Negative Leakage

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Abstract

We build a simple analytical general equilibrium model and linearize it, to find a closed-from expression for the effect of a small change in carbon tax on leakage – the increase in emissions elsewhere. The model has two goods produced in two sectors or regions. Many identical consumers buy both goods using income from a fixed stock of capital that is mobile between sectors. An increase in one sector's carbon tax raises the price of its output, so consumption shifts to the other good, causing positive carbon leakage. However, the taxed sector substitutes away from carbon into abatement capital. It thus absorbs capital, which shrinks the other sector, causing negative leakage. This latter effect could swamp the former, reducing carbon emissions in both sectors.

A common concern with unilateral pollution policy is that the restricted sector's abatement will be offset by "leakage", defined as the increase in pollution elsewhere. Within a region or country, a cap-and-trade system may apply only to one sector, such as electricity generation, which raises its price and shifts consumption to goods produced in other sectors not subject to the regulation. Purely domestic leakage may offset some of the regulated sector's abatement. In an international context, even without international capital flows, the regulating country puts itself at a competitive disadvantage. International capital mobility is thought to make leakage worse, if investment flees the taxed region to help produce more polluting output in the other region. The other country might be known as a "pollution haven", if it tries to attract investment via lax environmental regulation.[1] In the context of climate policy, carbon leakage is a particular concern due to the global impacts of greenhouse gases.

The literature has many estimates for carbon leakage associated with the Kyoto Protocol. For instance, Paltsev (2001) finds a carbon leakage rate of 10%, whereas

[1] Copeland and Taylor (2004) define a pollution haven effect (PHE) when "pollution regulation … (has) an effect on plant location decisions and trade flows" (p.9). In contrast, a pollution haven hypothesis (PHH) posits that "a reduction in trade barriers will lead to a shifting of pollution-intensive industry from countries with stringent regulations to countries with weaker regulations" (p.9).

Babiker (2005) finds rates as high as 130%. A recent contribution from Elliott *et al.* (2010) finds a 20% carbon leakage rate from the Annex-B Kyoto countries.

The purpose of this note is to demonstrate an offsetting effect that has not yet been identified in the literature. Moreover, we show that this negative effect on leakage could be so large as to swamp the usual positive effects, so that overall leakage could be negative. Worldwide pollution may fall by more than it does in the regulated region.

The usual positive leakage comes from an "output effect", where output shifts from the regulated sector to the other sector, but we show that negative leakage can arise from a "substitution effect": a carbon tax or permit price induces firms to abate carbon per unit of output by using more of a clean input such as abatement capital. The taxed sector draws resources away from the unregulated sector or region, which reduces their output and emissions. We call this an "abatement resource effect" (ARE).

The size of this negative leakage effect depends on parameters. If consumers can shift their purchases easily, then positive leakage may be high. Even then, however, leakage may be overstated in models that do not allow for substitution in production. If consumer flexibility is low compared to producers' ability to abate pollution by use of other resources, however, then we show that overall leakage may be negative.

To demonstrate these points, we build a simple analytical general equilibrium model in which two sectors use mobile capital and emit carbon dioxide (CO_2) in the production of two goods purchased by many identical consumers. Consumers earn income from their fixed stock of capital, and they receive rebate of all tax revenue. We then differentiate all equations to linearize the model and solve for effects of a small increase in one sector's pollution price. We identify the abatement resource effect in a closed-form expression for carbon leakage. Finally, we investigate this effect further, to see whether output in the other sector falls because revenue from the increased tax is not enough to compensate consumers for the higher price of one good. In some cases, the additional revenue is negative, which itself reduces consumer purchases.

