Leakage, Welfare, and Cost-Effectiveness of Carbon Policy

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Abstract

We extend the model of Fullerton *et al* (2011) to explore cost-effectiveness of unilateral climate policy in the presence of leakage. We ignore the welfare gain from reducing greenhouse gas emissions and focus on the welfare cost of the emissions tax or permit scheme. Whereas that prior paper solves for changes in emissions quantities and finds that leakage maybe negative, we show here that all cases with negative leakage in that model are cases where a unilateral carbon tax results in a welfare loss. With positive leakage, however, a unilateral policy can improve welfare.

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Policymakers fear that a unilateral carbon policy will reduce competitiveness, increase imports, and lead to higher carbon emissions elsewhere ("leakage"). In Fullerton *et al* (2011), we show that carbon policy in one sector may actually reduce emissions in other sectors ("negative leakage"). But if it reduces emissions in both sectors, that outcome may merely reflect welfare cost of carbon policy that reduces real income and thus reduces consumption of all commodities. All of these possible outcomes capture the concern that unilateral carbon policy may have a high cost per global unit of carbon abated (that is, low "cost-effectiveness").

Based on Harberger (1962), the two-input, two-output analytical general equilibrium model of Fullerton *et al* (2011) could represent two countries' outputs or two sectors of a closed economy. Each sector has some initial carbon tax or price, and the paper solves for the effect of a small increase in one sector's carbon tax on the quantity of emissions in each sector. But it does not solve for welfare effects. Here, we use the same model but derive expressions for the cost-effectiveness of a unilateral carbon tax – the total cost per ton of total emission reduction. We show that higher leakage does not always mean lower welfare. If one sector is already taxed at a higher rate, then a unilateral increase in the other sector's carbon tax might reduce deadweight loss from pre-existing misallocations and thus raise welfare. Cost-effectiveness most directly depends on the relative levels of tax in the two sectors. We show that negative leakage always corresponds to a negative income effect, but negative income effects can also arise with positive leakage. Conversely, positive leakage does not always mean low cost-effectiveness.

Actual carbon policy is not likely to be applied uniformly across all countries and sectors. The Waxman-Markey legislation in the U.S. proposed carbon policy primarily in the electricity sector. Also, the EU Emission Trading Scheme only covers about 40 percent of emissions (http://ec.europa.eu/clima/policies/ets/index_en.htm). Metcalf and Weisbach (2009) estimate that even a very broad carbon policy can only cover 80 to 90 percent of emissions, so actual carbon policy will likely leave some sectors uncovered. Raisings one sector's carbon tax may have welfare costs if the other sector has no carbon tax, but on the other hand, that other sector may face indirect taxes on carbon through taxes on fossil fuels such as gasoline. Those fuels may serve as substitutes for electricity, so a new carbon tax in the electricity sector may shift consumption back somewhat from the low-taxed electricity sector into fossil fuels. In that case, a new carbon tax just in the electricity sector may increase welfare despite positive leakage.

This paper makes several contributions. First, we demonstrate the generality of the Fullerton *et al* (2011) model by showing cases where leakage can exceed 100%. We solve for conditions under which total emissions increase or decrease. We also solve for welfare effects, and for "cost effectiveness" (the additional welfare cost per ton of net abatement). And we explore the relationship between the sign of leakage and the sign of the effect on welfare.

The change in deadweight loss has two components. First, a unilateral increase in carbon tax affects a distortion in consumption, the existing misallocation between the two outputs. Second, it also affects a distortion in production, the extent that the taxed sector substitutes from carbon to other inputs (such as labor or capital for abatement). Depending on the other sector's pre-existing carbon tax rate and carbon intensity, the distortion in consumption may increase or decrease. Thus, the efficiency cost of a change in carbon taxation depends largely on initial carbon tax rates in the two sectors.

Our prior paper shows that negative leakage is more likely when the elasticity of substitution in utility is small and the elasticity of substitution in production is large. Here, we show that these are the same conditions that lead to higher deadweight loss from an increased carbon tax in one sector: a low elasticity of substitution in utility means that any reduction in the consumption distortion is relatively small, while any increase in the distortion in production of the taxed good is relatively large. Conversely, positive leakage may be associated either with welfare gains or losses. The intuition is that welfare cost most directly relates to the relative levels of tax in the two sectors, rather than to the relative changes in emissions. That is, a high cost per ton of carbon abatement can be associated with either negative or positive leakage.

