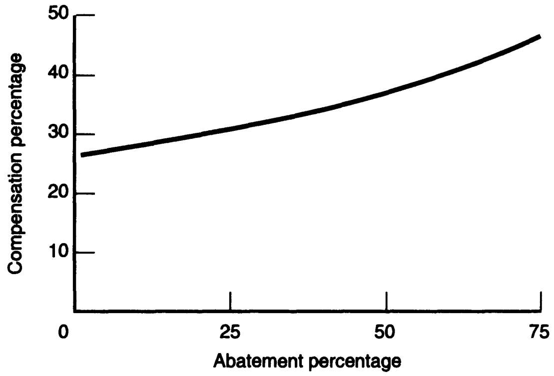
---

[23] Here the compensation ratio is calculated for large (as opposed to incremental) amounts of abatement. Thus it differs from the marginal-compensation ratio described in the analytical model: the ratio of additional compensation to additional potential revenue associated with an incremental increase in abatement.

[24] The upstream industry benefits by selling these permits to the downstream industry—the industry that actually generates emissions. Suppose that under this policy, n_X permits are freely allocated to the upstream industry, with n_Y

FIGURE 3

COMPENSATION RATIO FOR INDUSTRY Y (POLICY 2)



upstream and downstream industry. The bottom three rows of Table 3 display the pattern of cost impacts under these policies.

The second-to-last row shows the added efficiency costs of all the EVN policies, relative to policy 1. The relative increase in cost under policy 3 is about half as large as the relative increase under policy 2, and the relative added cost under policy 4 is roughly the sum of those under policies 2 and 3. Even though owners of upstream industry capital experience larger reductions in rental rates than do owners of downstream industry capital, it is less costly to insulate the profits of the former (compare results for policies 2 and 3). The reason is that the upstream sector is relatively small: its value added and capital income are only about a quarter of that in the downstream sector. The economy-wide costs of compensating the agents who suffer the largest relative losses (the owners of the upstream industry in this case) are thus relatively small. These results demonstrate that the efficiency costs of compensation can be effectively contained by restricting compensation to the relatively small group suffering the severest relative losses. Spreading the compensation net to include as well those who lose moderately from the policy yields substantial additional costs.

□ **Sensitivity analysis.** *SO_2 versus CO_2.* Our numerical applications consider the costs of avoiding profit losses associated with restrictions on SO_2 emissions in the electricity industry. As mentioned in the Introduction, earlier studies have examined the costs of avoiding losses of profit from CO_2 abatement policies, using large, multisector general equilibrium models. It is useful to explore similarities and differences between our results and earlier findings.

The earlier studies emphasized compensation to the upstream industries (fossil fuel producers). In Bovenberg and Goulder (2001) in particular, compensating the fossil fuel producers raised efficiency costs by 7.3% under central parameter values, when CO_2 emisssions must be reduced by 18%. In contrast, in the present model, compensating such producers (that is, industry X) raises efficiency costs by 23% when SO_2 emissions need to be reduced by the same percentage (see the results for policy 3 in Figure 2). What accounts for the differences in results?

A major factor is that the earlier studies consider emissions reductions by all users of fossil fuels, including the transportation sector, while the present study focuses on emissions reductions by the electricity sector only. The electricity industry depends significantly on coal, while the transportation sector depends primarily on refined petroleum-based fuels. Thus, oil is considerably more important in the earlier experiments. Oil producers are able to shift to consumers much of the cost of regulation. Because the marginal suppliers of oil to the United States are foreign, and this supply is highly elastic, most of the cost of emissions permits or taxes comes in the form of

---

permits auctioned to the downstream industry. This policy is equivalent to one in which (a) the upstream industry receives a lump-sum payment from the government of equivalent value to the n_X permits, and (b) the government auctions $n_X + n_Y$ permits to the downstream industry.

higher oil prices to downstream users of oil: the domestic producer price is relatively unchanged. In contrast, in the coal industry, imports are relatively insignificant and the supply is much less elastic. Producers thus bear a larger share of the costs of regulation. (See Bovenberg and Goulder (2001).)

In the present model the supply function for fossil fuels is less elastic (adjustment costs are higher), in keeping with the greater relative importance of the coal industry to emissions reductions. This implies, for given emissions reductions, a higher compensation ratio in the upsteam industry and a greater relative increase in efficiency costs. As a further experiment, we examined the added cost when the adjustment cost parameter σ_k is doubled (in absolute value), implying considerably lower adjustment costs and a more elastic supply function. In this case, the relative increase in efficiency cost under an 18% emissions reduction under policy 3 is 14.8%, considerably closer to the added cost obtained earlier. These results indicate that the added costs of achieving EVN depend importantly on the relevant fuels' supply elasticities, which in turn depend on the breadth of industries facing emissions controls.