Negative leakage does not arise in models of climate policy that assume fixed carbon content per unit of each output, nor in models without capital flows between differentially taxed sectors or regions.[2] In particular, we do not find any paper that

[2] Some papers allow for capital flows between regions but without abatement use of capital [e.g. Babiker (2001)]. Others allow for capital flow between sectors in the same region, but not for capital flows across regions or sectors with different carbon policies [e.g. Copeland & Taylor (2005)].

derives an expression for leakage in a model where firms can substitute into a clean input that is mobile across regions. Moreover, our model can be interpreted to represent either an international context, or a domestic context where two outputs are produced in the same region. For instance, the carbon policy could apply to electricity generation and not other goods, or it could apply in only one region within a country.[3]

In building a parsimonious model, we abstract from many important issues such as basic materials production and intermediate inputs [e.g. Felder and Rutherford (1993)], environmental quality as a normal good [Copeland and Taylor (2005)], endogenous number of firms [Gurtzgen and Rauscher (2000)], oligopolistic competition [Babiker (2005)], technological change [Di Maria and van der Werf (2008)], and strategic interaction [Fowlie (2009)]. Our model is also related to Holland (2009), who shows that welfare gains might be higher with an intensity standard than with a tax on emissions, because it causes less increase in the output price and therefore less leakage. Without an overall resource constraint, however, he cannot find negative leakage. The overall resource constraint in general equilibrium means that the *tax* can cause negative leakage, because the taxed sector draws resources from the untaxed sector. This effect would mitigate the relative welfare gain from an intensity standard compared to a tax.

Only Copeland and Taylor (2005) model negative leakage, but they allow neither factor mobility across regions nor our "abatement resource effect". Their mechanism operates through endogenous policy: in response to a cut in one region's emissions, the other region experiences income gains that induce them to choose more environmental quality through their own pollution restrictions. In our model, leakage can be negative even without strategic response by policymakers.

The next section presents the model, and section 2 solves it for the approximate change in carbon leakage from an exogenous policy tightening in one sector. Section 3 provides a brief numerical example, while Section 4 provides further discussion.

1. The Basic Model

Two competitive sectors each have many identical firms that use clean inputs K and carbon emissions C with decreasing marginal products in constant returns to scale

[3] As an example of sub-national policy, the Regional Greenhouse Gas Initiative (RGGI) is a conglomerate of Northeastern states in the U.S. that agree to limit their own carbon emission. Wing and Kolodziej (2009) find carbon leakage rates of more that 50%, due to electricity imports from non-RGGI states.

production functions, $X = X(K_X, C_X)$ and $Y = Y(K_Y, C_Y)$. The clean input is mobile and thus earns the same return, p_K, in either sector. It can be considered a composite of labor and capital, in fixed total supply $\left(\overline{K} = K_X + K_Y\right)$. Each sector faces its own tax or permit price for carbon, τ_i ($i = X,Y$). In response to an increased tax on emissions, a firm can reduce its carbon per unit of output by additional use of abatement technology, that is, by substitution from C_i into K_i. In the electricity generating sector, for example, firms can reduce emissions per kwh by investing in natural gas plants, wind turbines, or solar power. All revenue is returned via lump-sum rebate, $R \equiv \tau_X C_X + \tau_Y C_Y$.

Emissions from either sector add to total carbon, $C \equiv C_X + C_Y$, which negatively affects utility in a separable manner. Many identical households earn income from capital and the rebate of revenue, taking as given the total carbon and all market prices (p_X, p_Y, and p_K). They maximize utility by choice of X and Y subject to a budget:

$$\max_{\{X,Y\}} U(X,Y;C) \quad s.t. \quad p_K \overline{K} + R \geq p_X X + p_Y Y \,.$$

We have no need to specify which sector initially has the higher carbon tax rate, and so we simply investigate effects of a small increase in τ_Y with no change in τ_X. We compare the new long run equilibrium to the initial one, ignoring adjustments during the transition. The increase in τ_Y reduces equilibrium emissions in sector Y, and so leakage is defined as the effect on emissions in sector X.

