# Optimal regulation of carbon and co-pollutants with spatially differentiated damages

**Christine L. Crago**
Department of Resource Economics
University of Massachusetts, Amherst
ccrago@resecon.umass.edu

**John K. Stranlund**
Department of Resource Economics
University of Massachusetts, Amherst
stranlund@resecon.umass.edu

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# Optimal regulation of carbon and co-pollutants with spatially differentiated damages

Christine L. Crago & John K. Stranlund

**Correspondence to:** Christine L. Crago, Department of Resource Economics, 217C Stockbridge Hall, 80 Campus Center Way, University of Massachusetts-Amherst, Amherst, MA 01003, USA. Phone: (413) 545-5738, E-mail: ccrago@resecon.umass.edu.

**Abstract:** In this paper we investigate the optimal taxation of CO2 and its co-pollutants. While CO2 is a uniformly mixed stock pollutant, important CO2 co-pollutants like SO2, PM2.5 and PM10 are flow pollutants with spatially differentiated damages. Recent proposals have called for CO2 control that accounts for its effects on emissions of its co-pollutants, which implies that optimal CO2 taxes would have a spatial component. However we demonstrate that setting a CO2 tax that varies from its marginal damage is justified only if co-pollutants are regulated inefficiently. We demonstrate that the optimal CO2 tax deviates from the CO2 marginal damage across sources depending on the source-specific co-pollutant marginal damage, the level of inefficiency in the co-pollutant regulation, and the abatement cost interaction of the two pollutants. An alternative to adjusting CO2 policy to account for the inefficient regulation of a co-pollutant is to address the inefficiency directly by modifying the regulation of the co-pollutant. Since this approach is more efficient in general, we quantify the expected reduction in social costs from this regulation relative to adjusting CO2 taxes. With a simulation of CO2 and SO2 control from the U.S. power sector, we find that setting efficient taxes for both CO2 and SO2 provides a welfare gain that is likely to be many orders of magnitude greater than the gain from adjusting CO2 taxes to account for the inefficient regulation of SO2.

**Keywords: mutiple pollutants, co-pollutants, carbon tax, SO2 tax**

**JEL Codes**: H23, Q53, Q58

# 1 Introduction

Among the many policy challenges associated with controlling greenhouse gases is how to account for the co-benefits or adverse side effects of climate policies. For example, important flow pollutants like sulfur dioxide (SO2), nitrous dioxide (NO2), and fine and coarse particulate matter (PM2.5 and PM10) are emitted jointly with CO2 in combustion processes. Thus, reduction in CO2 emissions could also reduce the emissions of co-pollutants. The problem of regulating carbon while accounting for the co-benefits or adverse side effects of regulation is prominent in the recent Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2014).

The co-benefits of CO2 mitigation can be substantial. Nemet, Holloway, and Meier (2010) surveyed empirical studies of CO2 co-benefits and found a mean value of $49 (2008 dollars) per ton of CO2 reduction. Similarly, Parry et al. (2014) calculated the average co-benefits for the top 20 CO2 emitting countries to be about $57.5 for 2010 (in 2010 dollars). These values are close to estimates of the social cost of carbon used by the US Interagency Working Group on the Social Cost of Carbon (IWG 2013). Using a 3% discount rate, their central estimate of the social cost of carbon is $38 (2007 dollars) per ton CO2 in 2015 rising to $71 per ton in 2050.

The existence of CO2 co-pollutants suggests that efficient regulation of CO2 and its co-pollutants call for joint determination of optimal policies for these pollutants. However, pollutants tend to be regulated separately and for a host of reasons policies are likely to be inefficient. Complicating matters is the fact that while CO2 is a uniformly mixed pollutant, marginal damages from its co-pollutants are usually differentiated by source and space. For example, Muller and Mendelsohn (2009) find that marginal damage for PM2.5 in the United States varies from $250 to $41,770 per ton per year for the 1st and 99th percentile of pollution sources. The distinction between uniformly mixed and non-uniformly mixed pollutants is critical. Conceptually, uniformly mixed pollutants can be controlled with a single price that achieves the cost-effective distribution of emission among sources, but a single pollution price cannot be efficient for pollutants that are not uniformly mixed. While the literature on CO2 co-pollutant benefits is large, very little of it addresses the spatial component of the CO2 co-pollutants.

The existence of CO2 co-pollutants with spatially differentiated damages has led some to propose a more stringent CO2 regulation that accounts for reductions in co-pollutant emissions and that varies across sources and space to account for the heterogeneity of co-pollutant damages. For example, Muller (2012) and Boyce and Pastor (2013) emphasize the efficiency gains from non-uniform carbon pricing. Boyce and Pastor (2013) also highlight how such an approach can promote environmental justice. (Also see Kaswan 2012). In contrast, Schatzki and Stavins (2009) argue that environmental justice concerns involving co-pollutants should be addressed separately from policies designed to address climate change.

In this paper we seek to clarify some of the issues related to the question of whether climate policy should be modified to account for the spatially heterogeneous effects of its co-pollutants or whether these effects should be confronted directly by adjusting the regulation of the co-pollutants. Conceptually, we construct a static model of taxation of CO2 and a co-pollutant whose damages are differentiated by source. We focus on emissions taxes because "getting the prices right" can be a powerful guide to environmental policymaking. Besides, given the abatement cost uncertainty inherent in the policy problem, emissions taxes are likely to be the efficient policy choice (Weitzman 1974; Nordhaus 2007; Stranlund and Son 2015). The two pollutants interact in abatement so changes in the emissions of one of the pollutants changes the marginal abatement costs of controlling the other.

We first demonstrate that the efficient CO2 tax in a period is unaffected by the existence of a co-pollutant if the co-pollutant is also regulated efficiently. Thus, the only reason to adjust CO2 taxes to account for co-pollutants is if they are regulated inefficiently. This insight is not new. It is prominent in the IPCC's discussion of the co-benefits and adverse consequences of climate policy (IPCC 2014, especially Chapter 3), and in specific studies of the value of CO2 co-pollutant benefits (e.g. Burtraw et al. 2003; Parry et al. 2014). However, the notion that the benefits of CO2 co-pollutant reductions should be net of reductions attained by existing regulations is not universally applied (e.g. Bollen et al. 2009; Muller 2012; Nemet, Holloway, and Meier 2010).

Given inefficient taxation of a co-pollutant, we then demonstrate how the optimal CO2 tax varies from its marginal damage across pollution sources according to the variation in co-pollutant marginal damages, existing regulation on the co-pollutant, and variation in the abatement interaction of the two pollutants. The alternative to adjusting climate policy to account for the inefficient regulation of a co-pollutant is to modify the regulation of the co-pollutant instead. This approach is more efficient in general, but regulatory constraints may prevent the joint determination of efficient taxes for CO2 and its co-pollutants. In these cases, it is important to understand the trade-offs posed by these constraints so we quantify the expected reduction in social costs from fully efficient taxes relative to adjusting CO2 taxes instead. Although much of the analysis focuses on the efficiency consequences of alternative approaches to accounting for CO2 co-pollutants, we are also able to address environmental justice concerns by quantifying how co-pollutant damages change spatially with alternative policies.

To illustrate the magnitudes of welfare differences in accounting for co-pollutant damages by adjusting the CO2 tax or by modifying co-pollutant taxes, we perform a simulation exercise using CO2 and SO2 emissions from nearly 3,000 power plants in the US. We calculate emissions, damages and social welfare associated with different ways of regulating CO2 and SO2 emissions. We find adjusting the CO2 tax to account for SO2 co-benefits is likely to yield small welfare gains relative to a policy that taxes CO2 according to its marginal damage and ignores SO2 co-benefits. However, the welfare gains from setting efficient taxes for both CO2 and SO2 are several orders of magnitude larger. Thus, dealing with the inefficient regulation of SO2 through modification of CO2 regulation instead of implementing efficient taxes is likely to be very costly. The substantial welfare gain from setting efficient taxes is due to a large reduction in SO2 emissions and damages, especially for high marginal damage sources. Therefore, setting efficient SO2 taxes in this setting is likely to promote environmental justice more effectively than modifying CO2 taxes to account for SO2 co-benefits.

The rest of the paper proceeds as follows. In the next section we lay out a simple model of regulating interacting pollutants with taxes and examine the alternative methods for accounting for CO2 co-pollutant damages. In section 3 we present results of a policy simulation applying different forms of taxation to regulate CO2 and SO2 emissions in the US electricity generating sector. We conclude in Section 4.

# 2 Regulating CO2 and a co-pollutant

The model of this paper is of the regulation of heterogeneous firms under asymmetric information about their abatement costs. While CO2 has multiple co-pollutants our main insights are drawn from a model of only one co-pollutant. In addition, the model is a static model. It is straightforward to extend the analysis to a dynamic setting with multiple co-pollutants. Throughout, emissions of CO2 and its co-pollutant are controlled with taxes, which is useful to help guide our intuition about how climate policy may incorporate its co-pollutants.

