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Environmental Regulation in Oligopoly Markets: A Study of Electricity Restructuring

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Abstract

In an oligopoly market subject to environmental regulation through tradable pollution permits, polluters' output decisions affect the price of polluting. With a pollution tax, this feedback effect is absent. In a permit regime, I show that the feedback effect increases strategic firms' production and improves welfare. I empirically test the environmental implications of oligopoly behavior in the Pennsylvania, New Jersey, and Maryland electricity market. Air pollution fell substantially during 1999, the year in which both electricity restructuring and a tradable permit system took effect. Surprisingly, I show that 33-42 percent of the emissions reductions resulted from strategic behavior in the electricity market. Simulations suggest that welfare loss would have been seven percent greater under a tax than with tradable permits.

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This paper examines the welfare implications of introducing strategic behavior in a market subject to environmental regulation such as pollution taxes or tradable permits. Regulators have begun implementing these market-based instruments without considering whether or not markets are competitive. Strategic firms may produce inefficiently and alter pollution in comparison to a competitive market. Economists have examined how environmental regulations affect pollution and how oligopolies affect welfare. This paper examines the interactions of these research topics. I measure the implications of strategic behavior on pollution decisions in restructured wholesale electricity markets. I also ask: does environmental policy choice affect the welfare implications of imperfect competition?

Restructuring electricity markets has enabled firms to set wholesale prices. Oligopoly behavior results in notable price impacts because electricity demand is nearly completely inelastic (a result of retail regulation). As strategic firms produce less, the competitive "fringe" firms operate more expensive power plants. While every firm produces in a cost-minimizing manner, strategic firms optimize by producing where marginal revenue equals marginal cost. This leads to cross-firm production inefficiencies. This substitution among power plants may have environmental implications. In the short run, changes in pollution resulting from the strategic behavior will depend solely on the technologies that dominant firms use to withhold output in contrast with those that the competitive fringe uses to meet demand.[1]

The first contribution of this paper is a theoretical examination of incentive-based instrument choice in the context of imperfect product markets. Subject to uncertainty in abatement costs, Weitzman (1974) discusses the general case of regulators improving welfare by opting to use price or quantity regulations. In contrast to modeling this uncertainty, I examine whether imperfect competition also impacts environmental policy choice. In an oligopoly market subject to environ-

[1]In the short run, I assume consumers' retail prices and producers' abatement technology are fixed. The structure of the California electricity market suggests, for example, that market power may *increase* pollution while the PJM market is structured such that pollution will likely *decrease*. Section 1 elaborates on this point.

mental regulation through tradable pollution permits, polluters' output decisions affect the price of polluting. With a pollution tax, this feedback effect is absent. In a permit regime, I show that the feedback effect increases strategic firms' production and improves welfare.

The second contribution of this paper explores why air pollution from generating electricity fell substantially from 1998 to 1999 in the Mid-Atlantic region (see Figure 1).[2] These emissions reductions occurred despite an increase in the quantity of electricity demanded over this period. Firms changed the mix of types of power plants used to produce energy: the dirtiest plants produced less electricity while cleaner plants operated more. This resulted, in part, from the introduction of environmental regulation. Regulators mandated that Northeastern electricity producers possess tradable permits for summer nitrogen oxides (NO_x) emissions. These permits, which were quite expensive that summer, dramatically increased production costs at some power plants. States differed in how aggressive their firms were in abating pollution.[3]

An alternative explanation for why emissions fell in the Mid-Atlantic region is that regulators restructured the Pennsylvania, New Jersey, and Maryland (PJM) electricity market. This paper examines whether restructuring resulted in pollution changes associated with production inefficiencies. I compare actual emissions with estimates for a competitive market using a methodology common to the literature. My estimates of competitive production, which account for environmental regulation, explain approximately 64 percent of actual NO_x reductions. The remaining 36 percent can be attributed to firms exercising market power. Similar effects are found for emission reductions of sulfur dioxide and carbon dioxide.

The third contribution of this paper simulates the welfare consequences of policy choice. If

[2] Annual sulfur dioxide and carbon dioxide emissions from electric utilities fell by 13 and 12%, respectively (EIA, *Electric Power Annual*). These were the largest reductions in the 1990s for Delaware, Maryland, New Jersey, and Pennsylvania. Annual nitrogen oxides emissions were reduced by 17%, second only to a 22% reduction in 1993.