This simple model can be interpreted at least two ways. First, it can represent a closed economy, in which only sector Y faces a raised price of carbon that also raises the equilibrium output price. Purely domestic leakage might result if consumers buy more of the other good, X, which then emits more carbon dioxide. Second, the same model can represent an international context where Y is produced in one country that raises its carbon tax, and X is produced in the other country. In this case, we suppose that all consumers in both countries have the same utility function, $U(X,Y;C)$. Capital is owned by these identical worldwide consumers, and it can be used in either country to produce either output. The raised price of Y may induce consumers in both countries buy more X, which then emits more carbon dioxide.[4]

[4] Our model with a single type of worldwide consumer is not adequate to analyze effects on welfare in each country, but our goal here is only to look at effects on carbon emissions in each country.

This model omits an important type of positive leakage, namely, world trade of fossil fuel in fixed supply. If the taxing jurisdiction reduces its demand for oil, the fall in the world price of oil can increase consumption elsewhere. Instead, our best example is perhaps a cap-and-trade regime limited to coal-fired power plants, where coal is not scarce (its world price depends primarily on extraction cost).

Nonetheless, positive leakage occurs domestically in our model, if consumers buy less of one output and more of the other output, or it can occur internationally if capital flees one country to help produce more in the other country. If a single region or state like California decides to institute its own carbon policy, that policy raises the price of output, and so consumers in that state buy less electricity and might import more of the other good. In general, we show that leakage *can* be negative, but for this example we show it likely *is* negative. Demand for electricity is inelastic, so consumers buy almost as much of it. In order to produce almost as much, firms abate carbon by investing in alternative technologies. They draw capital away from production elsewhere, which reduces equilibrium output elsewhere. Firms in the other sector reduce output by shrinking use of both inputs, that is, both capital and carbon emissions. Hence worldwide emissions fall by *more* than the reduction in taxed emissions.

2. Solving for Equilibrium Effects

Given this set-up, we now log-linearize the model to solve for *n* linear equations in *n* unknowns. Totally differentiate the resource constraint $\overline{K} = K_X + K_Y$, and use the "hat" notation to denote a proportional change in any variable (e.g. $\hat{K}_X \equiv dK_X / K_X$):

$$0 = \alpha_X \hat{K}_X + \alpha_Y \hat{K}_Y \tag{1}$$

where $\alpha_i \equiv K_i / \overline{K}$ is the share of capital in production of i ($i = X,Y$), and $\alpha_X + \alpha_Y = 1$. Then totally differentiate production to show how changes to inputs affect final output:

$$\hat{X} = \theta_{XK} \hat{K}_X + \theta_{XC} \hat{C}_X \tag{2}$$

$$\hat{Y} = \theta_{YK} \hat{K}_Y + \theta_{YC} \hat{C}_Y \tag{3}$$

where θ_{ji} is the factor share of income for input j in the production of good i [e.g. $\theta_{XK} \equiv (p_K K_X)/(p_X X)$]. Then $\theta_{XK} + \theta_{XC} = 1$ and $\theta_{YK} + \theta_{YC} = 1$.

Perfect competition and constant returns to scale imply zero profits, so $p_X X = p_K K_X + \tau_X C_X$ and $p_Y Y = p_K K_Y + \tau_Y C_Y$. Totally differentiate these equations and use the firm's profit maximizing first-order conditions:

$$\hat{p}_X + \hat{X} = \theta_{XK}\left(\hat{p}_K + \hat{K}_X\right) + \theta_{XC}\left(\hat{\tau}_X + \hat{C}_X\right) \tag{4}$$

$$\hat{p}_Y + \hat{Y} = \theta_{YK}\left(\hat{p}_K + \hat{K}_Y\right) + \theta_{YC}\left(\hat{\tau}_Y + \hat{C}_Y\right) \tag{5}$$

Each production function has only two inputs, so factor intensity responds to a change in relative input prices according to each elasticity of substitution, σ_X and σ_Y. We define these elasticities to be positive. Differentiating their definitions yields:

$$\hat{C}_X - \hat{K}_X = \sigma_X\left(\hat{p}_K - \hat{\tau}_X\right) \tag{6}$$

$$\hat{C}_Y - \hat{K}_Y = \sigma_Y\left(\hat{p}_K - \hat{\tau}_Y\right). \tag{7}$$