Another difference between emissions abatement in the SO_2 and CO_2 cases is that SO_2 abatement allows for end-of-pipe treatment, while CO_2 abatement does not. The analytical model indicated that while opportunities for end-of-pipe treatment lower the absolute costs of abatement policies, they have an ambiguous effect on the relative cost increase from the EVN constraint. In additional sensitivity analysis below, we consider the implications of changes in the ease of end-of-pipe treatment for the added costs. In keeping with the analytical results, we find that changes in opportunities for end-of-pipe treatment significantly affect policy costs but have a very minor impact on the relative increase in cost from the EVN constraint. These results indicate that although limited opportunities for end-of-pipe treatment of CO_2 could explain higher absolute costs of emissions reductions under CO_2, they do not explain the lower relative costs of EVN obtained in the earlier studies.

Further sensitivity analysis. Figures 4 and 5 show the significance of key parameters for policy results. The panels of Figure 4 show the significance of these parameters for the compensation ratio; the panels of Figure 5 indicate their significance for the added cost of the EVN constraint.

End-of-pipe treatment. One distinguishing feature of the present article is its consideration of end-of-pipe treatment as one of the channels through which firms can reduce their pollution emissions. The ease of such treatment is governed by the parameter β_e, whose central case value is 2. The low case employs a value of .01 (implying virtually no possibility of end-of-pipe treatment) and the high case a value of 4.

Varying the ease of end-of-pipe treatment has little influence on the compensation ratios or on the relative increase in efficiency costs. The first panel of Figure 4 indicates that the differences in the compensation ratios implied by low and high values of β_e are almost imperceptible. The first panel of Figure 5 shows the efficiency cost of policy 2 relative to that under policy 1 (which involves no EVN constraint), under the low and high values for β_e. Ease of end-of-pipe treatment

FIGURE 4

COMPENSATION RATIO AS A FUNCTION OF···

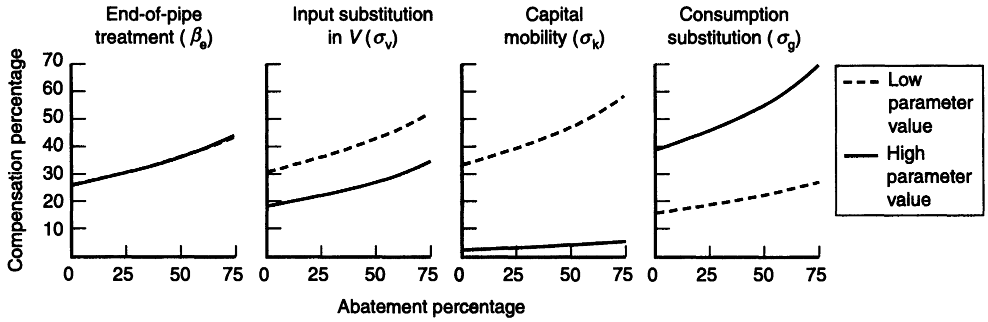
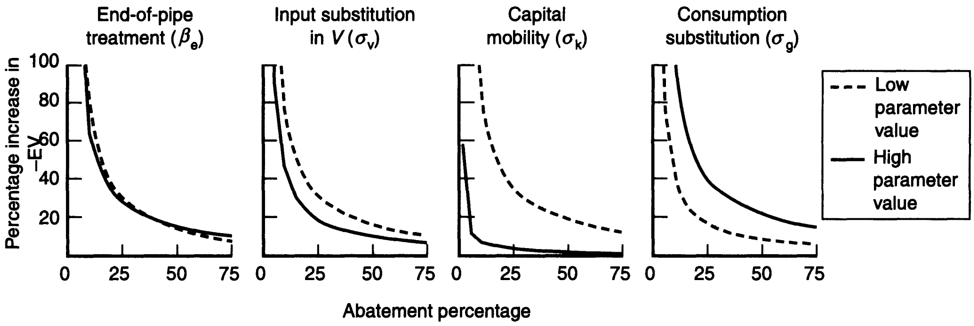


FIGURE 5

RELATIVE INCREASE IN EFFICIENCY COST AS A FUNCTION OF···



has relatively little effect on the relative increase in efficiency costs. This squares with the analytical model's findings.

However, the ease of end-of-pipe treatment substantially affects the *absolute* cost of achieving emissions reductions. This can be seen from Table 4, which contains the implications of alternative values of β_e and other parameters for the costs of achieving emissions reductions under policy 1. The numbers in the table are the ratio of efficiency costs under alternative parameters to efficiency costs in the central case. The costs under policy 1 are 8–10 times higher under policy 1 when the low value of β_e is used; they are about a third of the central case costs when the high value is used.

