

SPACE OR POWER: WHICH MATTERS MORE IN PERMIT MARKETS?

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Permit markets to control pollution have long been popular with economists. In recent years they have been embraced increasingly by policymakers as well. Conventional wisdom holds that a permit market must be competitive to be successful. In the case of the U.S. SO₂ allowance market, avoiding market power was deemed sufficiently important that the law created a single national market for allowances. Thus, any significant control over the spatial distribution of emissions was sacrificed. I argue that this prioritization was misguided. I develop a spatial framework that explicitly accounts for both costs and damages in a set of regions between which a single pollutant can travel. I show that the welfare losses due to spatial misallocation of emissions are likely to be much larger than any potential losses due to market power in the smaller regional markets. Moreover, I argue that a small number of traders is unlikely to be a problem, for two reasons. First, they will be on opposite sides of the permit market, so bilateral monopoly is more apt than the usual monopoly or monopsony analogy. Second, because they are large but few in number, such firms are likely to achieve a bargaining outcome that leads to the least-cost distribution of emissions.

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I. INTRODUCTION

The idea of using market forces to control pollution has been a favorite of economists for over 30 years, at least since Montgomery (1972) showed formally that the intuitive insight of Dales (1968) was correct. That is, for the single-receptor case a perfectly competitive market in the right to pollute can achieve a given level of environmental quality at least cost. In recent years the idea has moved from the academic journals to the world of actual policy. It has been put in practice on a large scale for the control of U.S. SO₂ emissions and is being debated seriously at the international level as a tool for reducing global emissions of greenhouse gasses.

The literature on permit trading is now large and continues to grow apace (Tietenberg, 2001). Much, perhaps most, of the work since Montgomery's landmark piece has dealt with factors that prevent a permit market from achieving the least-cost distribution of emissions. It appears to have become conventional wisdom, for example, that the presence of market power in a permit market is a leading barrier to its effective working. Hahn (1984) showed that if one firm has such power and faces a competitive fringe in the permit market, inefficiency is likely to result. In this case the initial allocation of permits becomes all-important, he argued, in determining how close the market comes to achieving the available cost savings.¹

This point, it should be emphasized, is more than just a theoretical curiosity. Indeed, early versions of the SO₂ allowance-trading title in the 1990 Clean Air Act Amendments called for allowance markets to be developed at the state level in Phase I. In this regime allowance allocations would have been determined by state, and trade across state lines would have been prohibited. An advantage of such a scheme is that it would have offered greater control over the geographic distribution of SO₂ loadings. The idea for state-level markets was discarded, however, evidently due to a concern that market power would have inhibited the

¹ Recent papers that explore the effects of market power include Bernstein *et al.* (1999), in an empirical piece, and Muller *et al.* (2002), who employ experimental methods. In both of these cases, market power is one-sided, with either a monopolist or a monopsonist facing a competitive set of buyers or sellers.

effectiveness of such small markets (Ellerman *et al.*, 2000). As it was passed, the bill created a single national allowance market and the potential for unacceptably high local SO₂ loadings may have been realized in some areas. As it turns out, the desire to foster competitive markets by including a large number of traders can be, and in the case of the SO₂ title is, in conflict with the desire to control the spatial distribution of emissions.

The problem of designing permit markets when the location of emissions matters has been studied at some length (*e.g.*, Montgomery, 1972, Atkinson and Tietenberg, 1982, and Nash and Revesz, 2001). There is a sizable literature concerning the performance of “zonal” permit systems in which trade between relatively small zones is prohibited or restricted (Roach *et al.*, 1981, Spofford, 1984, Atkinson and Tietenberg, 1982, Foster and Hahn, 1994). Tietenberg (1995, p.106) seems to capture the majority view: “However, while small zones allow more targeting, they also reduce trading opportunities. Would the restricted set of trading opportunities arising from a zonal permit system so undermine the zonal permit approach as to make its use inappropriate in this setting?” The present paper is aimed at showing that the answer to this question is ‘not in all cases’.

I make two related points. The first is that a small number of traders, in itself, may not keep a permit market from achieving all or most of the potential efficiency gains. I show that it is possible for an efficient solution to arise in the case in which all traders have market power. The second is that even where there is an asymmetry of market power among firms, the welfare losses due to permit market power are likely to be far less than the losses due to the spatial misallocation of abatement that occurs in a single large market.

The key to my first point, that a small number of market participants may not be a problem, is the recognition that a permit-trading scheme is not like the usual monopoly or monopsony (or oligopoly/oligopsony) situation. A small number of participants in a permit system must necessarily find themselves on opposite sides of the market, so that their strategic interaction becomes more akin to bilateral monopoly. It is in precisely the small-numbers case that participants are most likely to find a

way to bargain with each other, reaching a collective solution that closely or even exactly matches the cost-minimizing outcome. The closer analogy, I believe, is to Coase (1960), who underscored the requirements for an efficient bargaining solution to obtain in a small-numbers problem.² As in Coase, in my model potential difficulties with a market regime arise not because of small numbers or strategic behavior. Rather, problems stem from asymmetry in power between large firms and a fringe of small firms (a case that I examine) or from asymmetric information due to private information about costs (a case that I do not examine).³

I begin with a general model of a permit-trading scheme applied over multiple regions. A regulator who knows the cost functions for each firm in each region, as well as the function describing damages from pollution deposition in each region, could compute the optimal level of emissions from each region. She or he could then implement a permit scheme in any number of ways, including a series of regional markets that prohibits trade across regions or a single market that allows such trade. Of central importance in either case is the matrix of transfer coefficients that describes the way in which emissions from each region are transported to the other regions. I derive conditions on the underlying damage and abatement cost functions that must be met in order for the single market to achieve the globally optimal distribution of emissions. These conditions, it turns out, are extremely restrictive. The regional markets, on the other hand, appear to be more likely to approach the global optimum.