Finally, under the assumption that pollution is separable in utility, we use the single parameter σ_U to define the elasticity of substitution in utility between X and Y. Differentiating the definition of σ_U yields:

$$\hat{X} - \hat{Y} = \sigma_U\left(\hat{P}_Y - \hat{P}_X\right). \tag{8}$$

Suppose β is the share of income spent on Y, and η_{YY} is the usual own-price elasticity of demand (with no change in other prices). Then one can easily show $\eta_{YY} = -[\beta + \sigma_U(1-\beta)]$. In other words, a small σ_U can represent the trade-off between Y, a good like electricity with inelastic demand, and all other goods X.

Equations (1) – (8) are the log-linear system for general equilibrium effects of a small change in policy. We define capital as numeraire ($\hat{p}_K = 0$), which leaves the eight numbered equations above with eight unknowns (changes in X, Y, their two prices, and the four input quantities). We assume $\hat{\tau}_X = 0$, where $\hat{\tau}_Y$ is a small positive exogenous change in tax. Sector X experiences no change in relative input prices $\left(\hat{\tau}_X = \hat{p}_K = 0\right)$, so equation (6) simplifies to $\hat{C}_X = \hat{K}_X$. Note, we do not assume Liontief production in X. Those firms have a positive σ_X, but they *choose* not to alter input ratios because they face no relative input price changes. In addition, unchanged input prices means no change in the breakeven output price, so $\hat{p}_X = 0$ [from equations (2) and (4)].

Next, observe from (3) and (5) that $\hat{p}_Y = \theta_{YC}\hat{\tau}_Y > 0$. This additional carbon tax always raises the price of Y relative to the price of X. Further algebra reveals:

$$\hat{Y} = -(\sigma_U + \sigma_Y)\left(\frac{\theta_{YC}}{2}\right)\hat{\tau}_Y \tag{9}$$

Since all parameters in this equation are positive, the negative sign out front means that the increase in τ_Y unambiguously reduces output – to an extent that depends on substitution elasticities and the carbon share of production. Algebra also yields:

$$\hat{C}_Y = \left[\underbrace{-(\sigma_U + \sigma_Y)\left(\frac{\theta_{YC}}{2}\right)}_{\text{Output Effect}} - \underbrace{\theta_{YK}\sigma_Y}_{\text{Substitution Effect}}\right]\hat{\tau}_Y \tag{10}$$

The second term inside the large brackets is the "substitution effect", since the tax changes relative input prices and induces substitution through the elasticity σ_Y. Firms reduce carbon per unit of output. Then the first term is just $\hat{Y}$, from (9). It represents an "output effect", since the tax raises output price and reduces demand, so firms further reduce both inputs. The tax on carbon reduces carbon emissions through both of these channels, and so (10) shows that $\hat{C}_Y$ is unambiguously negative.[5]

The two effects operate in different directions in the other sector, however:

$$\hat{C}_X = \left[(\sigma_U - \sigma_Y)\left(\frac{\theta_{YC}}{2}\right)\right]\hat{\tau}_Y = \left[\underbrace{\frac{\sigma_U\theta_{YC}}{2}}_{\text{TTE}} - \underbrace{\frac{\sigma_Y\theta_{YC}}{2}}_{\text{ARE}}\right]\hat{\tau}_Y \tag{11}$$

The first effect in (11) is a terms-of-trade effect (TTE), because the higher price of Y induces consumer substitution into X (to an extent that depends on σ_U). Alone, it would raise production of X and therefore raise C_X (positive leakage). The other term in (11) is what we call the abatement resource effect (ARE). It depends on σ_Y, because the firms in Y substitute from carbon into capital for abatement, and thus bid capital away from X. Since $\hat{\tau}_X = \hat{p}_K = 0$, those firms choose not to substitute and instead reduce both K_X and C_X. This term yields negative leakage.

[5] In more general models, the tax might actually raise emissions [e.g. Fullerton and Heutel (2007)].