I. The Change in Carbon Emissions

Using the model of Fullerton *et al* (2011), we demonstrate here the conditions under which a small increase in one sector's carbon price may increase total emissions, and the conditions under which it is certain to decrease total emissions. The two competitive sectors have constant returns to scale production, $X = X(K_X, C_X)$ and $Y = Y(K_Y, C_Y)$, where a clean input K_i and carbon emissions C_i have decreasing marginal products ($i = X, Y$). The clean input can be labor, capital, or a composite of the two, with fixed total supply $\left(\overline{K} = K_X + K_Y\right)$. That input is mobile and earns the same equilibrium factor price p_K in both sectors. Sector i can use any amount of C_i, given price τ_i (which can be a tax rate or permit price). Either sector might initially have the higher carbon price. Total carbon emissions $C \equiv C_X + C_Y$ have a negative but separable effect on homothetic utility, $U(X, Y; C)$. Permit or tax revenue is $R \equiv \tau_X C_X + \tau_Y C_Y$, rebated in a lump sum. Many identical consumers use income $p_K \overline{K} + R$ to maximize utility by their choice of X and Y (facing prices p_X, p_Y, and p_K).

The simplest version of this model has no traded oil in limited supply, so it misses the positive leakage caused when a carbon tax reduces one sector's demand, thereby reducing the price of oil and increasing use elsewhere. Instead, think of τ_Y applying to coal-fired power plants where coal is not scarce. As shown below, the model does have positive leakage from the terms of trade effect (TTE) and negative leakage from the abatement resource effect (ARE). The goal in Fullerton *et al* (2011) is not to measure leakage but to demonstrate the ARE in a simple model that abstracts from other issues. That paper lists citations to other sources for these issues.

The model is used to derive effects of a small increase in τ_Y, with no change in τ_X, where firms in sector Y can substitute away from carbon by additional use of abatement capital (K_Y) such as natural gas plants, wind turbines, or solar power. The model ignores any transition but instead compares initial allocations to those in a new long run equilibrium. Leakage is defined as the effect on the other sector's emissions, C_X.

Given this set-up, Fullerton *et al* (2011) differentiate all equations above to derive a set of n linear equations with n unknowns, using a hat for each proportional change (e.g. $\hat{K}_X \equiv dK_X/K_X$). They differentiate production to get $\hat{Y} = \theta_{YK}\hat{K}_Y + \theta_{YC}\hat{C}_Y$, where θ_{ij} is a factor share [e.g. $\theta_{XK} = (p_K K_X)/(p_X X)$]. Define σ_Y as the elasticity of substitution in sector Y, to get $\hat{C}_Y - \hat{K}_Y = \sigma_Y(\hat{p}_K - \hat{\tau}_Y)$. The definition of σ_U implies $\hat{X} - \hat{Y} = \sigma_U(\hat{p}_Y - \hat{p}_X)$. Then, given a small exogenous increase in one carbon tax ($\hat{\tau}_Y > 0$), the system of linear equations is solved for the general equilibrium impact on each price and quantity as a function of parameters.

For sector Y, the increase in tax always raises the equilibrium price ($\hat{p}_Y = \theta_{YC}\hat{\tau}_Y > 0$) and reduces the equilibrium quantity ($\hat{Y} = -[\alpha_X\sigma_U + \alpha_Y\sigma_Y]\theta_{YC}\hat{\tau}_Y < 0$), where $\alpha_i = K_i/K$. The tax certainly reduces that sector's carbon emissions ($\hat{C}_Y < 0$). To calculate the total effect on carbon, we need to know the amount of leakage. As derived in our prior paper:

$$\hat{C}_X = \alpha_Y(\sigma_U - \sigma_Y)\theta_{YC}\hat{\tau}_Y = \left[\underbrace{\sigma_U\alpha_Y\theta_{YC}}_{\text{TTE}} - \underbrace{\sigma_Y\alpha_Y\theta_{YC}}_{\text{ARE}}\right]\hat{\tau}_Y \gtrless 0 \tag{1}$$

The first term in equation (1) is the terms-of-trade effect (TTE), where the higher price of Y induces households to substitute into X (by an amount that depends on σ_U). This effect by itself increases production of X and emissions C_X. This positive leakage term is offset by a negative second term, the abatement resource effect (ARE), where the higher price of carbon induces firms to substitute into K_Y (by an amount that depends on σ_Y). If sector Y increases its use of capital, then sector X must reduce its use of capital, its output, and its emissions. (The price of carbon in sector X does not change relative to the cost of other inputs, so those firms do not change their ratio of inputs; less capital in X therefore means less emissions and less output.)