The degree to which the regional-markets policy can approximate the optimal outcome depends, of course, on the structure of the individual regional permit markets. To my regional model I add another layer, which accounts formally for the way in which I might expect a permit market with a small number of participants to perform. My emphasis is upon the potential for the participants to engage in a (Nash) bargaining game. This game yields, as a solution, a distribution of abatement across firms as well as a set of transfer payments between and among them. I show that at the

² The question of how small the number of firms must be in order for my argument to apply is, of course, not easily answered. See Buchanan (1967).

³ If the trading firms do not have good information about the abatement cost functions of potential trading partners, then my results no longer hold (Farrell, 1987). In reality, I believe that large electric utilities do have relatively good information about each other's costs.

resulting outcome, the cost of achieving the pollution standard within each region is minimized.

This model is then extended, in sequence, to cases in which: (1) the permits are sold or auctioned by the regulator rather than handed out *gratis*; and (2) some of the firms behave competitively and are not part of the bargaining game. In case (1), the optimality of the regional permit equilibrium is preserved. In case (2) the presence of a competitive fringe does inhibit the market's efficiency performance. This result illustrates that it is the presence of *asymmetric* market power (as in Hahn, 1984), rather than the presence of market power, that causes inefficiency. I highlight, though, the particular tradeoff that must be made between this concern and that of spatial misallocation of emissions.

The paper concludes with some numerical simulations of a hypothetical situation in which the effects of spatial considerations are compared to those of market power.⁴ This exercise suggests that, so long as a few market participants can bargain with something approximating complete information, the welfare losses due to creating a single market rather than smaller regional markets can be quite large. Even if each of the regional markets is composed of a single monopolist or monopsonist facing a competitive fringe of permit buyers or sellers (as in Hahn, 1984), so long as the regulator issues permits appropriately by region, the losses due to regional market power are likely to be small relative to the losses due to creating a single market.

II. THE MODEL

Suppose that a single pollutant affects a geographical area made up of J regions, indexed by $j = 1, \dots, J$, and that a regulator wishes to control pollution over the entire area. Movement of the pollutant between regions is described by a $J \times J$ matrix H of transfer coefficients, where h_{jk} represents the portion of emissions from region j that land in region k . There are I^j polluting firms in region j , indexed by $i = 1, \dots, I^j$.

⁴ The difficulty associated with measuring the benefits to abatement for each state or region in the country makes the challenge of specifying an empirical version of my numerical model truly daunting. The example that I create yields a number of insights that I feel are likely to hold in a more realistic setting.

Emissions from firms within a region are indistinguishable; this is not true for firms located in different regions. The abatement cost function for firm i in region j is $C_i^j(e_i^j)$, where e_i^j is the firm's emissions. Each firm's cost function is assumed to be twice differentiable. I follow Montgomery (1972) in that the abatement cost function captures the reduction in profits that result from holding emissions at the level e_i^j , relative to some uncontrolled initial level e_i^{j0} . Marginal abatement costs, $-C_i^{j'}$, are assumed to be strictly positive and increasing in e_i^j , which implies that $-C_i^{j''} > 0$ and $C_i^{j''} \geq 0$. I assume that each polluting firm is independent and seeks to maximize profits. I also assume that the firms are price takers in the markets for their inputs (apart from the emissions permits) and outputs.

Let $E = (e^1, \dots, e^J)$ denote the vector of aggregate emissions by region, with $e^j = \sum_i e_i^j$. I use the term "deposition" to describe the cumulative loadings experienced in region j when the vector of regional emissions levels is E . Deposition in region j , denoted ε^j , is the j th element of the vector

$$\varepsilon = EH.$$

Region j experiences damages as a function of its deposition, $D^j(\varepsilon^j)$. For each region, the damage function is assumed to be strictly increasing and convex in ε^j .

A welfare-maximizing regulator with full information about damage and cost functions would choose emissions for each firm in each region so as to minimize the sum of aggregate damages and costs. This planner would solve

$$\min_{e \in \mathbb{R}_+^K} \left\{ \sum_{j=1}^J D^j(\varepsilon^j) + \sum_{j=1}^J \sum_{i=1}^{I^j} C_i^j(e_i^j) \right\}, \quad (1)$$

where $K = \sum_j I^j$ represents the total number of firms. Let e^* denote the solution to problem (1). In order to abstract away from the nonessential possibility of corner solutions, I will assume in what follows that each firm's emissions are strictly positive and strictly less than e_i^{j0} at e^* , and

that no firms are forced to shut down. This problem is sufficiently well behaved to ensure that a solution exists.

An important insight can be gleaned from the first-order necessary conditions of problem (1). The derivative of the objective function with respect to e_i^j may be rearranged to yield

$$\sum_k \frac{\partial D^k(\boldsymbol{\varepsilon}^{k*})}{\partial e_i^j} = \sum_k \frac{dD^k(\boldsymbol{\varepsilon}^{k*})}{d\boldsymbol{\varepsilon}^k} h_{jk} = -\frac{dC_i^j(e_i^{j*})}{de_i^j} \text{ for all } i \text{ and } j. \quad (2)$$

We know, first, that the sum of marginal damages over all regions caused by emissions of a single firm must equal that firm's marginal abatement costs. Second, because emissions from all sources in a region are assumed to be equivalent, at an efficient solution marginal costs must be equalized across all firms in a region. Because the marginal damage caused by emissions from different regions differ, though, it will not in general be true that marginal costs are the same for firms in different regions.

The point of the following section is that in a single national market things turn out very differently. There, the discipline of the single market ensures that marginal costs are equalized across all firms in all regions. The problem with a national market is that the second sum in (2) is likely not to be equal for different regions. The single large market, while perhaps increasing the level of competitiveness, ignores the different levels of damages caused by emissions from different locations in space.