## 2.1 Expected social costs with multiple pollutants

Assume that an industry of $n$ firms emit two kinds of pollutants. A firm $i$ emits $q_{ij}$ units of the $j^{th}$ pollutant $(j = 1, 2)$. Like several other papers in the literature on regulating multiple interacting pollutants (Ambec and Coria 2013; Woodward 2011; Montero 2001), we assume that a firm has a quadratic joint abatement cost function:

$$C_i\left(q_{i1}, q_{i2}, u\right) = c_{i0} - \left(c_{i1} + u\right)\left(q_{i1} + q_{i2}\right) + \frac{c_{i2}}{2}\left(q_{i1}^2 + q_{i2}^2\right) - w_i q_{i1} q_{i2}, \tag{1}$$

with $c_{i0} > 0$, $c_{i1} > 0$, and $c_{i2} > 0$. The abatement cost function is strictly convex in $(q_{i1}, q_{i2})$, which requires $c_{i2} > 0$ and $c_{i2}^2 - w_i^2 > 0$. Random shocks that affect the abatement costs of all firms are captured by changes in $u$, which is a random variable with a known probability density function and zero expectation. We assume $c_{i1} + u > 0$ so that the intercepts of firms' marginal abatement cost functions are strictly positive. Throughout, pollutant 1 is CO2 while pollutant 2 is its co-pollutant.

The interaction of the two pollutants in abatement costs is captured by the term $w_i$ whose sign determines whether the abatement of CO2 and its co-pollutant are substitutes or complements. If the pollutants are complements then $w_i$ is positive, indicating that the marginal cost of abating the co-pollutant, i.e., $-C_{i2} = c_{i1} + u - c_{i2}q_{i2} + w_i q_{i1}$, falls with reductions in the emissions of CO2. Of course, this works in the other direction as well. That is, reducing emissions of the co-pollutant reduces the marginal cost of abating CO2. On the other hand, if the two pollutants are substitutes, then reducing emissions of one of them increases the marginal cost of abating the other. The extent to which CO2 induces changes in emissions of the co-pollutant is determined by production and abatement technologies, which determines the parameters of the abatement cost function.[1]

Let the tax on $i$'s emissions of pollutant 1 be $t_{i1}$ and the tax on emissions of pollutant 2 be $t_{i2}$. The vector of firm-specific CO2 taxes is $\mathbf{t_1} = (t_{11}, ..., t_{n1})$ and the vector of co-pollutant

[1]Some authors incorporate co-benefits in the benefit function of CO2 control, and ignore the interaction of multiple pollutants in abatement costs. This is explicit in Nemet, Holloway, and Meier (2010) and Muller (2012), and implicit in Boyce and Pastor (2013). This approach assumes that abatement cost functions of CO2 and its co-pollutants are independent of each other. However, if pollutants come from the same source their marginal abatement costs are likely to be jointly determined, so that regulation of one pollutant affects the marginal abatement cost of its co-pollutant. Conceptually, this is how the regulation of CO2 affects the choice of emissions of its co-pollutants: firms change their emissions of the co-pollutants because the regulation of CO2 changes the marginal abatement costs of these pollutants. This cannot happen if abatement costs of multiple pollutants are independent of each other.

taxes is $\mathbf{t_2} = (t_{12}, ..., t_{n2})$. Defining $C_{ij} = \partial C_i / \partial q_{ij}$, $j = 1, 2$, firm $i$ chooses emissions so that:

$$\begin{aligned} C_{i1}(q_{i1}, q_{i2}, u) + t_{i1} &= -(c_{i1} + u) + c_{i2} q_{i1} - w_i q_{i2} + t_{i1} = 0; \\ C_{i2}(q_{i1}, q_{i2}, u) + t_{i2} &= -(c_{i1} + u) + c_{i2} q_{i2} - w_i q_{i1} + t_{i2} = 0. \end{aligned} \tag{2}$$

The solutions for these first order conditions are:

$$q_{i1}(t_{i1}, t_{i2}, u) = \frac{(c_{i1} + u)(c_{i2} + w_i) - c_{i2} t_{i1} - w_i t_{i2}}{c_{i2}^2 - w_i^2}; \tag{3}$$

$$q_{i2}(t_{i1}, t_{i2}, u) = \frac{(c_{i1} + u)(c_{i2} + w_i) - c_{i2} t_{i2} - w_i t_{i1}}{c_{i2}^2 - w_i^2}. \tag{4}$$

Note that $\partial q_{ij} / \partial t_{ij} = -c_2^i / \left(c_{i2}^2 - w_i^2\right) < 0$ and $\partial q_{ij} / \partial t_{ik} = -w_i / \left(c_{i2}^2 - w_i^2\right)$, for $j \neq k$. The own-price effect is always negative but the cross-price effect depends on the sign of $w_i$. If $w_i > 0$, then an increase in the price of emissions of one pollutant leads the firm to reduce emissions of both pollutants. Thus, if $w_i > 0$ then the two pollutants are complements in abatement. If $w_i < 0$, then an increase in the price of one pollutant leads the firm to reduce its emissions of that pollutant, but to increase emissions of the other pollutant. In this case, the two pollutants are substitutes in abatement.

CO2 is a uniformly mixed stock pollutant with aggregate emissions in a period $Q_1 = \sum_{i=1}^{n} q_{i1}$. Largely because climate change impacts are due to the accumulation of carbon in the atmosphere since the industrial revolution, the marginal damage of CO2 in a compliance period is essentially flat (Pizer 2002). Denote that marginal damage from CO2 in a compliance period as the constant $d_1$. Pollutant 2 is a spatially differentiated flow pollutant like SO2 and PM2.5. Muller and Mendelsohn (2009) found that source-specific marginal damages of these pollutants are effectively constant, because emissions from one source cause only small changes in pollutant concentrations at each receptor point. Accordingly we assume that the marginal damage of pollutant 2 associated with a source is flat and let $d_{i2}$ be the constant marginal damage of $i$'s emissions of pollutant 2.[2] The total damage from the industry's emissions in a period is:

$$d_1 \sum_{i=1}^{n} q_{i1} + \sum_{i=1}^{n} d_{i2} q_{i2}.$$

Of course, there is immense uncertainty about the marginal damage from CO2 and other pollutants and we have ignored this uncertainty in our specification of damages. It is well known that the optimal policies are unaffected by uncertainty in damages as long as that uncertainty is uncorrelated with uncertainty in abatement costs. Making that assumption in this case allows us to simply treat the marginal damage parameters as expected marginal damages. This is a common approach in the literature on emissions control under uncertainty.[3]

[2]For a single pollutant the combination of a flat marginal damage and asymmetric information about firms' abatement costs suggests that an emissions tax is the optimal policy choice. Stranlund and Son (2015) demonstrate that this is also true in a multi-pollutant setting.

[3]We have also assumed that there is no interaction in the damages caused by multiple pollutants. We are not aware of any work that suggests such an interaction.

Pulling all the components of the model together gives us expected social costs associated with CO2 and co-pollutant taxes:

$$S(\mathbf{t_1}, \mathbf{t_2}) = E\left[d_1 \sum_{i=1}^{n} q_{i1} + \sum_{i=1}^{n} d_{i2} q_{i2} + \sum_{i=1}^{n} C_i(q_{i1}, q_{i2}, u)\right] \quad (5)$$
$$\text{subject to } q_{ij} = q_{ij}(t_{i1}, t_{i2}, u),\ i = 1, ..., n,\ j = 1, 2.$$

## 2.2 Optimal CO2 taxes

Restricting ourselves to strictly positive tax rates throughout, in the appendix we show that the taxes that minimize (5) are:

$$\hat{t}_{i1} = \hat{t}_1 = d_1,\ \hat{t}_{i2} = d_{i2},\ i = 1, ..., n, \quad (6)$$

and expected social costs are $S(\hat{\mathbf{t}}_1, \hat{\mathbf{t}}_2) = S(\hat{t}_1, \hat{t}_{12}, ..., \hat{t}_{n2})$. Hence, the tax on CO2 should be equal to its marginal damage for every firm. Since marginal damage is constant for all firms, the tax does not vary across sources. In contrast, the optimal tax on pollutant 2 is equal to the constant marginal damage of emissions of the pollutant, which does vary across sources. The important finding here is that the optimal tax on CO2 is constant across sources, even considering its co-pollutants with spatially mixed damages, as long as those co-pollutants are also regulated efficiently. Therefore, if the optimal CO2 tax is to deviate from its marginal damage, and perhaps vary by sources, it must be because its co-pollutants are not regulated efficiently. We will investigate this situation shortly.

While the optimal CO2 price does not vary across sources if the co-pollutants are also regulated efficiently, abatement of CO2 varies with its effect on emissions of the co-pollutant. To see this, substitute (6) into (3) and (4) and take the expectations to calculate optimal expected emissions:

$$\hat{q}_{i1} = \frac{c_{i1}(c_{i2} + w_i) - c_{i2} d_1 - w_i d_{i2}}{c_{i2}^2 - w_i^2}; \quad (7)$$

$$\hat{q}_{i2} = \frac{c_{i1}(c_{i2} + w_i) - c_{i2} d_{i2} - w_i d_1}{c_{i2}^2 - w_i^2}. \quad (8)$$

(These quantities would also be the optimal standards for the firm under that kind of quantity regulation). Both $\hat{q}_{i1}$ and $\hat{q}_{i2}$ decrease as $d_1$ or $d_{i2}$ increase if the pollutants are complements in abatement. They move in opposite directions if they are substitutes. The intuition for these effects lies in how marginal abatement costs for the pollutants change as variation in marginal damages for co-pollutants change emissions. For example, suppose that the two pollutants are complements. An increase in the marginal damage of the co-pollutant $d_{i2}$ calls for a higher tax on the pollutant which results in lower expected emissions. Lower emissions of the co-pollutant reduces the marginal abatement cost function for CO2, which, given the fixed CO2 tax, results in lower expected CO2 emissions. On the other hand if the pollutants are substitutes, then an increase in $d_{i2}$ ultimately leads to higher marginal abatement costs and higher expected emissions for CO2.