Input substitution. We consider alternative values for σ_v, the elasticity of substitution between K and X in the production of the composite input v in the Y industry. We double and halve this elasticity, whose central value is .15. When σ_v is high, it is easier for the Y industry to substitute away from X and reduce emissions. The higher the value of σ_v, the smaller the loss of profit in the downstream industry (before compensation) associated with a given required reduction in emissions. Hence the compensation ratio is smaller. The second panel of Figure 4 bears this out.[25] Since less compensation is required, the relative cost of achieving EVN is lower as well (Figure 5, second panel). The absolute costs are lower, too, since the reference case values are lower when σ_v is large (Table 4).

Elasticity of supply of industry Y output. The elasticity of supply of output from industry Y depends on σ_k, which controls the ease of capital adjustment across industries. The third panels of Figures 4 and 5 relate the compensation ratios and relative efficiency costs to σ_k. The central case value for σ_k is -1; we consider alternative values of $-.5$ and -100, implying very low and extremely high capital mobility, respectively. When σ_k is low in absolute value, capital is relatively inelastic, and output supply is relatively inelastic as well. Under these conditions, capital bears a larger share of the burden of the environmental regulation and the required compensation is larger (Figure 4, third panel). By increasing the required compensation, a low value of σ_k also raises the relative efficiency costs of policy 2 (Figure 5, third panel).

Elasticity of demand for industry Y output. A key parameter controlling the elasticity of demand for the output from industry Y is σ_g, the elasticity of substitution between C and Y in the G subutility function. When this elasticity is high, the demand for Y is more elastic. The fourth panels of Figures 4 and 5 consider values for σ_g that are half and twice its central value of .9. When σ_g is high, capital bears a larger share of the burden of the pollution regulation. Hence the compensation ratio is higher. Correspondingly, the relative cost increase associated with achieving EVN is larger.

---

[25] It may be noted that a higher value of σ_v implies a larger loss of profit in the upstream industry, since a given required reduction in emissions will be associated with a larger reduction in demand for X and less use of end-of-pipe treatment.

TABLE 4 **Ratio of Costs Under Alternative Parameter Values to Costs in Central Case (For Policy 1: No Compensation)**

	Low Parameter Value			High Parameter Value		
Percentage Abatement	10	25	75	10	25	75
Parameter varied						
EOP treatment (β_e)	7.96	9.88	8.68	.34	.34	.38
Input substitution in V (σ_v)	1.02	1.02	1.05	.96	.96	.92
Consumption substitution (σ_g)	1.02	1.02	1.05	.98	.98	.94
Capital mobility (σ_k)	.96	.96	.92	1.02	1.02	1.04

4. Conclusions

■ A politically realistic approach to environmental policy requires consideration of distributional impacts. It seems important to consider, in particular, how to mitigate or avoid potentially adverse impacts on groups with effective veto power. Representatives of pollution-related industries seem to be one such group. In this article we have considered the efficiency costs of achieving equity value (that is, preventing profit losses) in pollution-related industries.

Losses of profit can be avoided through the free allocation of emissions permits or, equivalently, the exemption of inframarginal emissions from a pollution tax. However, such policies increase efficiency costs because they compel the government to forgo potential pollution-tax or pollution-permit revenue and rely more heavily on ordinary distortionary taxes. Our article has employed analytically and numerically solved models to examine the added efficiency costs implied by these compensation measures.

The analytical model shows that the relative increase in cost will be especially high when labor supply elasticities are large or the preexisting tax rate on factors is high. Moreover, this added cost will be substantial when the compensation ratio is high. This will be the case when the targeted industry is limited in its ability to shift the burden of regulation to demanders or consumers.

Under a wide range of parameter values, the numerical model shows that profits can be maintained in both upstream and downstream industries by freely allocating less (and sometimes considerably less) than 50% of pollution permits, and auctioning the rest. The relative increase in efficiency cost (compared to the cost in the case where profits are not protected) is highly sensitive to the extent of pollution abatement, ranging from above 100% when the required pollution abatement is modest to below 10% when the abatement requirement is extensive. Expanded opportunities for end-of-pipe treatment of pollution reduce the absolute efficiency costs of abatement policies, but they have little impact on the relative increase in efficiency costs attributable to the constraint on profits. Limiting compensation to the relatively small group suffering the most-severe losses substantially helps to contain the efficiency costs of compensation.

Some caveats are in order. First, while preventing profit losses might well increase the prospects for political acceptability of various policies, it does not guarantee it. The political process is complex and depends on more than this particular distributional issue. A second and closely related issue is that we have concentrated entirely on compensation to a single immobile factor, which in the numerical model is calibrated to be existing capital. One might wish to consider the costs of compensating other important stakeholders, including workers who suffer temporary or long-term unemployment. Third, our models are fairly simple. They have the attraction of transparency and flexibility, but more-detailed models could yield more-precise quantitative results. Finally, we have not considered the full range of potential environmental policies or compensation mechanisms. In future work we plan to examine the costs of compensation under other policies such as technology mandates and performance standards. In addition, we would like to explore other compensation instruments such as sector-specific cuts in capital or labor taxes. Some of these alternative instruments might well be more-efficient mechanisms for spreading more-evenly the burden of environmental policy initiatives.