III. A NATIONAL PERMIT MARKET

The first policy to which I wish to compare e^* is a single permit market encompassing all firms in all regions. As in the U.S. SO₂ allowance market, in this scenario firms in different regions can trade permits with each other one for one. This is an essential feature of the problem and of my model, for it means that the regulator has little control over the spatial distribution of emissions in equilibrium. I assume that all of the firms behave competitively in the permit market. Each firm is given an endowment of permits in the quantity q_i^{j0} , where the total number of permits may be set according to the socially optimal solution. Let q_i^j

denote the number of permits held by firm i in region j after trading has taken place.

Let p denote the permit price. An equilibrium in the (single) permit market is defined as follows.

DEFINITION. The vector $(e^{**}, p^{**}) \in \mathfrak{R}_+^{K+1}$, an emissions level e_i^{j**} for each firm together with associated price p^{**} , is an equilibrium if

1. For each firm i in each region j ,

$$e_i^{j**} \text{ solves } \min_{e_i^j \in \mathfrak{R}_+} C_i^j(e_i^j) + p^{**}[e_i^j - q_i^{j0}]; \text{ and}$$
2. $p^{**}[\sum_j \sum_i [e_i^j - q_i^{j0}]] = 0$.

The following result establishes the restrictive condition that is necessary in order for the market equilibrium to achieve the socially optimal distribution of emissions.

PROPOSITION 1. Assume that $D^j(\varepsilon^j)$ is increasing and convex with respect to ε^j for all j and that $C_i^j(e_i^j)$ is convex for all i and j . Assume also that there are no corner solutions in either the social planner's or the single-market problems. Then, the single permit market leads to efficiency loss unless

$$\sum_{k=1}^J \frac{dD^k(\varepsilon^{k*})}{d\varepsilon^k} h_{jk} = \sum_{k=1}^J \frac{dD^k(\varepsilon^{k*})}{d\varepsilon^k} h_{mk} \text{ for all } j, m = 1, \dots, J,$$

where $\varepsilon^{k*} = \sum_j (\sum_i e_i^{j*}) h_{jk}$.

Proof: First, recall equation (2) from the social planner's problem:

$$\sum_k \frac{\partial D^k(\varepsilon^{k*})}{\partial e_i^j} = \sum_k \frac{dD^k(\varepsilon^{k*})}{d\varepsilon^k} h_{jk} = -\frac{dC_i^j(e_i^{j*})}{de_i^j} \text{ for all } i \text{ and } j. \quad (2)$$

From the single-market equilibrium conditions we know that

$$\frac{dC_i^j(e_i^{j**})}{de_i^j} = \frac{dC_s^m(e_s^{m**})}{de_s^m} \quad \text{for all } i, s (s=1, \dots, I^m) \quad \text{and for all } j, m. \quad (3)$$

But (2) and (3) together guarantee that the single-market equilibrium achieves the optimal distribution of emissions only if

$$\sum_{k=1}^J \frac{dD^k(\varepsilon^{k*})}{d\varepsilon^k} h_{jk} = \sum_{k=1}^J \frac{dD^k(\varepsilon^{k*})}{d\varepsilon^k} h_{mk} \quad \text{for all } j \quad \text{and } m.$$

This completes the proof. ■

In order for the single-market equilibrium to be optimal, then, two conditions must be satisfied: (1) the marginal abatement cost for firms within each region must be equal; and (2) this marginal cost must equal the sum of marginal damages caused in all regions. The equilibrium in a single market satisfies requirement (1). Indeed, it goes further and equalizes marginal costs for all firms in all regions. Thus, for a given level of total emissions, the single-market equilibrium minimizes aggregate abatement costs. It is unlikely, however, that a single-market equilibrium will satisfy requirement (2) in the case of a pollutant for which the location of emissions matters, such as SO₂. Because it fails to account for the fact that marginal damages are different across regions, for a spatially differentiated pollutant the cost-minimizing outcome is not optimal.

As we will see in the following section, a set of regional markets can achieve an optimal solution by differentiating among regions. What is more, I lay out an argument that even if the number of traders is small, which may be the case with regional markets, each of the markets is likely to yield the cost-minimizing distribution of emissions within the regions. This contrasts with what has been asserted in the literature since Hahn (1984).

IV. REGIONAL PERMIT MARKETS WITH MARKET POWER

Given the preceding result, it would seem worthwhile to examine afresh the properties of a permit market with a small number of large participants. In this section I develop my argument that a small number of firms does not necessarily impede the efficient performance of a permit market.

The key, as I have said, is that the firms with market power are on opposite sides of the market. They have little reason to leave gains from trade on the table. Rather, I argue, they have a powerful incentive to bargain to exploit gains from trade. There are a number of approaches to modeling a bargaining situation; I use the Nash bargaining model.

I focus first upon a single region, so that the development of section II applies, but with $J = 1$. A social planner would select a vector of emission levels $e = (e_1, \dots, e_I)$ to solve

$$\min_{e \in \mathbb{R}_+^I} \left\{ \sum_i C_i(e_i) : \sum_i e_i \leq Q^0 \right\}, \quad (4)$$

where Q^0 is the chosen level of aggregate emissions for the region, with $Q^0 < \sum_i e_i^0$. Denote by e^* the solution to problem (4)

If the regulator decides to implement a permit-trading scheme in order to reach the emissions target, there is a potential problem: the number of market participants is small. Though I do not define what is meant by “small,” I assume that the number of firms is sufficiently small that the firms (1) have the incentive to bargain with each other and (2) are able to do so. So long as the initial distribution of permits q^0 is not a cost-minimizing vector, the potential exists for the polluting firms to achieve a mutually beneficial bargaining agreement.