Now suppose that pollutant 2 is regulated with source-specific taxes that may not be efficient. Let these taxes be $\mathbf{\bar{t}_2} = (\bar{t}_{12}, ..., \bar{t}_{n2})$. To characterize the optimal pricing of pollutant 1, given these taxes on pollutant 2, we choose $\mathbf{t_1} = (t_{11}, ..., t_{n1})$ to minimize:

$$S(\mathbf{t_1}, \mathbf{\bar{t}_2}) = E\left[d_1 \sum_{i=1}^{n} q_{i1} + \sum_{i=1}^{n} d_{i2} q_{i2} + \sum_{i=1}^{n} C_i(q_{i1}, q_{i2}, u)\right] \quad (9)$$
$$\text{subject to } q_{ij} = q_{ij}(t_{i1}, \bar{t}_{i2}, u),\ i = 1, ..., n,\ j = 1, 2..$$

The solution to this problem is a set of taxes for pollutant 1, $\mathbf{t_1^*}(\mathbf{\bar{t}_2}) = (t_{11}^*(\bar{t}_{12}), ..., t_{n1}^*(\bar{t}_{n2}))$, expected social costs, $S(\mathbf{t_1^*}(\mathbf{\bar{t}_2}), \mathbf{\bar{t}_2})$, and expected emissions of the two pollutants, $E(q_{ij}(t_{i1}^*(\bar{t}_{i2}), \bar{t}_{i2}, u))$, $i = 1, ..., n$, $j = 1, 2$. In the appendix we show that the optimal CO2 taxes are:

$$t_{i1}^*(\bar{t}_{i2}) = d_1 - (\bar{t}_{i2} - d_{i2}) \left(\frac{\partial q_{i2}/\partial t_{i1}}{\partial q_{i1}/\partial t_{i1}}\right) = d_1 - (\bar{t}_{i2} - d_{i2}) \left(\frac{w_i}{c_{i2}}\right),\ i = 1, ..., n, \quad (10)$$

while expected emissions are:

$$E(q_{i1}(t_{i1}^*(\bar{t}_{i2}), \bar{t}_{i2}, u)) = \hat{q}_{i1},\ i = 1, ..., n; \quad (11)$$

$$E(q_{i2}(t_{i1}^*(\bar{t}_{i2}), \bar{t}_{i2}, u)) = \hat{q}_{i2} + \frac{(d_{i2} - \bar{t}_{i2})}{c_{i2}}\ i = 1, ..., n. \quad (12)$$

The CO2 taxes in (10) are optimal, given taxes on the co-pollutant that for some reason cannot be adjusted. Except when the co-pollutant is regulated efficiently, these taxes will deviate from the marginal damage of CO2 and the deviation will vary across firms. The direction and size of this deviation for a specific firm depends on the deviation of the tax on the firm's co-pollutant from its marginal damage and how the marginal change in a firm's emissions of CO2 induced by the CO2 tax changes the firm's emissions of the co-pollutant. Therefore, the qualitative direction of the correction for the inefficient regulation of the co-pollutant depends on whether the pollutant is over- or under-regulated and whether the pollutants are complements or substitutes in abatement. For example, the optimal CO2 tax on a firm is higher than the marginal damage of CO2 if its co-pollutant is under-regulated (over-regulated) and the pollutants are complements (substitutes). However, the CO2 tax is lower than its marginal damage if its co-pollutant is over-regulated (under-regulated) and the pollutants are complements (substitutes).

It is important to emphasize that if CO2 taxes are to account for their effects on co-pollutants with spatially heterogeneous damages, it must be because the co-pollutants are not and cannot be regulated efficiently, not simply because reductions of CO2 produce co-benefits which are spatially differentiated. The variation of the optimal CO2 taxes from its marginal damage and its spatial component comes from the spatial variation of the marginal damage of the co-pollutant, *net of its existing regulation*, and variation in the abatement interaction of the two pollutants.[4]

[4] As noted in footnote 1, some authors incorporate co-benefits in the benefit function of CO2 control, and ignore the interaction of multiple pollutants in abatement costs (Nemet, Holloway, and Meier 2010; Boyce and Pastor 2013; Muller 2012). This approach does not recognize that potential adjustments to CO2 control to account for co-pollutants should be determined by the co-benefits of CO2 control, net of existing co-benefit

Interestingly, (11) reveals that the adjustment of the optimal CO2 tax to account for the inefficient pricing of its co-pollutant is done so that the firm's optimal expected CO2 emissions are constant at the optimal level $\hat{q}_{i1}$. Intuitively, the firm's response to the regulation of the co-pollutant shifts the marginal abatement cost for CO2 up or down depending on whether the co-pollutant is over- or under-regulated and whether the two pollutants are substitutes or complements. The shifting of the marginal abatement cost for CO2 causes the correct tax on CO2 to adjust to hold expected emissions of CO2 at the optimal level. In contrast, (12) shows that a firm's expected emissions of the co-pollutant deviates from its optimal value as the tax on the pollutant deviates from its marginal damage. For example, if the tax on the co-pollutant is too low ($\bar{t}_{i2} < d_{i2}$) then expected emissions will be too high.

Figure 1 illustrates the effect of inefficient regulation of the co-pollutant on the optimal CO2 tax. In this graph, $E(-\widehat{C}_{ij})$ is the firm's expected marginal abatement cost function for pollutant $j$, given that expected emissions of the other pollutant equals its optimal value. That is, $E(-\widehat{C}_{i1})$ is the marginal abatement cost function for pollutant 1 given that expected emissions of pollutant 2 is equal to $\widehat{q}_{i2}$ and $E(-\widehat{C}_{i2})$ is the marginal abatement cost function for pollutant 2 given that emissions of CO2 is equal to $\widehat{q}_{i1}$. Assume that the two pollutants are complements and that the tax on the co-pollutant is too low. Because $\bar{t}_{i2}$ is lower than the efficient tax, expected emissions of the co-pollutant are too high. To conserve notation, in the graph we denote expected emissions of pollutant 2, given $\bar{t}_{i2}$ and $t^*_{i1}(\bar{t}_{i2})$, as $E(q^*_{i1}(\bar{t}_{i2}))$. Since the pollutants are complements, this higher level of expected emissions for the co-pollutant shifts the expected marginal abatement cost for CO2 up to $E(-\overline{C}_{i1})$. Consequently, the optimal tax on CO2 for the firm must be higher than marginal damage to hold expected emissions to $\widehat{q}_{i1}$. If the two pollutants were substitutes instead, then $E(-\overline{C}_{i1})$ would be below $E(-\widehat{C}_{i1})$ and the optimal tax would be below marginal damage.

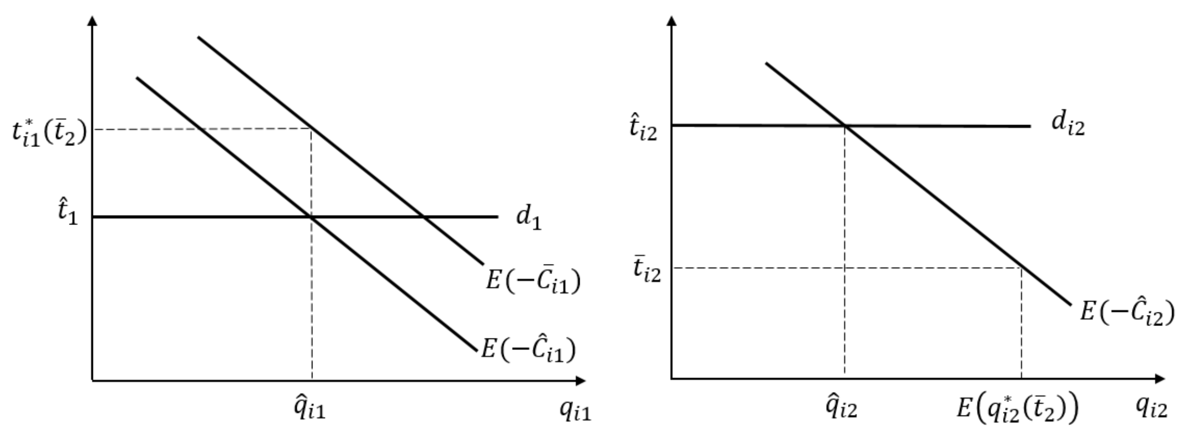


Figure 1: Effect of inefficient co-pollutant tax on optimal CO2 tax, given that the pollutants are complements.

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regulations. Using Muller's model, optimal CO2 taxes would be $\widetilde{t}_{i1} = d_1 + \theta_{i12}$, $i = 1, ..., n$, where $\theta_{i12}$ is the constant marginal effect of the firm's CO2 emissions on damage caused by emissions of the co-pollutant. Relative to the optimal CO2 taxes in (10), $\widetilde{t}_{i1}$ will tend to be too high (too low) if the two pollutants are complements (substitutes).