Theorem 1 (Fullerton *et al* 2011)*: Net leakage is negative when* $\sigma_Y > \sigma_U$. The first part of equation (1) provides this result. When consumers' substitution is low, they want to buy almost as much of the taxed output Y (as when electricity demand is inelastic). Producers' substitution is high, so they reduce carbon and use more capital, drawing capital from X.

From here, we develop several new theorems to characterize the conditions for total carbon emissions to fall in response to an increase in the carbon tax in one sector. Mathematical proofs of each theorem can be found in the online Appendix.

Theorem 2: *Net negative leakage in this model implies that total carbon falls.* An increase in the carbon tax in sector Y clearly decreases the carbon emissions of that sector. If the increase in τ_y also reduces carbon in sector X, then total carbon emissions clearly fall.

Theorem 3: *If sector Y is carbon intensive* ($C_Y/K_Y > C_X/K_X$)*, then total carbon falls*. Intuitively, increasing the carbon tax in the sector that uses carbon intensively creates a large decrease in emissions that overcomes any possible positive leakage. Importantly, these two situations are only sufficient conditions for a decrease in total carbon, as other parameter combinations may also lead to reductions of total carbon emissions.

Next, we identify necessary and sufficient conditions for an *increase* in total carbon emissions. Intuitively, for total emissions to rise, carbon leakage must be positive and large enough to exceed the reduction in sector Y. Thus, substitution in utility must be larger than substitution in sector Y production $(\sigma_U > \sigma_Y)$, and sector X must be more carbon-intensive than sector Y. In other words, $\alpha_Y > \beta_Y$ (where $\alpha_Y \equiv K_Y / K$ and $\beta_Y \equiv C_Y / C$).

Theorem 4: *A necessary and sufficient condition for total carbon to increase* ($\hat{C} > 0$) *is* $\frac{\sigma_U}{\sigma_Y} > \frac{(\alpha_Y \theta_{YC} + \beta_Y \theta_{YK})}{(\alpha_Y - \beta_Y)\theta_{YC}} > 1$. Carbon leakage can more than offset emission reductions in sector Y only if substitution in utility is enough larger than substitution in production. This condition also requires the denominator in the middle term to be positive ($\alpha_Y > \beta_Y$), which means that Y must be relatively capital-intensive. Intuitively, increasing the carbon tax in a *capital*-intensive sector has little direct effect on carbon, while it does raise the relative price of Y. If the elasticity of substitution in utility is sufficiently high, consumers switch from consuming Y to consuming X. Since the direct effect on C_Y is then small, and the substitution in consumption is large, carbon leakage can more than offset the direct reduction in carbon in the taxed sector.

II. The Change in Deadweight Loss

In Fullerton *et al* (2011), both sectors have pre-existing, non-zero carbon tax rates, with deadweight loss (DWL) via two channels. First, it creates a distortion in production; firms use too little carbon. Second, differential carbon tax rates change relative output prices and create a distortion in consumption. We assume that environmental damages from carbon are separable in utility, $U(X, Y; C)$, and focus on the loss in utility from consumption (the cost of abatement).

To quantify the change in deadweight loss resulting from an increase in the carbon tax in sector Y (ΔDWL), we totally differentiate the separable utility function and follow steps found in our online Appendix. Intuitively, the change in utility is merely the difference in the bundle of X

and Y that can be consumed before and after the tax change, and those changes in outputs can be written as changes in inputs. Then we can re-write *ΔDWL* as:

$$-\frac{dU}{\lambda} = \Delta DWL = -\left(\tau_X C_X \hat{C}_X + \tau_Y C_Y \hat{C}_Y\right). \quad \gtreqless 0 \tag{2}$$

where λ is the marginal utility of income, so dU/λ is the monetary value of the change in utility. Thus, the sign of the change in deadweight loss is a function not only of the pre-existing tax rates in the two sectors, but their relative carbon intensities. This derivation implies:

Theorem 5: *If sector Y has a higher carbon-weighted tax rate than sector X, then an increase in* τ_Y *raises deadweight loss. That is,* $\tau_Y(C_Y/K_Y) > \tau_X(C_X/K_X)$ *implies* $\Delta DWL > 0$. When the carbon-weighted tax rate in sector *Y* exceeds that in sector *X*, the further increase in τ_Y has welfare cost. The *ΔDWL* is positive because an increase τ_Y moves the weighted tax rates farther apart and thus increases distortions. Equation (2) also implies that if both sectors use less carbon, the deadweight loss of the tax increase must be positive. In other words:

Theorem 6: *Negative leakage means a positive change in deadweight loss. That is,* $\hat{C}_X < 0$ *implies* $\Delta DWL > 0$. The increase in τ_Y always shrinks *Y*. If it also shrinks *X*, then utility of consumption must fall. Since deadweight loss also depends on initial tax rates, however, $\Delta DWL > 0$ does not imply negative leakage. We next explore whether and when an increase in tax leads to a decrease in deadweight loss.