Let q_i denote the number of permits held by firm i after trading and let T_i denote the monetary transfer received by firm i as a result of the bargaining agreement, where $T_i < 0$ if firm i pays a transfer. The conditions on the cost functions, together with the assumption that $Q^0 < \sum_i e_i^0$, guarantee that $q_i = e_i$. It must be true that $\sum_i T_i = 0$. A

bargaining outcome, then, is a vector of permit allocations $\mathbf{q} \in \mathfrak{R}_+^I$ and a vector of transfer payments $\mathbf{T} \in \mathfrak{R}^I$. I say that the von Neumann-Morgenstern utility of firm i associated with the *agreement* (\mathbf{q}, \mathbf{T}) can be expressed as $u_i(q_i, T_i) = [-C_i(q_i) + T_i]$.⁵

I proceed by defining a Pareto-optimal outcome and showing that this outcome yields \mathbf{e}^* . I then show that the Nash bargaining solution is Pareto optimal and, hence, cost minimizing. A Pareto-optimal outcome, which is denoted $(\hat{\mathbf{q}}, \hat{\mathbf{T}}) \in \mathfrak{R}_+^I \times \mathfrak{R}^I$, solves the following problem:

$$\min_{(\mathbf{q}, \mathbf{T}) \in \mathfrak{R}_+^I \times \mathfrak{R}^I} \left\{ \sum_i [-C_i(q_i) + T_i] : \sum_i (q_i - q_i^0) \leq 0 \right\}. \quad (5)$$

Because $q_i = e_i$ and $\sum_i T_i = 0$ by assumption, a solution to problem (5) must be a solution to problem (4).

In an I -player fixed-threat bargaining game the I players must select a vector of payoffs $\mathbf{u} = (u_1, \dots, u_I)$ from a compact, convex set G of possible payoff vectors, called the *agreement space*. The game is fully specified by three components: the agreement space, the players' payoff functions, and the *threat point* or disagreement payoff, denoted \mathbf{d} , that describes payoffs in the event that bargaining fails. In my model the firms are the players, their payoff functions are given by $u_i(q_i, T_i)$ as defined above, and the agreement space is given by

$$G = \{ \mathbf{u} \in \mathfrak{R}^I : \sum_i (q_i - q_i^0) \leq 0, \sum_i T_i \leq 0, \text{ and } \mathbf{u} \geq \mathbf{d} \}.$$

I assume that the threat point for firm i is simply the firm's utility when no trade occurs: $d_i = -C_i(q_i^0)$.

Because the Pareto-optimal allocation of permits among the firms, $\hat{\mathbf{q}}$, solves the problem $\max_{\mathbf{q} \in \mathfrak{R}_+^I} \{ \sum_i u_i(q_i, T_i) : \sum_i (q_i - q_i^0) \leq 0 \}$, the set G may also be defined as

$$G = \{ \mathbf{u} \in \mathfrak{R}^I : \sum_i u_i \leq -\sum_i C_i(\hat{q}_i), \sum_i T_i \leq 0, \text{ and } \mathbf{u} \geq \mathbf{d} \}.$$

⁵ It will be assumed throughout that the firms are risk neutral, and that their monetary outcome is also their von Neumann-Morgenstern utility payoff.

Note that in this form one can see that the northeast boundary of the set G is an $(I-1)$ -dimensional hyperplane in \mathfrak{R}^I , and moreover that its gradient vector is $\nabla = -1$. The set G is clearly convex and compact in \mathfrak{R}^I . Also, by the definition of G we know that $\mathbf{d} \in G$. Except in the case with $\mathbf{q}^0 = \hat{\mathbf{q}}$, in which \mathbf{d} is on the northeast boundary of G , it is also true that G contains at least one element \mathbf{g} for which $\mathbf{g} \gg \mathbf{d}$. Thus, the pair (G, \mathbf{d}) is an I -person fixed-threat bargaining game.

Let $\tilde{\mathbf{u}}$ denote the (unique) Nash bargaining solution to the n -person fixed-threat bargaining game (G, \mathbf{d}) . This solution is defined as

$$\tilde{\mathbf{u}} = \arg \max_{\mathbf{u} \in G} \prod_i (u_i - d_i) \quad (6)$$

That is, a Nash bargaining solution to the game (G, \mathbf{d}) is the (unique) element of G that maximizes the product of the firms' gains from agreement, relative to the disagreement outcome.⁶

Let $(\tilde{\mathbf{q}}, \tilde{\mathbf{T}})$ denote the vector of final permit holdings (and, thus, emissions levels) and transfers associated with the Nash bargaining solution, where as always we know that emissions and permit levels coincide: $\tilde{\mathbf{q}} = \tilde{\mathbf{e}}$. From Friedman (1990), whose proof serves to establish the following result, we know that the bargaining outcome must be Pareto optimal.

PROPOSITION 2. *The bargaining outcome $(\tilde{\mathbf{q}}, \tilde{\mathbf{T}})$ is Pareto optimal. That is, there does not exist $(\mathbf{q}', \mathbf{T}')$ such that (i) $u_i(\mathbf{q}'_i, \mathbf{T}'_i) \geq u_i(\tilde{\mathbf{q}}_i, \tilde{\mathbf{T}}_i)$ for all $i = 1, \dots, n$ and (ii) for some j , $u_j(\mathbf{q}'_j, \mathbf{T}'_j) > u_j(\tilde{\mathbf{q}}_j, \tilde{\mathbf{T}}_j)$.*

I have now established that the emissions vector $\tilde{\mathbf{e}}$ associated with the Nash bargaining outcome must necessarily be cost minimizing. Thus, the bargaining process results in a vector of emission levels that equalizes marginal abatement costs across the firms. It is important to note, though, that in a multi-region setting overall efficiency is achieved only if the

⁶ So long as the three requisite conditions — G is convex and compact $\mathbf{d} \in G$, and there exists $\mathbf{g} \in G$ with $\mathbf{g} > \mathbf{d}$ — are met, if Nash's (1953) four axioms are satisfied, the solution will be as given in (6). The axioms are: joint efficiency; symmetry; linear invariance; and independence of irrelevant alternatives. See Harsanyi (1977, p.198).

emissions cap Q^{j0} is chosen correctly for each region. Though bargaining within a region delivers half of the required result, overall efficiency also requires the other half — spatial coordination between the regions.