Clearly, from (11), the relative size of these offsetting effects depends on the relative size of σ_U and σ_Y. If consumers can substitute easily between goods, then the terms-of-trade effect dominates, and leakage is positive. This effect would be large for the case with international trade in close substitutes. Using the Armington (1969) assumption, for example, then σ_U would be large, and leakage is positive. Even in that case, however, researchers might overstate leakage if they do not allow for any negative effect on leakage through home substitution into abatement capital (the ARE effect).

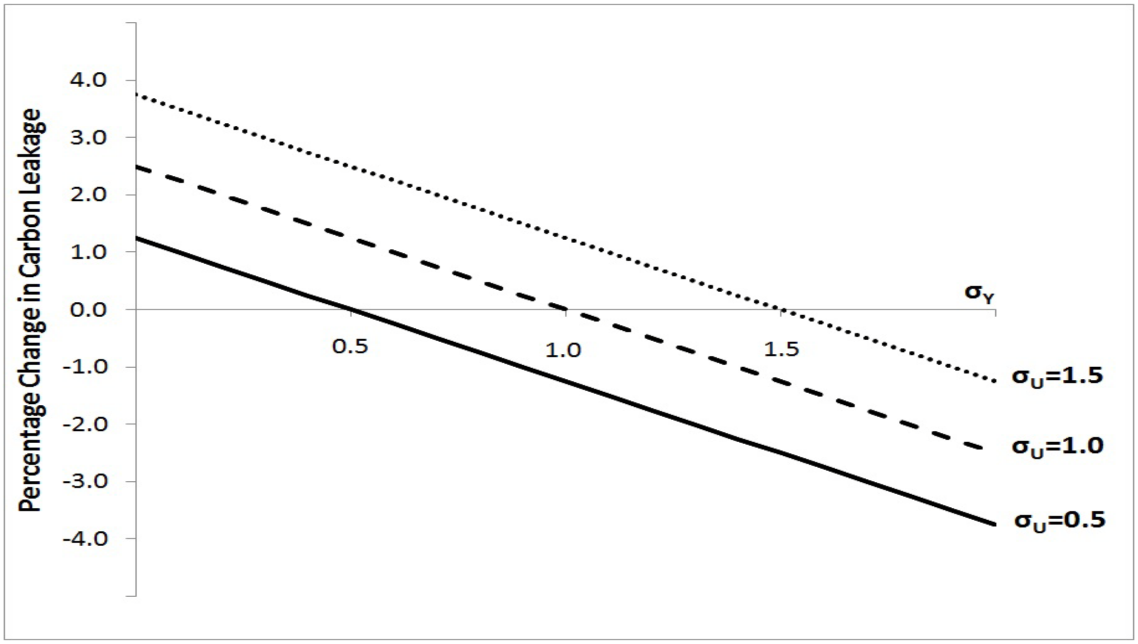
In other cases such as the pricing of carbon permits in the electricity sector, demand is inelastic, and so σ_U is small. If technology allows for abatement per unit of output, then σ_Y may exceed σ_U, and overall leakage is negative. In this case, models that ignore the ARE would find the wrong sign for overall leakage. The net effect of unilateral pollution regulation could be overall pollution reduction beyond what is achieved within the regulating sector, region, or country.

3. Numerical Magnitudes

To see the size of these effects, we assign values to parameters and calculate the leakage response to a ten percent increase in tax $\left(\hat{\tau}_Y = 0.1\right)$. To calculate $\hat{C}_X$ in equation (11), however, we need only three parameters. First, we set the initial carbon intensity $\left(\theta_{YC} = 0.5\right)$. Then in figure 1, we show carbon leakage on the vertical axis as a function of the elasticity of substitution in production $\left(\sigma_Y\right)$. The top dotted line in the figure is for σ_U =1.5, where leakage declines from +4.0% to –1.5% as σ_Y varies from zero to 2.0 on the horizontal axis. Thus negative leakage is possible, even with high σ_U, but it is more likely with lower σ_U. The middle dashed line is for σ_U =1.0, and the bottom solid line is for σ_U =0.5, where leakage declines from +1.0% to –4.0% as σ_Y varies from zero to 2.0 on the horizontal axis.