We decompose the welfare loss into the share from the consumption distortion and the share from the production distortion, we rearrange *ΔDWL* as shown in the online Appendix:

$$\Delta DWL = R\left\{\sigma_U\left[\alpha_X - \delta_X\right]\theta_{YC} + \sigma_Y\left[\alpha_Y\theta_{YC} + \delta_Y\theta_{YK}\right]\right\}\hat{\tau}_Y \tag{3}$$

where R is total tax revenue, $\delta_X \equiv \tau_X C_X / R$, and $\delta_Y \equiv \tau_Y C_Y / R$. Inside the curly brackets, the first term is the change in the consumption distortion associated with σ_U, and the second term is the change in production distortion associated with σ_Y. An increase in τ_Y always worsens the production distortion in that sector (as firms switch from C_Y to K_Y). Also, the magnitude of the welfare effect increases with the size of the initial tax level, τ_Y [through *R* in equation (3)]. Finally, ΔDWL is zero when $\sigma_U = \sigma_Y = 0$, because then τ_Y is essentially a lump-sum tax (with revenue rebate also lump-sum).

For an increase in τ_Y to provide a welfare gain ($\Delta DWL < 0$), Theorem 6 tells us that leakage must be positive. Thus, the relative size of substitution in consumption must outweigh substitution in production ($\sigma_U > \sigma_Y$). Further, equation (3) implies that the share of carbon in sector X must be smaller than the share of carbon revenue from X ($\alpha_X < \delta_X$). Thus, the carbon-weighted carbon tax in sector *X* must be larger than the carbon-weighted carbon tax *Y*. From these two conditions and equation (3) above, we have:

Theorem 7: *The ΔDWL<0 if and only if* $\frac{[\alpha_Y \theta_{YC} + \delta_Y \theta_{YK}]}{[\delta_X - \alpha_X]\theta_{YC}} > \frac{\sigma_U}{\sigma_Y} > 1$. Note that this condition requires $\sigma_U > \sigma_Y$ and $\alpha_X < \delta_X$. It looks similar to the condition for an increase in total carbon emission (in Theorem 4), except that the ratio here must be larger than the ratio of the elasticities, and the δ_i (shares of revenue) replace the β_i (shares of carbon). The intuition behind this result is somewhat complex, but it boils down to the idea that the initial τ_X must be large, so that an increase in τ_Y reduces the consumption distortion.

In summary, an increase in one sector's carbon tax can have negative marginal abatement cost, if it reduces DWL by raising the *low* carbon tax rate. Next, we use ΔDWL and the quantity of carbon reduction to calculate of the cost-effectiveness of the policy.

III. Cost-Effectiveness

We measure the cost-effectiveness of a policy change as the "marginal cost of abatement" (MCA), the dollar value of the change utility divided by the change in carbon emissions:

$$\text{MCA} = \frac{dU/\lambda}{dC} = \left[\frac{\alpha_Y(\sigma_U - \sigma_Y)\theta_{YC} - \delta_Y(\sigma_U\theta_{YC} + \sigma_Y\theta_{YK})}{\alpha_Y(\sigma_U - \sigma_Y)\theta_{YC} - \beta_Y(\sigma_U\theta_{YC} + \sigma_Y\theta_{YK})}\right]\left(\frac{R}{C}\right). \tag{4}$$

The fraction R/C is the *average* tax paid by firms per unit of carbon emissions at the initial tax rates; this ratio is always positive. The scalar in square brackets contains just elasticity and share parameters; it reflects the distortions in production and consumption. As demonstrated above, the sign of the numerator is ambiguous ($\Delta DWL \gtreqless 0$), as is the sign of the denominator ($dC \gtreqless 0$). In the "normal" case, where the increase in carbon tax reduces carbon emissions, the denominator is negative. Then we have:

Theorem 8: *If* $dC<0$ *in* (4)*, then* $\tau_Y < \tau_X$ *implies the scalar is less than one (the MCA is less than the average cost, R/C).* In the normal case, increasing the carbon tax in a sector with a rate that already exceeds the rate in the other sector generates a marginal welfare cost larger than the average cost. To further explore this intuition, we consider a series of specific cases.