Sale of permits by the regulator

I now turn to the claim that the initial distribution of permits, q^0 , is irrelevant to the result that the Nash bargaining solution leads to the cost-minimizing distribution of emissions. To see this, note that the Pareto-optimal allocation of permits, \hat{q} , and hence the emissions \tilde{e} corresponding to the Nash bargaining outcome, is independent of q^0 . This is due to the fact that the first-order conditions from problem (5), which are necessary and sufficient for (\hat{q}, \hat{T}) to solve (6), depend on $\sum_i q_i^0$ but not on the individual q_i^0 .⁷

The fact that the efficiency of the bargaining outcome does not depend on the way in which permits are allocated initially is appealing in that it emphasizes the desirable characteristics of the market for the case under study. For a number of reasons, however, the regulator may choose not to distribute the permits at zero cost. The regulator may wish to control the distribution of gains in a particular way. It may also be desirable to capture the value of the permits for the public through a permit sale, rather than to transfer these valuable assets to the polluting sector. The advantage of taxes over freely distributed permits is well known in the literature on carbon trading (Goulder et al., 1997).

In order to examine this question, I suppose that firms must purchase permits from the regulator rather than receive them at no cost.⁸ I extend the model of the previous section to include the regulator as a player. The regulator, denoted as player $I+1$, begins with all of the permits, $q_{I+1}^0 = Q^0$. All of the firms begin with no permits: $q_i^0 = 0$ for $i = 1, \dots, I$. The

⁷ The result that the cost-minimizing property of a permit market is independent of the rule used in the initial distribution of permits is shown formally in Montgomery (1972) for the case of a competitive permit market.

⁸ One could consider a formal auction or any number of alternative mechanisms by which firms could be given the opportunity to obtain permits. So long as the regulator is the monopoly supplier of permits, presumably there is no legal barrier to his or her behaving in a perfectly discriminating manner.

regulator does not engage in pollution or abatement activity. The utility function for the regulator is therefore $u_{I+1}(q_{I+1}, T_{I+1}) = T_{I+1}$. In the event of no agreement with the firms, the regulator retains all permits and receives no transfer payments so that the threat point for the regulator is 0.

Now consider the $(I+1)$ -player bargaining game including the regulator as a player. This situation is formally identical to the case considered in the previous section. By defining the game in this fashion I can use the results derived above to obtain Proposition 3, whose proof follows the lines of the proof of Proposition 2.

PROPOSITION 3. *The result of bargaining between I firms and the regulator, where the regulator begins with all of the permits and where firms must purchase permits from the regulator, is Pareto optimal.*

In a Pareto-optimal solution, the distribution of permits will be identical to that for the case in which the regulator distributes the permits at zero cost. The only difference is in the transfer payments. When the regulator begins with the permits it will gain transfer payments that previously were retained by firms.

A Competitive Fringe

I turn now to the case in which a few large firms are dominant in the permit market while a number of smaller firms are relegated to the position of a competitive fringe, forced to take the permit price as given. Specifically, suppose that there are $I + K$ firms, of which K firms are price takers in the permit market and the remaining I firms enjoy market power jointly. The I market-power firms, indexed by $i = 1, \dots, I$, are assumed to engage in a bargaining game amongst themselves, but together they behave as a unified leader, exercising their monopoly or monopsony power against the followers in the fringe.

Each of the price-taking firms, indexed by $k = 1, \dots, K$, can do no more than observe the price offered by the large firms and then choose its level of emissions and the number of permits it must buy or sell. Again noting that with strictly positive marginal costs I will have $e_k = q_k$, firm k

solves the problem

$$\min_{q_k \in \mathfrak{R}_+} \{C_k(q_k) + p(q_k - q_k^0)\},$$

where p is the permit price set by the I large firms. The first-order condition for this problem, $C_k'(q_k) + p = 0$, implicitly defines firm k 's excess demand function for permits, $q_k(p)$. The fringe's aggregate excess demand for permits may be written $Q_K(p) = \sum_k q_k(p)$.

The large firms, who participate in the bargaining game, are assumed to know this excess demand function and to take it into account in solving their joint optimization problem. This problem now includes two separate parts. First, they must select a price at which permits will be offered for sale or purchase to or from the fringe firms. Second, they must divide the remaining permits amongst themselves and select a vector of transfers.

I assume that the I large firms first choose the permit price. They do this by colluding, solving the joint optimization problem

$$\min_{p \in \mathfrak{R}_{++}} \left\{ \sum_i C_i(q_i) + p \left[\sum_i (q_i - q_i^0) \right] : \sum_i q_i \leq \sum_i q_i^0 + Q_K^0 - Q_K(p) \right\}, \quad (7)$$

where $Q_K^0 (= \sum_k q_k^0)$ and $\sum_i q_i^0$ are the fringe's and the market-power firms' aggregate endowment of permits, respectively. Let p^* denote the price that solves problem (7). This price will equal the marginal abatement cost of the large firms only in the special case in which there is no net trade between the fringe and the large firms. The bargaining solution will, however, ensure the equality of marginal abatement costs across the large firms. The associated value $R^* = p^* [Q_K(p^*) - Q_K^0]$ is the revenue that flows from the fringe firms to the market-power firms. It can be either positive or negative. In either case, the sum of the money transfers that are exchanged among the large firms in their bargaining game will equal R^* and the total number of permits that they will divide among themselves will equal $\sum_i q_i^0 + [Q_K^0 - Q_K(p^*)]$. This first part of the decision problems defines the northeast boundary of the agreement space in the bargaining game to follow.