## 2.3 Policy comparisons

This paper is motivated by the problem of whether and how to incorporate spatially differentiated co-benefits in CO2 mitigation policy. The efficient policy (6) is to set all taxes equal to their marginal damages, with expected social costs $S(\hat{t}_1, \hat{\mathbf{t}}_\mathbf{2})$, and expected emissions (7) and (8). This policy promotes dealing with the inefficient regulation of the co-pollutant by setting its optimal tax rates (along with the optimal tax rate for CO2) rather than adjusting the CO2 tax rates. However, this might not be feasible, so the alternative is to adjust CO2 taxes, given the tax rates on the co-pollutant; that is $(\mathbf{t}_\mathbf{1}^*(\bar{\mathbf{t}}_\mathbf{2}), \bar{\mathbf{t}}_\mathbf{2})$. Expected social costs are $S(\mathbf{t}_\mathbf{1}^*(\bar{\mathbf{t}}_\mathbf{2}), \bar{\mathbf{t}}_\mathbf{2})$, the correct CO2 taxes are in (10), and expected firm-level emissions are (11) and (12). Because this policy is inefficient it leads to higher expected social costs in the amount:

$$S(\mathbf{t}_\mathbf{1}^*(\bar{\mathbf{t}}_\mathbf{2}), \bar{\mathbf{t}}_\mathbf{2}) - S(\hat{t}_1, \hat{\mathbf{t}}_\mathbf{2}) = \sum_{i=1}^{n} \left[ \frac{\left(\bar{t}_{i2} - d_{i2}\right)^2}{2c_{i2}} \right] > 0. \tag{13}$$

From (11) and (12), the differences in firm-level expected emissions are:

$$\begin{aligned} \hat{q}_{i1} - E(q_{i1}(t_{i1}^*(\bar{t}_{i2}), \bar{t}_{i2}, u)) &= 0; \\ \hat{q}_{i2} - E(q_{i2}(t_{i1}^*(\bar{t}_{i2}), \bar{t}_{i2}, u)) &= -\frac{(d_{i2} - \bar{t}_{i2})}{c_{i2}}. \end{aligned}$$

From these values we can determine the differences in aggregate expected damages of the two policies. Let $D_j$ denote expected damages for the period for pollutant $j$. Using the differences in firm-level expected emissions and the marginal damage parameters gives us the differences in aggregate expected damages:

$$D_1(\mathbf{t}_\mathbf{1}^*(\bar{\mathbf{t}}_\mathbf{2}), \bar{\mathbf{t}}_\mathbf{2}) - D_1(\hat{t}_1, \hat{\mathbf{t}}_\mathbf{2}) = 0;$$

$$D_2(\mathbf{t}_\mathbf{1}^*(\bar{\mathbf{t}}_\mathbf{2}), \bar{\mathbf{t}}_\mathbf{2}) - D_2(\hat{t}_1, \hat{\mathbf{t}}_\mathbf{2}) = \sum_{i=1}^{n} \left( \frac{d_{12}(d_{i2} - \bar{t}_{i2})}{c_{i2}} \right).$$

While the policies produce the same expected CO2 emissions and damage for a period, expected damages from emissions of the co-pollutant will vary according to the distribution of marginal damages, the distribution of marginal damages net of existing taxes, and the distribution of the slopes of firms' marginal abatement costs. If the co-pollutant tends to be under-regulated, then moving toward efficient regulation of the co-pollutant rather than adjusting CO2 policy not only reduces expected social costs, but also reduces damage from the co-pollutant, and hence, may promote environmental justice goals.

Of course, the much more common recommendation is to set the CO2 tax equal to its marginal damage and ignore the effect of the CO2 policy on emissions of the co-pollutant. The expected social cost of this policy is $S(\hat{t}_1, \bar{\mathbf{t}}_\mathbf{2})$. This policy is less efficient than $(\mathbf{t}_\mathbf{1}^*(\bar{\mathbf{t}}_\mathbf{2}), \bar{\mathbf{t}}_\mathbf{2})$, so it has higher expected social costs by the amount:

$$S(\hat{t}_1, \bar{\mathbf{t}}_\mathbf{2}) - S(\mathbf{t}_\mathbf{1}^*(\bar{\mathbf{t}}_\mathbf{2}), \bar{\mathbf{t}}_\mathbf{2}) = \sum_{i=1}^{n} \left[ \frac{\left(w_i(\bar{t}_{i2} - d_{i2})\right)^2}{2c_{i2}\left(c_{i2}^2 - w_i^2\right)} \right] > 0. \tag{14}$$

Using the tax rates and (3) and (4), it is straightforward to show that the differences in firm-level expected emissions are:

$$E(q_{i1}(\hat{t}_1, \bar{t}_{i2}, u)) - E(q_{i1}(t^*_{i1}(\bar{t}_{i2}), \bar{t}_{i2}, u)) = \frac{w_i(d_{i2} - \bar{t}_{i2})}{c_{i2}^2 - w_i^2};$$
$$E(q_{i2}(\hat{t}_1, \bar{t}_{i2}, u)) - E(q_{i2}(t^*_{i1}(\bar{t}_{i2}), \bar{t}_{i2}, u)) = \frac{w_i^2(d_{i2} - \bar{t}_{i2})}{c_{i2}\,(c_{i2}^2 - w_i^2)},$$

and the differences in aggregate expected damages are:

$$D_1(\hat{t}_1, \bar{\mathbf{t}}_\mathbf{2}) - D_1(\mathbf{t}^*_\mathbf{1}(\bar{\mathbf{t}}_\mathbf{2}), \bar{\mathbf{t}}_\mathbf{2}) = \sum_{i=1}^{n} \left( \frac{d_1 w_i(d_{i2} - \bar{t}_{i2})}{c_{i2}^2 - w_i^2} \right);$$

$$D_2(\hat{t}_1, \bar{\mathbf{t}}_\mathbf{2}) - D_2(\mathbf{t}^*_\mathbf{1}(\bar{\mathbf{t}}_\mathbf{2}), \bar{\mathbf{t}}_\mathbf{2}) = \sum_{i=1}^{n} \left( \frac{d_{12} w_i^2(d_{i2} - \bar{t}_{i2})}{c_{i2}\,(c_{i2}^2 - w_i^2)} \right).$$

In terms of expected social costs, the policy $(\mathbf{t}^*_\mathbf{1}(\bar{\mathbf{t}}_\mathbf{2}), \bar{\mathbf{t}}_\mathbf{2})$ is an intermediate step between the policies $(\hat{t}_1, \bar{\mathbf{t}}_\mathbf{2})$ and $(\hat{t}_1, \hat{\mathbf{t}}_\mathbf{2})$. The full welfare loss associated with $(\hat{t}_1, \bar{\mathbf{t}}_\mathbf{2})$ is

$$S(\hat{t}_1, \bar{\mathbf{t}}_\mathbf{2}) - S(\hat{t}_1, \hat{\mathbf{t}}_\mathbf{2}) = \sum_{i=1}^{n} \left[ \frac{c_{i2}\left(\bar{t}_{i2} - d_{i2}\right)^2}{2\,(c_{i2}^2 - w_i^2)} \right] > 0. \tag{15}$$

Substituting the tax rates into (3) and (4), taking the expectations, and subtracting (7) and (8) gives us the differences in firm-level expected emissions:

$$E(q_{i1}(\hat{t}_1, \bar{t}_{i2}, u)) - \hat{q}_{i1} = \frac{w_i(d_{i2} - \bar{t}_{i2})}{c_{i2}^2 - w_i^2}\ ,\ i = 1, ..., n;$$

$$E(q_{i2}(\hat{t}_1, \bar{t}_{i2}, u)) - \hat{q}_{i2} = \frac{c_{i2}(d_{i2} - \bar{t}_{i2})}{c_{i2}^2 - w_i^2}\ \ i = 1, ..., n,$$

and the differences in expected damages are:

$$D_1(\hat{t}_1, \bar{\mathbf{t}}_\mathbf{2}) - D_1(\hat{t}_1, \hat{\mathbf{t}}_\mathbf{2}) = \sum_{i=1}^{n} \left( \frac{d_1 w_i(d_{i2} - \bar{t}_{i2})}{c_{i2}^2 - w_i^2} \right);$$

$$D_2(\hat{t}_1, \bar{\mathbf{t}}_\mathbf{2}) - D_2(\hat{t}_1, \hat{\mathbf{t}}_\mathbf{2}) = \sum_{i=1}^{n} \left( \frac{d_{12} c_{i2}(d_{i2} - \bar{t}_{i2})}{c_{i2}^2 - w_i^2} \right).$$

# 3 Application to regulation of CO2 and SO2 emissions in the US electricity generation sector

To quantify the adjustment of the CO2 tax to account for co-pollutant co-benefits net of existing regulation and differences in welfare, emissions and damages from this approach relative to setting efficient taxes for both CO2 and a co-pollutant, we apply our conceptual model to the US electricity generation sector. We focus on the regulation of CO2 with SO2 as its co-pollutant. In contrast to CO2, SO2 is a flow pollutant whose marginal damage has been shown to vary depending on the location of emissions, including the height at which emissions are released (Muller and Mendelsohn 2009). SO2 has been subject to regulation through the SO2 permit trading program under the 1990 Clean Air Act Amendments. The regulation of SO2 allows us to explore adjustments to the CO2 tax that takes into account the effect of existing regulation on the CO2 co-pollutant.

## 3.1 Data and Parameterization

Three datasets are combined to obtain information on power plants' emissions and marginal damages of CO2 and SO2. The EPA's Emissions & Generation Resource Integrated Database (eGRID) contains data on almost all (5,587) power plants operating in the United States, along with environmental characteristics of these plants such as emissions of CO2, SO2, and other criteria pollutants (EPA 2014). These power plants are located in 1,740 unique state-county locations. We use Version 9 of the database which gives emissions for year 2010.