A. Special case where the tax rates in the two sectors are equal

Assume both sectors have the same initial tax rate, $\tau_X = \tau_Y = \tau_C > 0$. Then the share of revenue from sector Y matches its share of carbon emissions ($\delta_Y = \beta_Y$), and from equation (4) we have:

$$\left.\frac{(dU/\lambda)}{dC}\right|_{\delta_Y=\beta_Y} = \frac{R}{C} = \tau_C$$

All firms in both sectors increase abatement until the MCA equals the tax rate, common to all firms in both sectors, so the equi-marginal principle guarantees efficient allocation of abatement.

Moreover, a higher initial tax rate means higher marginal cost of additional abatement. The model is not defined when either initial tax rate is zero, so we do not consider such cases.

B. Special case with no leakage

Assume $\sigma_U = \sigma_Y$, which mean no leakage (from eq.1, $\hat{C}_X = 0$). The MCA can be written simply as the change in utility over the change in carbon:

$$\frac{(dU/\lambda)}{dC} = \frac{\tau_X C_X \hat{C}_X + \tau_Y C_Y \hat{C}_Y}{C_X \hat{C}_X + C_Y \hat{C}_Y} \quad \text{and thus:} \quad \left.\frac{(dU/\lambda)}{dC}\right|_{\sigma_U=\sigma_Y} = \tau_Y .$$

Since leakage is zero, and input prices in sector *X* remains constant, all consumption changes come from decreases in *Y*. Thus, the dollar-equivalent utility cost is the carbon tax rate in *Y*.

C. Special case with offsetting leakage and no change in total carbon

The increase in τ_Y always reduces carbon emissions in *Y*, but leakage may increase other emissions and leave total carbon unchanged. When overall dC approaches zero in the denominator, the MCA approaches infinity. Since leakage is positive, however, we know that the numerator (ΔDWL) could be positive or negative. With nearly zero overall abatement, the MCA is an arbitrarily large positive or negative number.

IV. The Relationship between Leakage and Welfare

We now explore the relationship between leakage and welfare effects from unilateral climate policy, using numerical examples and figures to help with intuition. When does the sign of one determine the sign of the other? Two key parameters for the signs of leakage and ΔDWL are σ_Y and σ_U. Therefore, figures below show the elasticity of substitution in production (σ_Y) on the horizontal axis and the elasticity of substitution in utility (σ_U) on the vertical axis. We know that leakage is zero when these two parameters equal each other, so the 45° line shows the boundary between cases where leakage is positive ($\sigma_U > \sigma_Y$) or negative ($\sigma_U < \sigma_Y$).

To get the boundary for the sign of the welfare effect, we set ΔDWL to zero in equation (3) above, and solve for σ_U in terms of σ_Y (see Appendix):

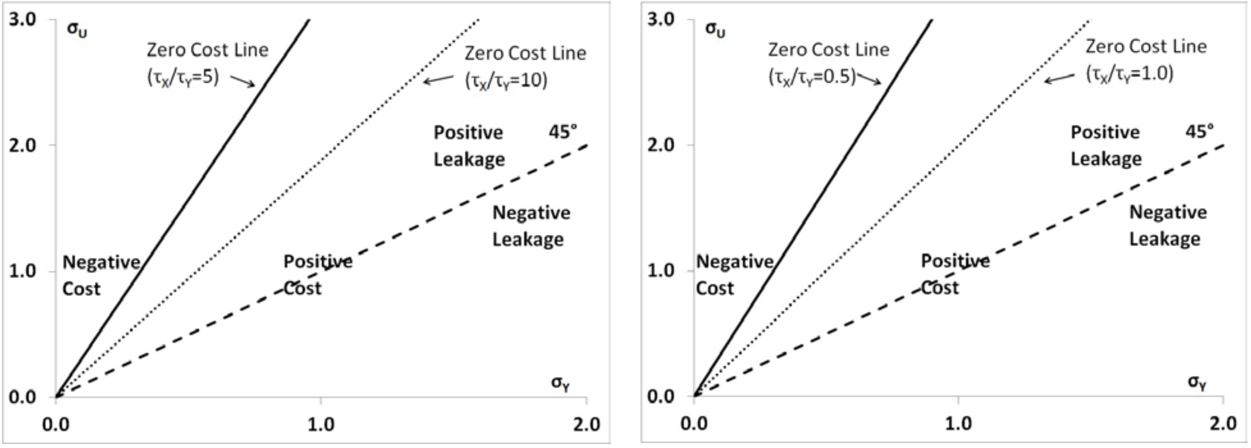
$$\sigma_U = \sigma_Y \left[1 + \frac{\delta_Y}{(\alpha_Y - \delta_Y)\theta_{YC}} \right]. \tag{5}$$