In the second part of their problem the large firms engage in a

bargaining game that is very much like that defined above. The payoff to firm i is $u_i(q_i, T_i) = [-C_i(q_i) + T_i]$. The agreement space is

$$G = \{\mathbf{u} \in \mathfrak{R}^I : \sum_i (q_i - q_i^0) \leq (Q_K - Q_K^0), \sum_i T_i \leq R^*, \text{ and } \mathbf{u} \geq \mathbf{d}\}.$$

Therefore, the problem is the same as that encountered above, with the exception that the sum of transfers need not equal zero. It is easy to see that the bargaining solution will yield an optimal distribution of emissions among the large firms, given the quantity of permits that they hold in aggregate, $\sum_i q_i^0 + [Q_K^0 - Q_K(p^*)]$.

It is not true, however, that the least-cost distribution of emissions will necessarily be achieved across the industry. This is because the large firms are able to extract rents from the competitive fringe, driving a wedge between the marginal abatement cost observed in each of the two groups of firms. Only in the unlikely case that the net trade of permits between the large firms and the fringe firms is zero will total abatement costs be minimized.

This model is a generalization of Hahn (1984), whose model contains a single firm with market power. The theme of the section is very much in the same spirit. That is, a collection of collusive firms with market power can exploit the competitive fringe and undermine the efficiency of the permit market. It is easy to see that Hahn's model is a special case of the model described in this section, with $I = 1$. Note that the fact that some firms are strategic while other firms are not, which creates asymmetric market power, is the source of the inefficiency. If all firms participate in the bargaining game, as in the previous section, an efficient result is obtained. Even with asymmetric market power, it would still be possible to obtain an efficient distribution of abatement if one allows the colluding firms to act as a perfectly discriminating monopolist or monoposonist against the competitive fringe.

V. NUMERICAL SIMULATION

The U.S. SO₂ allowance program employs a single national market for allowances. Allowances can be traded one for one between any two

sources, regardless of location. This means that the system offers almost no control over regional deposition of acid rain.⁹ A series of regional markets, I have argued, would allow regulators to reduce the potential for hot spots, and the small numbers of traders might achieve the socially optimal distribution of abatement in each region. A regional trading system that recognizes the relationship between emissions and deposition can achieve the socially optimal outcome.

This section contains an example that illustrates the point for a hypothetical trading scheme. The situation I consider consists of nine trading regions, as illustrated in Figure 1.

[Figure 1] Regions in the simulation

1	2	3
4	5	6
7	8	9

A single pollutant, which crosses regional boundaries, is to be regulated. Emissions from all sources in a region are assumed to be equivalent. In each region there are two polluting firms, one with high abatement costs and one with low abatement costs. Their cost functions are

$$C_H(e_H^j) = \frac{(e_H^{j0} - e_H^j)^2}{4} \quad \text{and} \quad C_L(e_L^j) = \frac{(e_L^{j0} - e_L^j)^2}{8},$$

respectively, where e_i^{j0} denotes the level of uncontrolled emissions. This quantity is assumed to be $e_i^{j0} = 120$ for each firm. The prevailing wind patterns are mainly from west to east, with some northward drift. The portion of emissions from region j that lands in region k is denoted h_{jk} . The values of these transfer coefficients are given in the following matrix:

⁹ But certain provisions of the 1977 Clean Air Act are still in force and some trades could be disallowed in principle if they are shown to worsen air quality in nonattainment areas.

$$H = \begin{bmatrix} 2/9 & 2/9 & 2/9 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 2/9 & 2/9 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2/9 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1/9 & 1/9 & 2/9 & 2/9 & 2/9 & 0 & 0 & 0 \\ 0 & 0 & 1/9 & 0 & 2/9 & 2/9 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2/9 & 0 & 0 & 0 \\ 0 & 0 & 1/9 & 0 & 1/9 & 1/9 & 2/9 & 2/9 & 2/9 \\ 0 & 0 & 0 & 0 & 0 & 1/9 & 0 & 2/9 & 2/9 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2/9 \end{bmatrix}.$$

Most of the emissions from region 1 land in regions 1, 2, and 3, with some drifting northward out of the area. Emissions from region 3 land either in region 3 itself or out of the area. Emissions from region 7 land to the east and northeast, in regions 3, 5, 6, 7, 8, and 9. Let $\mathbf{E} = (e^1, \dots, e^9)$ denote the vector of emissions by region, with $e^j = e_H^j + e_L^j$. The level of deposition in region j is the j th element of the vector

$$\boldsymbol{\varepsilon} = \mathbf{EH}.$$

Figure 2 indicates the pre-regulation level of deposition for each region.

[Figure 2] Pre-regulation deposition levels

53.3	133.3	240.0
53.3	133.3	213.3
53.3	106.7	160.0

Each region experiences the same damages as a function of deposition in that region, ε^j . Given the initial emissions levels, this function is

$$D^j(\varepsilon^j) = \frac{(\varepsilon^{j0} - \varepsilon^j)^2}{12} - 40(\varepsilon^{j0} - \varepsilon^j).$$

The social planner's solution

A social planner would select an emissions level for each firm in each region so as to minimize the sum of abatement costs and damages. The planner solves

$$\min_{e \in \mathfrak{R}_+^{18}} \left\{ \sum_{j=1}^9 D^j(\varepsilon^j) + \sum_{j=1}^9 [C_H^j(e_H^j) + C_L^j(e_L^j)] \right\}.$$

The solution to this problem was obtained numerically. Table 1 contains the results. Note that in this and the following results I report abatement benefits, which are simply the reduction in damages.

[Table 1] Numerical results, planners solution.