Perhaps the overall point is clear from equation (11), but figure 1 conveys size and makes it visual: negative leakage is possible, and it is made more possible by high values of σ_Y (where substitution into abatement technology is easier) or low values of σ_U (where consumers buy nearly as much of the taxed sector's output).

Figure 1 – Carbon Leakage as a Function of σ_Y and σ_U [θ_{YC}=0.5, $\hat{\tau}_Y$ =0.1]



4. Discussion

This analysis raises several questions, which we now address. First, we find that leakage $\hat{C}_X$ is negative when output declines ($\hat{X}$ <0), but how is that consistent with a decline in the relative price of X? Recall that $\hat{p}_Y$ >0, while $\hat{p}_X$ =0. Does demand for X have the wrong slope? No, we can calculate the usual own-price elasticity of demand for X with no change in other prices, $\eta_{XX} = -[(1-\beta) + \sigma_U\beta]$, which is clearly negative. A fall in p_X alone would raise X, partly because it would increase real income. In contrast, the increase in p_Y reduces real income and therefore tends to decrease world demand for both goods. In fact, the cross-price elasticity of demand for X with respect to a change in p_Y is $\eta_{XY} = \beta(\sigma_U-1)$, which can have either sign.

Second, however, consumers receive back all of the tax revenue, so how can this *compensated* increase in p_Y/p_X reduce X? Recall that consumers earn $I = p_K\overline{K} + R$, where $R = \tau_Y C_Y + \tau_X C_X$. The answer is that the rebate of revenue is never enough to reach the same indifference curve. An increase in the distorting tax τ_Y always reduces the utility from consumption (even if it provides benefits from a better environment). In fact, distortions from an input tax are the reason for a Laffer Curve, where revenue is a hump-shaped function of the tax rate. Initial increases in τ_Y may raise positive revenue, but successive increases yield zero and then negative revenue.

Third, and finally, we wonder if our negative leakage result is related to this insight about the Laffer curve. Is the sign of $\hat{C}_X$ related to the sign of $\hat{R}$? As it turns out, the set of parameters for which leakage is negative is not a subset of the parameters for which the effect on revenue is negative, nor the other way around.

Since the capital stock and its price are fixed, the only change to income is the change in the rebate of revenue. We totally differentiate that expression for *R* and find:

$$\hat{R} = \left\{ \sigma_U \left(\delta_X - \delta_Y\right)\left(\frac{\theta_{YC}}{2}\right) - \sigma_Y \left(\delta_Y \theta_{YK} + \frac{\theta_{YC}}{2}\right) + \delta_Y \right\} \hat{\tau}_Y \qquad (12)$$

where $\delta_X \equiv \tau_X C_X / R$, $\delta_Y \equiv \tau_Y C_Y / R$, and $\delta_X + \delta_Y = 1$.

To see how the change in revenue and leakage each depend on substitution parameters, figure 2 plots σ_Y on the horizontal axis and σ_U on the vertical axis. First note that $\hat{C}_X$ in equation (11) has a term ($\sigma_U - \sigma_Y$) times $\hat{\tau}_Y$, so leakage is zero whenever $\sigma_U = \sigma_Y$ (on the 45 degree dashed line in figure 2). Leakage is positive to the upper-left of that line (with higher σ_U) and negative to the lower-right (with higher σ_Y).

To find areas for positive or negative changes in revenue in figure 2, we set $\hat{R} = 0$ in equation (12) and solve:

$$\sigma_U = -\frac{\delta_Y}{A} + \left(\frac{B}{A}\right)\sigma_Y \qquad (13)$$