Thus, the ΔDWL=0 line always goes through the origin. Also, Theorem 6 says that negative leakage implies positive ΔDWL. Therefore the ΔDWL=0 line must have a slope greater than one.

Since $\delta_Y \equiv \tau_Y C_Y / R$, the slope of the ΔDWL=0 line is determined primarily by the initial τ_X relative to τ_Y and by relative carbon intensity of the two sectors. In Figure 1A, we set the *Y* sector to be carbon intensive ($\alpha_Y = 0.4$ and θ_{YC} = 0.33, with initial intensities C_X/K_X = 0.167 and C_Y/K_Y = 0.25). We then plot ΔDWL=0 lines for two different values of τ_X/τ_Y. When the initial τ_X is high relative to τ_Y, the policy to raise τ_Y is more likely to improve efficiency. Therefore the solid line shows ΔDWL=0 when τ_X/τ_Y =5. Yet Figure 1A shows a relatively small area where the policy has negative cost (that is, only with high values of σ_U). The dotted line shows the case with initial τ_X/τ_Y = 10, with somewhat larger area of negative cost (welfare gain). The larger discrepancy in initial tax rates means a larger initial consumption distortion, which can be improved by raising τ_Y.

Can raising τ_Y improve welfare when that tax rate is already higher than τ_X? Yes, as shown in Figure 1B, where *X* is carbon intensive (C_X/K_X = 1.00 and C_Y/K_Y = 0.25). The solid line indicates ΔDWL=0 when the initial τ_X/τ_Y is only 0.5, so all the area above that line shows combinations of σ_U and σ_Y where raising τ_Y has negative cost. When $\tau_X = \tau_Y$, the dotted line shows an even wider area where raising τ_Y has negative cost. The bottom line, as shown in both figures, is that the change in deadweight loss can be either sign when leakage is positive.

Figure: 1: Relationship between Leakage and the Change in Deadweight Loss



1A: with $C_X/K_X = 0.167$ and $C_Y/K_Y = 0.25$

1B: with $C_X/K_X = 1.00$ and $C_Y/K_Y = 0.25$

V. Conclusions

For unilateral climate policy, this paper uses a simple two-sector, two-input general equilibrium model to explore how leakage is related to welfare changes and the cost per ton of abatement (cost effectiveness). Even with this simple model, Fullerton *et al* (2011) find that leakage can be negative. Here, we find that positive leakage can more than offset the direct abatement achieved by the tax. We also explore the effect of the tax change on deadweight loss (the cost of abatement). As it turns out, the conditions that give rise to negative leakage always result in welfare costs. Yet positive leakage can be associated either with gains or losses.

One might think that a policy with no leakage is more cost efficient than a policy where some of the abatement is offset by leakage. Yet this relation does not always hold. If the initial carbon tax in the *other* sector is relatively high, then one sector’s tax increase can reduce the consumption distortion by more than it increases the production distortion. A higher elasticity of substitution in consumption increases this welfare gain, but it also increases leakage. In other words, when the tax increase cuts the gap between the two tax rates, the conditions that give rise to a welfare gain also give rise to leakage. In summary, positive leakage is not always associated with a decrease in welfare.

For two reasons, we believe this finding is important for policy. First, most carbon policy proposals are likely to cover only a fraction of emissions. Even if the same tax rate could apply to emissions from electricity and from other sectors, it could not apply to all emissions. For example, homeowners can cut their own firewood for heat, which would be difficult to monitor. Second, most sectors already face taxes that represent an implicit price on carbon. In particular, the EU Emissions Trading Scheme covers only "major industries" such as electricity generation, cement, and some other manufacturing (only 40 percent of emissions), but other sectors also face implicit taxes on carbon (such as gasoline taxes in the transportation sector or BTU taxes on home heating fuel). Therefore, even if explicit carbon taxes are introduced only in one sector such as electricity, it may still raise economic welfare by reducing the consumption distortion associated with high levels of fuel taxes in other sectors.

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