Region	Abatement		Reduction in Deposition	Abatement Cost	Abatement Benefits	Net Benefits
	Hi-cost	Lo-cost				
1	39.9	79.7	26.6	1,192.1	1,004.3	-187.8
2	24.1	48.1	59.6	434.1	2,086.5	1,652.3
3	10.7	21.4	95.6	85.7	3,063.6	2,977.8
4	50.8	101.6	33.9	1,935.0	1,258.9	-676.1
5	28.8	57.7	72.4	623.9	2,460.5	1,836.7
6	11.1	22.2	90.4	92.1	2,934.3	2,842.2
7	58.1	116.1	38.7	2,529.4	1,423.7	-1,105.7
8	31.6	63.2	59.8	749.5	2,093.7	1,344.2
9	12.7	25.4	68.3	121.4	2,342.4	2,221.0
Total	803.2			7,763.2	18,667.9	10,904.7

The western regions, 1, 4, and 7, experience the highest costs because their emissions impose the highest damages. This is especially true of region 7, whose emissions affect itself and all of the regions to the east northeast. Region 3, on the other hand, affects nobody but itself, so it is not required to reduce its emissions very much. In addition to experiencing the lowest costs of abatement, the eastern regions (3, 6, and 9) also experience the greatest reduction in damages. Thus, while net regional benefits are negative in the western regions they are positive and quite large in the eastern regions. Overall, benefits from abatement exceed

the cost of abatement by 140 percent.

Figure 3 illustrates the way in which deposition levels are changed by the optimal regulation. The top number in each cell in the figure represents actual deposition in the region; the number in parentheses is the percentage reduction compared to the no-regulation situation. Though the regions with the highest initial deposition (regions 3, 6, and 9) achieve the greatest absolute reductions, and thus the greatest absolute improvements in environmental quality, the cleanest regions (1, 4, and 7) achieve the greatest percentage reductions in deposition. This is because emissions from these regions cause the most harm and thus optimality requires greater abatement there.

[Figure 3] Socially optimal deposition levels

26.8 (49.8%)	73.8 (44.7%)	144.4 (39.9%)
19.5 (63.5%)	60.9 (54.3%)	123.0 (42.4%)
14.6 (72.6%)	46.9 (56.1%)	91.7 (42.7%)

Separate regional markets with bargaining

Suppose now that the regulator chooses to establish separate permit markets for each region, with trade between regions prohibited. Permits are allocated to each region in an optimal manner, so that emissions from each region agree with the socially optimal solution. These quantities can be found from Table 1 by subtracting the entries in the column “Reduction in Deposition” from 240, which is initial emissions for every region. The distribution of permits across the two firms has no bearing on the bargaining outcome in this case.

If the firms in each region bargain with each other in the way I have described, they will achieve the socially optimal distribution of emissions among themselves. Thus, abatement costs will be equal, for each firm, to the socially optimal outcome. Because of the way permits are allocated by region, and because inter-regional trade is not allowed, abatement benefits will also be the same. In short, with regional markets and perfect

bargaining, under these assumptions the social optimum is achieved.

The single-market solution

I now turn to the case in which the regulator creates a single market for permits, disregarding, as the U.S. SO₂ allowance market essentially does, concerns over the spatial distribution of emissions and loadings. I assume that the regulator issues a total number of permits equal to the optimal level of emissions under the socially optimal solution. Thus, $\sum_{j=1}^9 \sum_i q_i^{j0} = 1,356.8$, where q_i^{j0} denotes the initial endowment of permits granted to firm i ($i = H, L$) in region j . Each firm, then, receives an endowment of $q_i^{j0} = 75.38$ permits. The 18 firms behave competitively in the single permit market.

With a single market, because firms have no concern for abatement benefits each of the nine low-cost firms and each of the nine high-cost firms behave in the same manner. The low-cost firms sell permits; their excess supply function is $e(p) = 4p - (120 - q_i^{j0})$. The high-cost firms buy permits; their excess demand function is $e(p) = (120 - q_i^{j0}) - 2p$. By setting the sum of the nine excess demand functions equal to the sum of the nine excess supply functions, I can obtain the equilibrium permit price: $p^* = 14.875$.

In equilibrium, abatement by each of the high- and low-cost firms is $a_H^j = 29.75$ and $a_L^j = 59.50$, respectively. Aggregate abatement in each region is $a^j = 89.25$ and total abatement under the single permit market is, by design, the same as in the optimal case: $\sum_j a^j = 803.2$. Each high-cost firm, then, must purchase 14.88 permits; each low-cost firm sells the same amount. After accounting for their permit revenue, though their abatement levels are much higher, low-cost firms' total costs (abatement costs and permit sales combined) are lower. The numbers are:

$$\text{High-cost firms: } TC_H^j = \frac{(120 - e^H)^2}{4} + p^*(e^H - 120) = 442.5 \text{ and}$$

$$\text{Low-cost firms: } TC_L^j = \frac{(120 - e^L)^2}{8} + p^*(e^H - 120) = 221.3.$$

Total abatement cost under the single-market solution is 5,974, lower than that under the optimal solution. Abatement benefits, though, at 14,934 are much lower than the optimum. The overall result is that net benefits are 8,960, considerably below the value of 10,905 for the optimal outcome. The loss of net benefits under the single-market solution is due solely to the fact that abatement is not distributed optimally. Figure 4 illustrates this point. Because abatement is identical in each region, the percentage reductions in deposition are also identical. A comparison of Figures 3 and 4 shows that deposition is higher in every region under the single-market solution than under the socially optimal solution.