Marginal damages of SO2 at the point source level are obtained from estimates using the Air Pollution Emissions Experiments and Policy Analysis (APEEP) model developed by Muller and Mendelsohn (2007). The APEEP model reports marginal damages of different pollutants such as SO2, NOx, VOC, and fine particulate matter for ground and point sources at the level of the county. Marginal damages of point source emissions are further differentiated by release of emissions at different stack heights of less than 250 meters, 250 to 500 meters, and over 500 meters. Data from EPA's Form 860 Annual Electric Generator Report for 2010 are used to obtain information on the height of stacks at each powerplant. Stack heights are only reported for generators with over 100 MW of capacity. Since the number of tall stacks in the EIA Form 860 data (343) corresponds to the Government Accounting Office's estimate of the number of tall stacks in the United States, we assume that power plants that are not represented in the EIA Form 860 data have short stacks (GAO 2011).

Of the 5587 power plants in the eGRID data, 5422 have marginal damages reported in the APEEP dataset. Some plants do not have data on either CO2 emissions or SO2 emissions or both, and some plants are not operational. Our final dataset consists of 2953 operational plants for which we have data on emissions and marginal damages. Together these plants accounted for nearly all reported CO2 emissions in the power generation sector, which in turn accounted for 40% of the United States CO2 emissions in 2010 (EIA 2014).

Marginal damages of SO2 for individual power plants are used to obtain values for $d_{i2}$. For $d_1$, the marginal damage of CO2, we use a range of \$12 to \$55 with \$35 as the central value (in 2010 \$) based on the Interagency Working Group's estimate of the social cost of carbon in 2010 assuming different discount rates (IWG 2013). Table 1 shows the distribution of CO2 and SO2 emissions, as well as the source-specific marginal damage of SO2 for power plants in our sample.

To calculate changes in social welfare, damages, and emissions corresponding to changes in CO2 and SO2 regulation, we also need to assign values for the slope of the marginal abatement cost curve ($c_{i2}$) and as well as $w_i$, the parameter that indicates whether CO2 and SO2 are complements or substitutes in abatement. Since our cost function is specified as a joint abatement cost function, the $c_{i2}$ parameter is the slope of marginal costs for both CO2 and SO2. The literature does not provide much guidance on the values of $c_{i2}$ and

Table 1: Distribution of emissions and marginal damages at the plant level

| | Percentiles | | | | | Mean |
|---|---|---|---|---|---|---|
| | 1% | 25% | 50% | 75% | 99% | |
| $CO_2$ emissions (tons) | 5 | 767 | 26416 | 354711 | 13100000 | 831687 |
| $SO_2$ emissions (tons) | 0 | 0 | 1 | 71 | 33579 | 1784 |
| Ratio $SO_2$ to $CO_2$ | 0.0000 | 0.0000 | 0.0002 | 0.0015 | 0.0382 | 0.0027 |
| Marginal damage per ton $SO_2$ | 0 | 1471 | 2376 | 3598 | 54873 | 3894 |
| Marginal damage of $SO_2$ per ton $CO_2$ | 0 | 0 | 0 | 3 | 81 | 6 |

Note: The last column shows the mean. Marginal damages in 2010 \$.

$w_i$. Pizer (2002) reports that the slope of the carbon marginal cost curve for the entire US economy is \$5.4 per gigaton carbon. Karp and Zhang (2006) use a value of \$1.9 per gigaton carbon. These estimates are for economy-wide abatement costs whereas we are interested in the marginal abatement cost at the level of the firm. For SO2, Muller and Mendelsohn (2009) use a value of -0.25 and -0.5 for the percentage change in the (firm-level) marginal abatement cost with respect to a percentage change in quantity of emission. In our simulations we use a range of values between 0.1 and 10 based on values assumed by Muller (2012) for the firm-level slope of the marginal abatement cost curve for carbon. Equation (10) shows that $\frac{w_i}{c_{i2}} = \frac{\partial q_{i2}/\partial t_{i1}}{\partial q_{i1}/\partial t_{i1}}$. We use the ratio of SO2 and CO2 emissions for each power plant ($\phi_i$) as a measure of $\frac{\partial q_{i2}/\partial t_{i1}}{\partial q_{i1}/\partial t_{i1}}$. Thus $w_i$ is obtained my multiplying the ratio of SO2 and CO2 emissions by $c_{i2}$. Calculated values of $w_i$ are all positive indicating a complementary relationship between CO2 and SO2. Table 2 summarizes our assumptions.

Table 2: Parameter values and sources

| | Central | Min | Max | Source |
|---|---|---|---|---|
| $c_{i2}$ | 5 | 0.1 | 10 | Based on values used by Muller (2009). |
| $\phi_i$ | 0.002* | 0 | 0.2 | Calculated using data from eGRID (EPA, 2014). |
| $w_i$ [a] | 0.005* | 0 | 0.41 | Equal to the ratio of SO2 and CO2 emissions ($\phi_i$) multiplied by $c_{i2}$. |
| $d_1$ | 35 | 12 | 55 | 2010 \$ per ton CO2. Based on the Interagency Working Group (2013). |
| $d_{i2}$ | 3894* | 0 | 54873 | 2010 \$ per ton SO2. Calculated using data from APEEP and EIA Form 860 data (Muller and Mendelsohn 2007, EPA 2014). |

* Denotes mean.

[a] Assuming $c_{i2} = 5$.

## 3.2 Adjusted CO2 tax

We first present estimates of the adjusted CO2 tax. Table 3 shows the magnitude of adjusted CO2 taxes for different levels of the tax on SO2 assuming that the marginal damage of CO2 is \$35 per ton. Percentiles indicate the share of power plants facing the given levels of CO2 taxes. For example, 25% of power plants face CO2 taxes of \$35 or lower, while 75% of power plants face CO2 taxes between \$35.4 and \$37.7. The case where $\bar{t}_{i2} = 0$ represents the scenario where there is no regulation of SO2. It is also representative of the current SO2 market where the SO2 permit price is less than \$1 (EPA 2015). The case where $\bar{t}_{i2} = 200$ represents the period in the SO2 trading program from 2000-2002 during which SO2 prices were most stable at around \$200 (in 2010 \$) (EIA 2011). The mode of marginal damages of SO2 across power plants in the dataset is \$1600. Thus the case $\bar{t}_{i2} = 1600$ represents a scenario of uniform taxation of SO2 based on the most prevalent marginal damage estimate.

Table 3 shows that as SO2 regulation becomes more stringent (i.e. a higher tax on SO2), the mean adjustment in the CO2 tax is smaller. The mean CO2 tax is 10% lower when $\bar{t}_{i2} = 1600$ compared to $\bar{t}_{i2} = 0$. For the 1% most polluting plants (in terms of SO2 emissions), the adjusted CO2 tax is between \$57 to \$178 per ton for $\bar{t}_{i2} = 1600$ and \$100 to \$396 per ton for $\bar{t}_{i2} = 0$.

Without any tax on SO2, the CO2 tax is adjusted upward for all power plants, with 83% of power plants being taxed below the mean adjusted tax of \$39.7 per ton. With the SO2 tax at \$200 per ton the carbon tax is adjusted upward for approximately 97% of power plants with 84% taxed below the mean adjusted tax of \$39.1 per ton. With the SO2 tax at \$1600 per ton the carbon tax is adjusted upward for approximately 64% of power plants with 25% taxed below the mean adjusted tax of \$35.4 per ton. At this tax rate, 36% of plants are "over regulated" and are taxed at \$32.9 on average or 6.4% lower than the marginal damage of CO2.

The results show that for a majority of power plants, a policy that adjusts the CO2 tax to account for SO2 damages will see a modest increase in the CO2 tax. Across the different levels of SO2 tax considered, 75% of power plants are levied CO2 taxes that are at most 7% higher than the marginal damage of CO2, while plants at the 90th percentile face taxes that are around 32% higher. We now turn to a discussion of the characteristics of power plants that are above the 90th percentile of CO2 taxes, i.e. those plants that require a significant upward adjustment of the CO2 tax. Recall that the adjustment of the carbon tax depends on two factors, the difference between a plant's marginal damage of SO2 and the prevailing SO2 tax, and the quantity of SO2 emitted per unit of CO2. Across firms experiencing different levels of adjustment in the CO2 tax, the mean SO2 damage is fairly similar. However, firms that face higher adjusted CO2 taxes tend to have higher levels of SO2 emissions and greater ratios of SO2 emissions to CO2 emissions. For example, with $t_{21} = 0$, plants below the 90th percentile of adjusted CO2 taxes have mean emissions of SO2 at 1350 tons and a mean ratio of SO2 to CO2 emissions at 0.0008. On the other hand, plants at or above the 90th percentile of CO2 taxes have a mean of SO2 emissions that is 360% greater at 6196 tons and a mean ratio of SO2 and CO2 emissions that is 150% greater (0.02). Plants that face a higher level of adjusted CO2 taxes also appear to be smaller, with an average net generation of 752,876 MWh for plants in the 90th percentile, compared with over 1 million MWh for plants below the 90th percentile. Together, plants in the 90th percentile of CO2 taxes account for 7.5% of total generation, while plants in the 99th percentile account for 0.3% of total generation. The implication of this result is that it may be possible to reduce SO2 emissions (and damages associated with these emissions) significantly by focusing on a few power plants that have very high emission levels.