where $A \equiv \left[\left(\delta_X - \delta_Y\right)\left(\frac{\theta_{YC}}{2}\right) \right]$ and $B \equiv \left[\delta_Y \theta_{YK} + \frac{\theta_{YC}}{2} \right] > 0$. The iso-revenue line in figure 2 has slope *B*/*A*, with sign that depends on $\delta_X - \delta_Y$. If the tax in sector *Y* is already raising more than half of carbon tax revenue ($\delta_Y > \delta_X$), then this slope is negative. Figure 2 depicts the case where $\delta_Y = 0.75$, with a dotted iso-revenue line. To the lower-left of this line where both σ elasticities are small, the increase in τ_Y raises positive revenue; to the upper right of this line, the larger responsiveness means that an increase in τ_Y reduces the tax base by enough that revenue falls. If $\delta_Y = \delta_X$, then the line is vertical, and if $\delta_Y < \delta_X$ the slope is positive.[6] In any case, the figure clearly shows four different areas: the signs of ($\hat{C}_X$, $\hat{R}$) can be (+,+), (+,-), (-,+), or (-,-).

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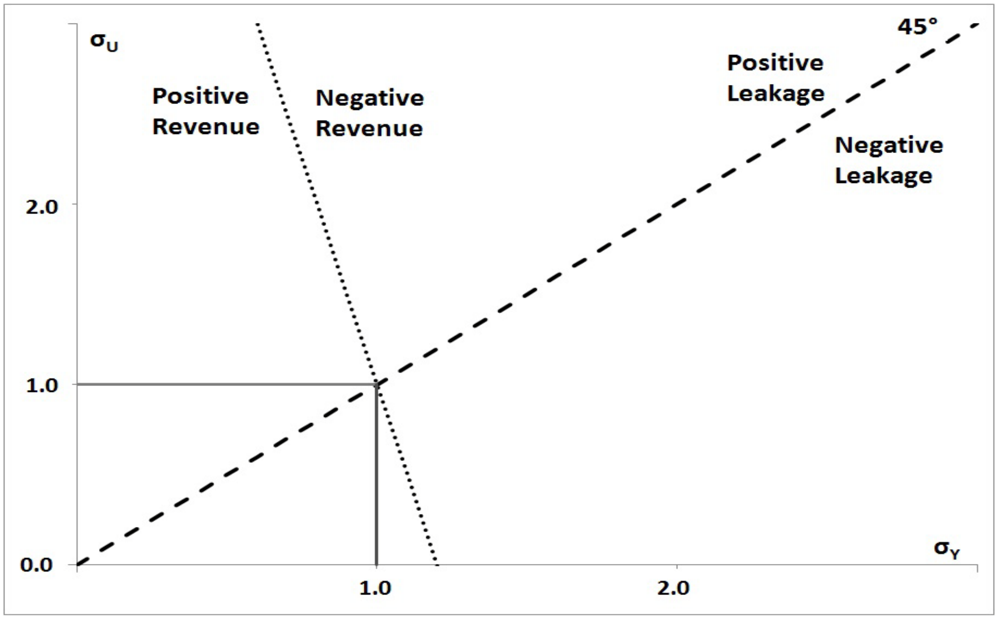
[6] The iso-leakage and iso-revenue lines always intersect where σ_U and σ_Y both equal one.

Figure 2 – The Carbon Tax in Sector Y Provides Most Revenue (δ_Y=0.75, θ_{YC} =0.5)



So far, leakage is not related very closely to revenue. But suppose the initial τ_Y is zero, so that no tax revenue comes from sector Y ($\delta_Y = 0$, and $\delta_X = 1$). Then equation (13) shows that the iso-revenue line has no intercept and a slope of one. In this case, it is coincident with the iso-leakage line. In other words, an initial increase in τ_Y from zero necessarily has both negative leakage and negative net revenue whenever $\sigma_Y > \sigma_U$. The initial increase in τ_Y induces sector Y to substitute into abatement capital, which draws capital away from sector X. The output of X shrinks, along with both of its inputs. Less C_X means negative leakage, and it also means less revenue from $\tau_X C_X$.

The point of our paper is not that leakage must be negative. Various extensions might reduce the size of our negative leakage effect. Rather, we show that in some cases leakage might be negative. More importantly, policymakers and economists who ignore the abatement resource effect might be overstating the size of carbon leakage.

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