[Figure 4] Deposition levels with a single market

33.5 (37.2%)	83.8 (37.2%)	150.8 (37.2%)
33.5 (37.2%)	83.8 (37.2%)	134.0 (37.2%)
33.5 (37.2%)	67.0 (37.2%)	100.5 (37.2%)

Regional markets, competitive fringe

With a spatially sensitive pollutant, regional markets are to be preferred as long as it is reasonable to anticipate that the markets will approximate the least-cost solution through bargaining or other means. It is possible, however, that the smaller regional markets will not perform well. Here, in each of the regional markets I assume that market power is as severe as it can be.¹⁰ Specifically, I divide the nine regions into two groups. In the odd-numbered regions, I assume that the low-cost firm has monopoly power and that the other firm behaves competitively. This is equivalent to a fringe of small, competitive firms facing the monopoly seller of permits. In the even-numbered regions, I assume that the high-cost firm has monopsony power, and that the other firm behaves competitively. This is

¹⁰ But note that the degree of severity of market power depends, as Hahn (1984) showed, upon the initial allocation of permits to the dominant firm and the fringe. Although my specification with a single dominant firm in each region is extreme, this may not be true of my allocation of permits is.

equivalent to a case with a single monopsony buyer of permits facing a fringe.

Table 2 contains the results of the numerical exercise for the case with a single powerful firm and a competitive fringe in each region. In the case of regional markets with maximal market power, because the regulator is able to issue the socially optimal number of permits to each region, the losses due to spatial misallocation are zero. Losses are due solely to misallocation of abatement between low- and high-cost firms in each region.

[Table 2] Numerical results, regional markets with fringe

Region	Abatement		Reduction in Deposition	Abatement Cost	Abatement Benefits	Net Benefits
	Hi-cost	Lo-cost				
1	47.8	71.8	26.6	1,216.0	1,004.3	-211.7
2	27.1	45.1	59.6	437.5	2,086.5	1,648.9
3	12.8	19.2	95.6	87.5	3,063.6	2,976.1
4	57.1	95.2	33.9	1,950.1	1,258.9	-691.2
5	34.6	51.9	72.4	636.3	2,460.5	1,824.2
6	12.5	20.8	90.4	92.9	2,934.3	2,841.5
7	69.7	104.5	38.7	2,580.0	1,423.7	-1,156.3
8	35.6	59.3	59.8	755.3	2,093.7	1,338.4
9	15.3	22.9	68.3	123.8	2,342.4	2,218.6
Total	803.2			7,879.3	18,667.9	10,788.6

Summary and Comparison

Table 3 compares the overall welfare outcomes for the three scenarios. Regional markets with the socially optimal level of permits issued to each region can achieve the socially optimal outcome, so long as bargaining is perfect. A single market, which is often thought to be desirable because it minimizes the likelihood of noncompetitive behavior, turns out to be quite costly in welfare terms, leading to a loss of 17.8 percent in net benefits. Even if the market in each region is characterized by a single monopolist or monopsonist, the welfare losses due to this sort of market power are relatively small. The reason is that our regulator is able to control emissions regionally by issuing the optimal number of permits to each region and prohibiting inter-regional trade. Spatial concerns appear to

trump market-power concerns.

[Table 3] Overall welfare comparisons

	Social Optimum and Regional Market	Single Market	Regional Market with Fringe
Total cost	7,763	5,974	7,879
Total Benefits	18,668	14,934	18,668
Net Benefits	10,905	8,960	10,789

VI. DISCUSSION

The fact that a competitive permit market achieves the least-cost distribution of emissions across firms is well known. One of the strengths of this result is that the market is completely decentralized. No firm needs to know anything about the other firms' costs; the permit price is sufficient to achieve efficiency. For some time now, it seems that the consensus view among economists has been that a small number of large, powerful participants in the permit market constitutes one of the primary threats to the usual efficiency result. Where they compete, concerns over market power have apparently been judged to be more important than concerns over space.

Yet there is a strong likelihood that, in the U.S. market for SO₂ allowances, space matters more than power. The political process that produced the SO₂ policy apparently discounted spatial concerns in order to reduce the potential for market power to impede the allowance market. My results suggest that the two concerns were prioritized incorrectly. Spatial misallocation of abatement and deposition can be very costly, while it seems that the welfare losses due to market power are relatively small.

I have argued that this last is due to two factors. First, we believe that the few utility companies that would be in a position to wield power in a given regional permit market do know each other's cost structure quite well. Moreover, they have a powerful incentive to achieve the distribution of abatement amongst themselves that minimizes their joint costs. And in few cases would the few powerful participants be on the same side of the market — more likely one or more powerful buyers would face one or

more powerful sellers of permits. Thus, it is not unreasonable to suppose that they would bargain and reach a reasonably efficient solution. Second, even if market power is completely one-sided, the welfare losses caused by the exercise of this type of market power are likely to be dwarfed by the welfare losses due to spatial misallocation of emissions and abatement.

The reader may wonder how a set of regional markets of the kind I describe could be operationalized. Among other things, it would be difficult to decide how large each region should be. Ideally, of course, a regulator who knows as much as ours does could simply impose a command-and-control policy, dictating to each source exactly how much it can emit and dispensing altogether with the permit market. This would amount to treating each individual firm as its own region. Any departure from this ideal that results in the grouping of different sources into regions, which effectively assumes that emissions from all sources in a region are equivalent environmentally, leads to some diminution in welfare.

It is doubtless true that the extreme of treating each firm as a separate “region” would be utterly infeasible politically, and would have been in 1990 when the U.S. SO₂ program was passed into law. This fact should not, however, cause us to overlook another fact: that the single national market that was implemented is also extreme. It effectively treats a ton of SO₂ emitted in New Mexico as equivalent to a ton of SO₂ emitted in Indiana. Given the vastly different emission rates in those two places, and the different downwind acidic conditions, it should be no surprise that treating all allowances, anywhere in the country, as equivalent would lead to spatial deposition problems. I have argued here for a middle ground, in which the economic and political benefits of decentralized trading that accrue only to an effective permit market are balanced against the desire to control emissions and deposition spatially.

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