Table 3: Adjusted CO2 taxes

| | Percentiles | | | | | Mean |
|---|---|---|---|---|---|---|
| | 1st | 25th | 50th | 75th | 99th | |
| $\bar{t}_{i2} = 0$ | 35.0 | 35.0 | 35.4 | 37.7 | 100.3 | 39.8 |
| $\bar{t}_{i2} = 200$ | 35.0 | 35.0 | 35.3 | 37.4 | 94.6 | 39.3 |
| $\bar{t}_{i2} = 1600$ | 21.6 | 35.0 | 35.0 | 35.4 | 57.8 | 35.4 |

Assumptions: Marginal damage of CO2 equals \$35/ton, $c_{i2} = 2$.

### 3.3 Effect of regulation on welfare, emissions, and damages

Using results presented in subsection 2.3, we obtain estimates of changes in emissions, damages and welfare (Table 4). We will refer to the policy that taxes CO2 and SO2 according to their respective marginal damages as the Efficient policy. The policy that adjusts the CO2 tax to account for SO2 regulation and co-benefits will be referred to as the Tax Adjustment policy, and the policy that sets the CO2 tax equal to the marginal damage of CO2 without considering SO2 regulation and co-benefits will be called the No Tax Adjustment policy.

Table 4: Change in welfare, emissions, and damages

| | Δ Welfare ( million \$) | Δ CO2 emissions | Δ SO2 emissions | Δ CO2 damages ( million \$) | Δ SO2 damages ( million \$) | Δ Total damages ( million\$) |
|---|---|---|---|---|---|---|
| $\bar{t}_{i2} = 0$ | | | | | | |
| Tax Adjustment to Efficient | 11,600 | | -1,879,946 | 0.000 | -23,300 | -23,300 |
| No Tax Adjustment to Efficient | 11,600 | -2,859 | -1,880,057 | -0.100 | -23,300 | -23,300 |
| No Tax Adjustment to Tax Adjustment | 0.096 | -2,859 | -112 | -0.100 | -0.191 | -0.291 |
| $\bar{t}_{i2} = 200$ | | | | 0.000 | | |
| Tax Adjustment to Efficient | 11,300 | | -1,757,706 | 0.000 | -22,900 | -22,900 |
| No Tax Adjustment to Efficient | 11,300 | -2529.911 | -1,757,801 | -0.089 | -22,900 | -22,900 |
| No Tax Adjustment to Tax Adjustment | 0.075 | -2530 | -95 | -0.089 | -0.169 | -0.257 |
| $\bar{t}_{i2} = 1600$ | | | | | | |
| Tax Adjustment to Efficient | 9,410 | | -902,007 | 0.000 | -20,300 | -20,300 |
| No Tax Adjustment to Efficient | 9,410 | -223.5052 | -902,026 | -0.008 | -20,300 | -20,300 |
| No Tax Adjustment to Tax Adjustment | 0.021 | -224 | 19 | -0.008 | -0.013 | -0.020 |

Welfare and damages are in 2010 dollars. Assumption: $d_1 = 35$, $c_{it} = 5$.

#### 3.3.1 Welfare

Recall that a motivation for this study is to investigate the effects of different types of regulation for CO2 and SO2, and to determine whether the magnitude of welfare gains merit the adjustment of $CO_2$ to account for $SO_2$ co-benefits. We find that there is a large welfare gain associated with changing policy from either the No Tax Adjustment or Tax Adjustment to the Efficiency policy. Welfare also increases when policy shifts from No Tax Adjustment to Tax Adjustment, although the magnitudes of the welfare changes are at least five orders of magnitude smaller.

Assuming that the tax on SO2 is zero, the welfare change associated with moving from the No Tax Adjustment policy to the Efficient policy is in the range of 5.8 billion to 582 billion (in 2010 \$) corresponding to $c_{i2} = 10$ and $c_{i2} = 0.1$ respectively. Assuming that $c_{i2} = 5$, Table 4 shows that depending on the assumed tax on SO2 welfare gains from switching to the Efficient policy are in the range of 9.4 to 11.6 billion (in 2010 \$). These estimates can be compared with the findings of Muller and Mendelsohn (2009) who estimate welfare gains of about 7 to 8 billion dollars from decreasing the SO2 cap from 10.2 million tons of a level that equates marginal abatement cost with marginal damage of SO2 in the regulation of emissions from US power plants.

From the No Tax Adjustment policy to the Tax Adjustment policy, welfare gains are in the range of 47,000 to 4.7 million (in 2010 \$) corresponding to $c_{i2} = 10$ and $c_{i2} = 0.1$ respectively and $\bar{t}_{i2} = 0$. Comparing these estimates to the change in welfare from moving to the Efficiency policy, it is evident that the welfare gain from moving to a policy that addresses SO2 damages with efficient SO2 taxes is at least five orders of magnitude greater than switching to a policy that indirectly addresses SO2 damages through adjustments in the CO2 tax. Assuming that $c_{i2} = 5$, Table 4 shows that depending on the assumed tax on SO2, welfare gains of switching from the No Tax Adjustment policy to the Tax Adjustment policy leads to welfare gains in the range of 21,296 to 95,504 (in 2010 \$). These welfare changes can be compared with values reported by Muller (2012) who estimates the welfare gains of a differentiated CO2 policy under a framework that adjusts the marginal benefit of CO2 according to co-benefits from co-pollutant reduction. Muller (2012) finds that adjusting the CO2 tax for spatially heterogeneous co-pollutant damages (including those from NOX, PM2.5, and VOCs in addition to SO2) leads to a welfare gain of \$1.6-\$83.7 million per year, depending on the slope of the MAC curve of carbon. His estimates are considerably higher than our estimates likely because he includes other co-pollutants such as NOx, VOCs, PM2.5 and PM10.

A change in policy from Tax Adjustment to Efficient does not result in any change in CO2 emissions. Thus, the difference in welfare from emissions reduction in these two scenarios is entirely due to reduced SO2 damages. This gain from emissions reduction is partially offset by increased SO2 abatement costs leading to net welfare gains shown in Table 4. A change in policy from No Tax Adjustment to Tax Adjustment leads to a modest reduction in CO2 and SO2 emissions (and damages), although much of the gain from reduced damages is offset by increased abatement costs for both CO2 and SO2 leading to very small welfare gains.

In summary, while adjustments to the CO2 tax to account for SO2 benefits and regulation increase welfare and reduce emissions, especially in areas with high SO2 marginal damages, the net welfare effect is many orders of magnitude smaller compared to a policy that sets taxes for both pollutants equal to their marginal damage. If the choice to deal with inefficient SO2 regulation with CO2 taxes is due to regulatory constraints that prevent setting efficient SO2 taxes, our results suggest that these constraints are very costly. The limitation of CO2 policy to deal with SO2 damages is due to the fact the regulation has to be based on SO2 emissions and damages per unit of CO2. In power plants, the ratio of SO2 and CO2 emissions is very small, with a mean value of 0.002 in our data. Thus, unless the adjustment in the CO2 tax is extremely large (which may be unwarranted from a CO2 regulation standpoint), changes in the CO2 tax is unlikely to lead to large changes in SO2 emissions. In contrast, a policy that taxes SO2 directly will lead to large reductions in SO2 emissions and damages.

### 3.3.2 Emissions and damages

The adjustment of the CO2 tax to account for SO2 regulation and co-benefits works such that expected CO2 emissions are at the same levels as when both CO2 and SO2 are regulated efficiently. Thus, a change from the Tax Adjustment policy to the Efficient policy does not lead to a change in CO2 emissions. However, a change from the No Tax Adjustment policy to the Efficient policy or to the Tax Adjustment policy leads to a decrease in CO2 emissions as the CO2 tax increases to account for the under-regulation of SO2.[5] As the regulation of SO2 becomes more stringent, the increase in CO2 tax becomes smaller leading to smaller changes in CO2 emissions as the policy is changed from a No Tax Adjustment policy to a Tax Adjustment or Efficient policy.

In terms of SO2 emissions, moving from a policy that does not tax SO2 according to its marginal damage (either the No Tax Adjustment or Tax Adjustment policy) to the Efficient policy decreases SO2 emissions significantly. The initial quantity of SO2 is greater under the No Tax Adjustment policy due to higher CO2 taxes and fewer CO2 emissions compared to the Tax Adjustment policy. Thus, the reduction in SO2 emissions is slighty larger if No Tax Adjustment is the initial policy.

SO2 damages change according to the change in SO2 emissions. However, unlike CO2 emissions that have uniform marginal damage across sources, the damages of SO2 vary by source. Thus, it is of interest to examine the changes in SO2 damages by location. One argument for adjusting CO2 policy to account for SO2 damages is environmental justice considerations. Boyce and Pastor (2013) argue that the lower income and minority areas in the United States tend to suffer most harm from air pollutants. As expected, moving from a policy that makes no adjustment to the CO2 tax to an efficient policy that taxes CO2 and SO2 according to their marginal damages decreases SO2 emissions and damages. Assuming that the slope of firms' MAC curves are equal, the reduction in emissions and damages will be greater the larger the difference in the SO2 tax and marginal damage. [6] Thus, moving to the Efficient policy has the potential to address environmental justice concerns by reducing SO2 damages in areas that bear a disproportionate share of the burden of air pollution.

A change from the No Tax Adjustment policy to the Tax Adjustment policy (which holds SO2 regulation constant at an inefficient level) shifts firms' MAC curves of SO2 downward due

[5] Recall from the discussion above that SO2 is under-regulated for a majority of plants.