References

ANDERSON, S. AND NEWELL, R. "Prospects for Carbon Capture and Storage Technologies." Discussion Paper no. 02-68. Resources for the Future, Washington, D.C., 2003.

BARRETO, D., GURNEY, D.J., XIE, X., AND GOULDER, L.H. "An Intertemporal General Equilibrium Model for Analyzing U.S. Energy and Environmental Policies: Data Documentation." Working Paper, Stanford University, 2002.

BOVENBERG, A.L. AND GOULDER, L.H. "Neutralizing the Adverse Industry Impacts of CO_2 Abatement Policies: What Does It Cost?" In C. Carraro and G. Metcalf, eds., *Behavioral and Distributional Effects of Environmental Policy*. Chicago: University of Chicago Press, 2001.

BURTRAW, D., PALMER, K., BHARVIRKAR, R., AND PAUL, A. "The Effect on Asset Values of the Allocation of Carbon Dioxide Emission Allowances." Discussion Paper 02-15, Resources for the Future, Washington, D.C., March 2002.

CHIRINKO, R.S., FAZZARI, S.M., AND MEYER, A.P. "That Elusive Elasticity: A Long-Panel Approach to Estimating the Price Sensitivity of Business Capital." Working Paper, Emory University, January 2002.

DINAN, T.M. "Shifting the Cost Burden of a Carbon Cap-and-Trade Program." U.S. Congressional Budget Office, Washington, D.C., July 2003.

FARROW, S. "The Duality of Taxes and Tradeable Permits: A Survey with Applications in Central and Eastern Europe." *Environmental and Development Economics*, Vol. 4 (1999), pp. 519–535.

FREEMAN, A.M. *The Measurement of Environmental and Resource Values: Theory and Methods*. Resources for the Future, Washington, D.C., 1993.

FULLERTON, D. AND METCALF, G.E. "Environmental Controls, Scarcity Rents, and Pre-Existing Distortions." *Journal of Public Economics*, Vol. 80 (2001), pp. 249–267.

GOULDER, L.H., PARRY, I.W.H., WILLIAMS, III, R.C., AND BURTRAW, D. "The Cost-Effectiveness of Alternative Instruments for Environmental Protection in a Second-Best Setting." *Journal of Public Economics*, Vol. 72 (1999), pp. 329–360.

JORGENSON, D.W. AND WILCOXEN, P.J. "Energy, the Environment, and Economic Growth." In A.V. Kneese and J.L. Sweeney, eds., *Handbook of Energy and Natural Resource Economics*, Vol. 3. Amsterdam: Elsevier, 1993a.

——— AND ———. "Energy Prices, Productivity, and Economic Growth." In R.H. Socolow, D. Anderson, and J. Harte, eds., *Annual Review of Energy and the Environment*. Amsterdam: Elsevier, 1993b.

OLSON, M. *The Logic of Collective Action*. Cambridge, Mass.: Harvard University Press, 1965.

PARRY, I. AND OATES, W.E. "Policy Analysis in the Presence of Distorting Taxes." *Journal of Policy Analysis and Management*, Vol. 19 (2000), pp. 603–613.

RUSSEK, F.S. "Labor Supply and Taxes." Working paper, Macroeconomic Analysis Division, Congressional Budget Office, Washington, D.C., 1996.

SMITH, V.K. "Nonmarket Valuation of Environmental Resources: An Interpretive Appraisal." In R.N. Stavins, ed., *Economics of the Environment: Selected Readings,* 4th ed. New York: W.W. Norton, 2000.

SMITH, A.E., ROSS, M.E., AND MONTGOMERY, W.D. "Implications of Trading Implementation Design for Equity-Efficiency Trade-offs in Carbon Permit Allocations." Working Paper, Charles River Associates, Washington, D.C., December 2002.

UNITED STATES BUREAU OF ECONOMIC ANALYSIS. *Benchmark Input-Output Accounts of the United States, 1992*. Washington, D.C.: Department of Commerce, Economics and Statistics Administration, 1998.

UNITED STATES ENERGY INFORMATION ADMINISTRATION. *Annual Energy Review 1999*. Washington, D.C.: Department of Energy, 1999.

WILLIAMS, III, R.C. "Prices vs. Quantities vs. Tradable Quantities." Working Paper, Department of Economics, University of Texas at Austin, 2002.