[6] Our simulations assume that the slope of firms' MAC curves ($c_{i2}$) are equal. If $c_{i2}$ is different for each firm, the change in SO2 emissions given a unit change in the tax will be different across firms. Consequently, it is not guaranteed that firms with the greatest difference in SO2 tax and marginal damage will also see the greatest reduction in SO2 damages given a policy change from No Tax Adjustment to Efficient. Rather, the change in damage for firm 1 compared to that of firm 2 will be greater if $\frac{(d_{12}-t_{12})}{c_{12}} > \frac{(d_{22}-t_{22})}{c_{22}}$ or $\frac{(d_{12}-t_{12})}{(d_{22}-t_{22})} > \frac{c_{12}}{c_{22}}$. That is, the ratio of the differences in marginal damages and taxes for firms 1 and 2 should be greater than the ratio of the slopes of MAC curves for the two firms.

to greater $CO_2$ abatement. This reduces $SO_2$ emissions (and damages) but the reduction is almost negligible compared to the reduction in emissions when moving to the Efficient policy. Because the adjustment in the $CO_2$ tax is based on the deviation of $SO_2$ regulation from its marginal damage, the reduction in $SO_2$ emissions and damages is also greater in areas where marginal damage of $SO_2$ emissions is larger. [7] Thus, compared to the No Tax Adjustment policy, a Tax Adjustment policy addresses environmental justice concerns although at a much smaller scale than what would be expected from the Efficient policy.

# 4 Conclusion

In this paper we have addressed the problem of whether climate policy should be modified to account for the spatially heterogeneous effects of $CO_2$ co-pollutants, or if these effects should be confronted directly by adjusting co-pollutant regulations. Efficient regulation of $CO_2$ and its flow co-pollutants in a period would involve a uniform $CO_2$ tax set equal to its marginal damage, and non-uniform taxes on the co-pollutants set equal to their space- and source-specific marginal damages. However, this may not be feasible given existing policy constraints or prohibitive administrative costs. Alternatively, $CO_2$ policy could be adjusted to account for its effect on co-pollutant emissions. This may or may not be a simpler approach than making co-pollutant regulation efficient. Regardless, it is important to know how the two approaches compare in specific settings to quantify the loss from failing to pursue efficient policies for $CO_2$ and its co-pollutants. For US power sector emissions of $CO_2$ and $SO_2$, our results suggest that designing a $CO_2$ tax to account for $SO_2$ effects is likely to provide a very small welfare gain, while setting efficient $SO_2$ taxes provides a gain that is at least five orders of magnitude larger. Thus, dealing with inefficient regulation of $SO_2$ via a $CO_2$ tax instead of taxing $SO_2$ efficiently is likely to be very costly. The welfare gain from setting efficient $SO_2$ taxes is due to a large reduction in $SO_2$ emissions and damages with no effect on $CO_2$ emissions. Thus, to the extent that high $SO_2$ marginal damages are associated with areas of low income and high concentration of minorities, setting efficient co-pollutant taxes is likely to promote environmental justice more effectively than modifying $CO_2$ taxes to account for co-pollutant co-benefits.

[7] This holds assuming $c_{i2}$ is constant for all firms. The condition given in the previous footnote for the case in which $c_{i2}$ is not constant also holds for a policy change from No Tax Adjustment to Tax Adjustment.

# 5 Appendix

## 5.1 Calculate (6), (7) and (8).

The optimal taxes are strictly positive so the following necessary conditions are also sufficient to minimize (5):

$$(d_1 + E(C_{i1}))(\partial q_{i1}/\partial t_{i1}) + (d_{i2} + E(C_{i2}))(\partial q_{i2}/\partial t_{i1}) = 0,\ i = 1, ..., n \tag{16}$$

$$(d_1 + E(C_{i1}))(\partial q_{i1}/\partial t_{i2}) + (d_{i2} + E(C_{i2}))(\partial q_{i2}/\partial t_{i2}) = 0,\ i = 1, ..., n \tag{17}$$

Using $C_{ij} + t_{ij} = 0$, $j = 1, 2$, from (2) and $\partial q_{ij}/\partial t_{ij} = -c_{i2}/\left(c_{i2}^2 - w_i^2\right) < 0$ and $\partial q_{ij}/\partial t_{ik} = -w_i/\left(c_{i2}^2 - w_i^2\right)$ for $j \neq k$ from (3) and (4), rewrite (16) and (17) as:

$$c_{i2}(d_1 - t_{i1}) + w_i(d_{i2} - t_{i2}) = 0,\ i = 1, ..., n; \tag{18}$$

$$w_i(d_1 - t_{i1}) + c_{i2}(d_{i2} - t_{i2}) = 0,\ i = 1, ..., n. \tag{19}$$

Write these in matrix form:

$$\begin{bmatrix} c_{i2} & w_i \\ w_i & c_{i2} \end{bmatrix} \begin{bmatrix} d_1 - t_{i1} \\ d_{i2} - t_{i2} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix},\ i = 1, ..., n,$$

and use Cramer's rule to show $d_1 - t_{i1} = d_{i2} - t_{i2} = 0$ for each $i$, which is the desired result. Substitute these taxes into (3) and (4) and take the expectations to obtain (7) and (8).

## 5.2 Calculate (10), (11). and (12).

The first-order conditions to minimize (9) are:

$$\begin{aligned} &(d_1 + E(C_{i1}))(\partial q_{i1}/\partial t_{i1}) + (d_{i2} + E(C_{i2}))(\partial q_{i2}/\partial t_{i1}) = 0,\ i = 1, ..., n \\ \Rightarrow &(d_1 - t_{i1})c_{i2} + (d_{i2} - \bar{t}_{i2})w_i = 0,\ i = 1, ..., n. \end{aligned}$$

Rearrange terms to obtain (10).

Now let's calculate expected emissions. Using (3) and (4), we have:

$$E(q_{i1}(t_{i1}^*(\bar{t}_{i2}), \bar{t}_{i2}, u)) = \frac{c_{i1}(c_{i2} + w_i) - c_{i2}t_{i1}^*(\bar{t}_{i2}) - w_i\bar{t}_{i2}}{c_{i2}^2 - w_i^2}; \tag{20}$$

$$E(q_{i2}(t_{i1}^*(\bar{t}_{i2}), \bar{t}_{i2}, u)) = \frac{c_{i1}(c_{i2} + w_i) - c_{i2}\bar{t}_{i2} - w_i t_{i1}^*(\bar{t}_{i2})}{c_{i2}^2 - w_i^2}. \tag{21}$$

With (7), (8), (20) and (21), calculate:

$$E(q_{i1}(t_{i1}^*(\bar{t}_{i2}), \bar{t}_{i2}, u)) - \hat{q}_{i1} = \frac{c_{i2}(d_1 - t_{i1}^*(\bar{t}_{i2})) + w_i(d_{i2} - \bar{t}_{i2})}{c_{i2}^2 - w_i^2}; \tag{22}$$

$$E(q_{i2}(t_{i1}^*(\bar{t}_{i2}), \bar{t}_{i2}, u)) - \hat{q}_{i2} = \frac{c_{i2}(d_{i2} - \bar{t}_{i2}) + w_i(d_1 - t_{i1}^*(\bar{t}_{i2}))}{c_{i2}^2 - w_i^2}. \tag{23}$$

From (10), $d_1 - t_{i1}^*(\bar{t}_{i2}) = -(d_{i2} - \bar{t}_{i2})(w_i/c_{i2})$, which upon substitution into (22) and (23) produces

$$E(q_{i1}(t_{i1}^*(\bar{t}_{i2}), \bar{t}_{i2}, u)) - \hat{q}_{i1} = \frac{1}{c_{i2}^2 - w_i^2}\left\{-c_{i2}(d_{i2} - \bar{t}_{i2})\left(\frac{w_i}{c_{i2}}\right) + w_i(d_{i2} - \bar{t}_{i2})\right\} = 0, \quad (24)$$

$$E(q_{i2}(t_{i1}^*(\bar{t}_{i2}), \bar{t}_{i2}, u)) - \hat{q}_{i2} = \frac{1}{c_{i2}^2 - w_i^2}\left\{c_{i2}(d_{i2} - \bar{t}_{i2}) - w_i(d_{i2} - \bar{t}_{i2})\left(\frac{w_i}{c_{i2}}\right)\right\} = \frac{(d_{i2} - \bar{t}_{i2})}{c_{i2}}, \quad (25)$$

which are (11) and (12).

## 5.3 Calculate welfare differences, (13), (14), and (15).

For an individual firm, the expected social cost of its emissions and emissions control, given tax rates $(t_{i1}, t_{i2})$, is

$$S_i(t_{i1}, t_{i2}) = E\left\{C_i\left(q_{i1}(t_{i1}, t_{i2}, u), q_{i2}(t_{i1}, t_{i2}, u), u\right) + d_1 q_{i1}(t_{i1}, t_{i2}, u) + d_{i2} q_{i2}(t_{i1}, t_{i2}, u)\right\},$$

where $C_i(\cdot)$ is the firm's abatement cost function from (1), and $q_{ij}(t_{i1}, \bar{t}_{i2}, u)$, $j = 1, 2$, are the firm's emissions responses to the taxes as defined in (3) and (4). It can be shown that

$$S_i(t_{i1}, t_{i2}) = K_i + \frac{c_{i2}(t_{i1}^2 + t_{i2}^2) - 2(c_{i2}d_1 + w_i d_{i2})t_{i1} - 2(c_{i2}d_{i2} + w_i d_1)t_{i2} + 2w_i t_{i1} t_{i2}}{2\left(c_{i2}^2 - w_i^2\right)}, \quad (26)$$

where $K_i$ is independent of the taxes.

It is convenient for us to calculate (14) and (15) and use the results to calculate (13). To begin, suppose that $t_{i2} = \bar{t}_{i2}$ and consider two values for $t_{i1}$, $t_{i1}^0$ and $t_{i1}^1$. Then

$$S_i(t_{i1}^0, \bar{t}_{i2}) = K_i + \frac{c_{i2}((t_{i1}^0)^2 + \bar{t}_{i2}^2) - 2(c_{i2}d_1 + w_i d_{i2})t_{i1}^0 - 2(c_{i2}d_{i2} + w_i d_1)\bar{t}_{i2} + 2w_i t_{i1}^0 \bar{t}_{i2}}{2\left(c_{i2}^2 - w_i^2\right)}$$

and

$$S_i(t_{i1}^1, \bar{t}_{i2}) = K_i + \frac{c_{i2}((t_{i1}^1)^2 + \bar{t}_{i2}^2) - 2(c_{i2}d_1 + w_i d_{i2})t_{i1}^1 - 2(c_{i2}d_{i2} + w_i d_1)\bar{t}_{i2} + 2w_i t_{i1}^1 \bar{t}_{i2}}{2\left(c_{i2}^2 - w_i^2\right)}.$$

Subtract these two values and collect terms to obtain

$$S_i(t_{i1}^0, \bar{t}_{i2}) - S_i(t_{i1}^1, \bar{t}_{i2}) = \frac{(t_{i1}^0 - t_{i1}^1)\left[c_{i2}\left(t_{i1}^0 + t_{i1}^1 - 2d_1\right) + 2w_i\left(\bar{t}_{i2} - d_{i2}\right)\right]}{2\left(c_{i2}^2 - w_i^2\right)}. \quad (27)$$

To calculate (14), substitute $t_{i1}^0 = \hat{t}_1 = d_1$ and $t_{i1}^1 = t_{i1}^*(\bar{t}_{i2}) = d_1 - (\bar{t}_{i2} - d_{i2})(w_i/c_{12})$ from (10) into (27) to obtain

$$S_i(\hat{t}_1, \bar{t}_{i2}) - S_i(t_{i1}^*(\bar{t}_{i2}), \bar{t}_{i2}) = \frac{\left[w_i\left(\bar{t}_{i2} - d_{i2}\right)\right]^2}{2c_{i2}\left(c_{i2}^2 - w_i^2\right)}. \quad (28)$$

Sum this over firms to obtain (14).

Now suppose that $t_{i1} = \bar{t}_{i1}$ and consider two values for $t_{i2}$, $t_{i2}^0$ and $t_{i2}^1$. Then

$$S_i(\bar{t}_{i1}, t_{i2}^0) = K_i + \frac{c_{i2}(\bar{t}_{i1}^2 + (t_{i2}^0)^2) - 2(c_{i2}d_1 + w_i d_{i2})\bar{t}_{i1} - 2(c_{i2}d_{i2} + w_i d_1)t_{i2}^0 + 2w_i\bar{t}_{i1}t_{i2}^0}{2\left(c_{i2}^2 - w_i^2\right)}$$

and

$$S_i(\bar{t}_{i1}, t_{i2}^1) = K_i + \frac{c_{i2}(\bar{t}_{i1}^2 + (t_{i2}^1)^2) - 2(c_{i2}d_1 + w_i d_{i2})\bar{t}_{i1} - 2(c_{i2}d_{i2} + w_i d_1)t_{i2}^1 + 2w_i\bar{t}_{i1}t_{i2}^1}{2\left(c_{i2}^2 - w_i^2\right)}.$$

Subtract these two values and collect terms to obtain

$$S_i(\bar{t}_{i1}, t_{i2}^0) - S_i(\bar{t}_{i1}, t_{i2}^1) = \frac{(t_{i2}^0 - t_{i2}^1)\left[c_{i2}\left(t_{i2}^0 + t_{i2}^1 - 2d_{i2}\right) + 2w_i\left(\bar{t}_{i1} - d_1\right)\right]}{2\left(c_{i2}^2 - w_i^2\right)}. \quad (29)$$

To calculate (15), substitute $\bar{t}_{i1} = \hat{t}_1 = d_1$, $t_{i2}^0 = \bar{t}_{i2}$, and $t_{i2}^1 = \hat{t}_{i2} = d_{i2}$ into (29) to obtain

$$S_i(\hat{t}_1, \bar{t}_{i2}) - S_i(\hat{t}_1, \hat{t}_{i2}) = \frac{c_{i2}\left(\bar{t}_{i2} - d_{i2}\right)^2}{2\left(c_{i2}^2 - w_i^2\right)}. \quad (30)$$

Sum this over firms to obtain (15).

Finally, to calculate (13), note first that

$$S_i(t_{i1}^*(\bar{t}_{i2}), \bar{t}_{i2}) - S_i(\hat{t}_1, \hat{t}_{i2}) = \left[S_i(t_{i1}^*(\bar{t}_{i2}), \bar{t}_{i2}) - S_i(\hat{t}_1, \bar{t}_{i2})\right] - \left[S_i(\hat{t}_1, \hat{t}_{i2}) - S_i(\hat{t}_1, \bar{t}_{i2})\right].$$

Substitute (28) and (30) into this to obtain

$$S_i(t_{i1}^*(\bar{t}_{i2}), \bar{t}_{i2}) - S_i(\hat{t}_1, \hat{t}_{i2}) = \frac{\left(\bar{t}_{i2} - d_{i2}\right)^2}{2c_{i2}}.$$

Sum this last over firms to obtain (13).

# References

Ambec, S., and J. Coria. 2013. "Prices vs quantities with multiple pollutants." *Journal of Environmental Economics and Management* 66(1):123–140.

Bollen, J., B. van der Zwaan, C. Brink, and H. Eerens. 2009. "Local air pollution and global climate change: A combined cost-benefit analysis." *Resource and Energy Economics* 31:161–181.

Boyce, J.K., and M. Pastor. 2013. "Clearing the air: incorporating air quality and environmental justice into climate policy." *Climatic change* 120:801–814.

Burtraw, D., A. Krupnick, K. Palmer, A. Paul, M. Toman, and C. Bloyd. 2003. "Ancillary benefits of reduced air pollution in the US from moderate greenhouse gas mitigation policies in the electricity sector." *Journal of Environmental Economics and Management* 45(3):650–673.

EIA. 2014. "US energy-related carbon dioxide emissions for selected sectors, 1900-2013."

—. 2011. "Weighted average price of spot sulfur dioxide for winning bids." Energy Information Administration.

EPA. 2015. "2015 Acid Rain SO2 Allowance Auction Results." Environmental Protection Agency.

—. 2014. "The Emissions and Generation Resource Integrated Database: Technical Support Document for the 9th Edition of eGRID with Year 2010 Data." Clean Air Markets Division, Environmental Protection Agency. Prepared by Abt Associates.

GAO. 2011. "Information on Tall Smokestacks and Their Contribution to Interstate Transport of Air Pollution." United States Government Accounting Office.

IPCC. 2014. "Climate Change 2014: Mitigation of Climate Change." Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlmer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)].Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IWG. 2013. "Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866."

Karp, L., and J. Zhang. 2006. "Regulation with anticipated learning about environmental damages." *Journal of Environmental Economics and Management* 51(3):259–279.

Kaswan, A. 2012. "Climate Change, the Clean Air Act, and Industrial Pollution." *UCLA Journal of Environmental Law & Policy* 30:51–120.

Montero, J.P. 2001. "Multipollutant markets." *RAND Journal of Economics*, pp. 762–774.

Muller, N.Z. 2012. "The design of optimal climate policy with air pollution co-benefits." *Resource and Energy Economics* 34:696–722.

Muller, N.Z., and R. Mendelsohn. 2009. "Efficient pollution regulation: getting the prices right." *The American Economic Review*, pp. 1714–1739.

Nemet, G., T. Holloway, and P. Meier. 2010. "Implications of incorporating air-quality co-benefits into climate change policymaking." *Environmental Research Letters* 5:014007.

Nordhaus, W.D. 2007. "To tax or not to tax: Alternative approaches to slowing global warming." *Review of Environmental Economics and policy* 1:26–44.

Parry, I.W., D. Heine, I.W. Parry, and C. Veung. 2014. "How Much Carbon Pricing is in Countries' Own Interests?" Working paper, International Monetary Fund WP/14/174 Washington, DC.

Pizer, W.A. 2002. "Combining price and quantity controls to mitigate global climate change." *Journal of Public Economics* 85:409–434.

Schatzki, T., and R. Stavins. 2009. "Addressing environmental justice concerns in the design of Californias climate policy." The Analysis Group.

Stranlund, J.K., and I. Son. 2015. "Prices versus quantities versus hybrids in the presence of co-pollutants." Working paper, Department of Resource Economics, Univeristy of Massachusetts Amherst.

Weitzman, M.L. 1974. "Prices vs. quantities." *The Review of Economic Studies* 41:477–491.

Woodward, R.T. 2011. "Double-dipping in environmental markets." *Journal of Environmental Economics and Management* 61(2):153–169.