[3] In fact, utilities in Massachusetts increased emissions from 1998 to 1999 (EIA *Electric Power Annuals*). Sulfur dioxide emissions in the state increased from 98 thousand tons in 1998 to 113 thousand tons in 1999. Nitrogen oxides increased from 33 thousand tons to 41 thousand tons.

permit prices are endogenous, then market power in the PJM electricity market may have welfare implications on regulators' policy choice. I simulate these welfare effects using a model of permit supply by firms affected by the NO_x environmental regulation but not in PJM. The PJM electricity market is modeled both as a competitive market and assuming Cournot behavior. I estimate the welfare effects from strategic behavior at the observed permit price. Then I simulate what the permit price would have been had PJM been competitive. I estimate that the permit price would have been 93 percent higher than observed. I model regulators as setting the tax optimally with the assumption of this competitive behavior. At this higher price for pollution, strategic firms would have distorted the market and caused even more welfare loss than under the permit system. The welfare loss in PJM would have been seven percent larger under a tax than under the permit price.

Section 1 of this paper discusses the literature on environmental regulation in imperfect markets. I construct a theoretical model of the environmental implications of oligopoly behavior and discuss the policy choice over market-based regulation. Section 2 describes the environmental regulation and electricity restructuring in the Mid-Atlantic states. Section 3 reviews the methodology and data used to estimate the environmental implications of strategic behavior. Then the section displays evidence that restructuring resulted in production inefficiencies leading to emissions reductions in PJM and discusses the economic consequences of these pollution reductions. In section 4, I simulate how NO_x permit prices respond to market power in the PJM electricity market and quantify the welfare impacts of the policy choice of taxes versus tradable permit. Section 5 offers concluding remarks.

1 Environmental Regulation of Imperfect Markets

Since Pigou, many economists have examined the theory of environmental regulation in imperfect markets. As an example of the theory of the second best, Buchanan (1969) examines the issue of regulating a polluting monopoly. He argues that a monopolist facing a Pigouvian tax, which is set equal to the marginal external cost, may cause more welfare loss than an unregulated competitive market.[4] In practice, however, Oates and Strassmann (1984) argue that ignoring market structure will probably lead to small inefficiencies when determining pollution regulation given these concerns are second order. On the other hand, Browning (1997) explains that second order implications *do* matter in a general equilibrium setting because of distortions in other markets, like labor markets.[5]

Monopolies distort overall production but produce using the least costly technology. In contrast, in addition to distorting overall production, oligopolies also cause production inefficiencies by substituting production across firms. In these markets, the pollution implications of market power depend on total production and the technologies employed. Key factors include demand elasticity, the costs and emissions associated with various technology types, the distribution of technologies among firms, and the exact oligopoly game. Therefore, determining second-best taxes becomes more complicated when an imperfect market includes several producers. Levin (1985) demonstrates that taxes, even when proportional to emissions rates, may increase pollution from an oligopolistic industry with asymmetric cost functions.[6] I now model how exerting market power affects firms' production and abatement decisions and thus has policy implications for market-based instruments.

1.1 Model of Environmental Regulation

Suppose that there are several independent, competitive product markets with a total of N firms that emit pollution into a common air shed.[7] For firm i, emissions (e_i) equal the firm's output (q_i)

[4] Due to additional distortion in the product market, Lee (1975) and Barnett (1980) note that the second-best tax for a monopolist is less than the marginal external cost.

[5] In general, environmental policy makers may improve welfare by considering: when the product market is economically regulated (Cropper and Oates; 1992); when markets are regulatory constructs (such as permit markets) that may be either set sub-optimally initially or cannot respond optimally to market shocks; and when product market regulations or structure have large environmental impacts.

[6] Since market structure leads to production inefficiencies and distorts the total quantity produced, the second-best tax may exceed the marginal environmental cost (Shaffer, 1995; Simpson, 1995; and Carlsson, 2000).

[7] To be consistent with the literature on pollution regulation, I use the term "product market" to distinguish markets that produce goods (and pollute in the process) as opposed to a market, like a permit market, where firms trade property rights.

times its emissions rate (r_i):

$$e_i = q_i r_i, \quad i \in \{1, ..., N\}. \tag{1}$$

In the short run, I assume firms cannot change abatement technology nor consider entering or exiting the product markets: r_i and N are fixed. Pollution results in environmental and health damages. Assume a convex damage function that depends only on aggregate emissions and not on their spatial distribution:

$$D = D(\sum_{i=1}^{N} q_i r_i). \tag{2}$$

Regulators can set a tradable permits cap or an environmental tax to limit pollution in an effort to correct for the externality. In the case of a permit system, firm i is allocated permits of amount $\overline{e}_i$. If the product markets and the permit market are competitive, firm i will take as given its product market's price (P_i) and the permit price (τ). Firm i has convex production costs $c_i(q_i)$ and will choose q_i in order to maximize profits (π_i). Profits equal total revenue less total production costs, but also less the environmental regulation costs of any additional pollution beyond the firm's allocated permits. Dropping the subscripts, in a competitive market, firm i will solve:

$$\max_{q} \{Pq - c(q) - \tau \cdot (qr - \overline{e})\}. \tag{3}$$

Therefore, in the case of a price taking firm, the first order condition of (3) implies:

$$P - c'(q) = \tau r.^{8} \tag{4}$$

Efficiency is defined by the set of output decisions $\{q_1^*, ..., q_N^*\}$ that solve the vector of equations where, for each firm, the marginal net benefits of production equal the marginal damages from that production:

$$P_i - c_i'(q_i^*) = D'(\sum_{i=1}^{N} q_i^* r_i) \cdot r_i, \text{ for all } i \in \{1, .., N\}. \tag{5}$$

[8] This assumes an interior solution, an assumption made throughout this paper. Note that the second order condition for profit maximization is met: $-c''(q) < 0$.

Note that the source of emissions is not relevant to the marginal damage function. Therefore, the social optimum will be achieved under a tradable permit system when the permit price τ equals the marginal damages from emissions $D'(\sum_{i=1}^{N} q_i^* r_i)$ where firms produce $\{q_1^*, ..., q_N^*\}$. The regulator allocates permits in aggregate equal to the optimal level of emissions:

$$\sum_{i=1}^{N} \overline{e}_i = \sum_{i=1}^{N} q_i^* r_i. \tag{6}$$

Assume that firm i is allocated permits equal to its optimal level of emissions: $\overline{e}_i = q_i^* r_i$.[9] In the case of an environmental tax, τ_0, the regulator levies the tax equal to the marginal damages from emissions at q^* for all firms: $\tau_0 = D'(\sum_{i=1}^{N} q_i^* r_i)$.

1.2 Pollution Implications of Imperfect Product Markets

The first question I examine is whether introducing strategic behavior into a product market affects the total pollution emitted by firms in that product market. Even though total emissions are fixed under a permit system, the share of emissions from any one product market may change. I define "local" pollution as the emissions from the product market with strategic behavior.

Under a permit system, a strategic firm recognizes that its output may affect prices $P(q)$ and $\tau(q)$. The firm will solve:

$$\max_{q} \{P(q) \cdot q - c(q) - \tau(q) \cdot (qr - \overline{e})\}. \tag{7}$$

The first order condition then implies:

$$P(q) + P'(q) \cdot q - c'(q) = \tau(q) \cdot r + \tau'(q) \cdot (qr - \overline{e}).^{10} \tag{8}$$

Let $\widetilde{q}$ solve (8). I assume that a firm acting strategically will produce less than it would have in a competitive market, $\widetilde{q} < q^*$. This will be the case provided that the firm's incentive to increase the

[9] If there are any transaction costs associated with trading permits, then under competitive markets, the regulator will minimize these costs with this allocation rule.

[10] Here, the second order condition for profit maximization is $2P'(q)+P''(q) \cdot q - c''(q) - 2\tau'(q) \cdot r - \tau''(q) \cdot (qr - \overline{e}) < 0$. Note that $P'(q) < 0$ and that $c''(q) > 0$. However, I have not imposed restrictions on $\tau(q)$. This section discusses the sign of $\tau'(q)$ for two possible cases: when the strategic firm is relatively dirty and when the strategic firm is relatively clean.

price in the product market either does not conflict with, or otherwise dominates, the incentive to distort the permit price.[11]

Under a tax, the firm cannot affect the regulation price ($\tau_0' = 0$) and therefore will have the first order condition:

$$P(q) + P'(q) \cdot q - c'(q) = \tau_0 \cdot r.^{12} \tag{9}$$

Let $\widehat{q}$ solve (9). In the face of a tax, given $P'(q) < 0$, the strategic firm will always produces less than it would have in a competitive market: $\widehat{q} < q^*$.

I assume that the imperfect product market consists only of a dominant firm (which produces q_m) and a competitive fringe (q_f). As with wholesale electricity markets, I model demand as perfectly inelastic ($\overline{q}$).[13] In equilibrium, the quantity supplied equals the quantity demanded: $q_m + q_f = \overline{q}$.

Figures 2 and 3 present the local pollution effects of introducing market power. Under competition, the marginal abatement cost equals forgone profits. Rearranging (4), the marginal abatement cost of a firm in a competitive market ($mca^{comp}(q)$) will be:

$$mca^{comp}(q) = \frac{P - c'(q)}{r}, \tag{10}$$

[11] As in Hahn (1984), firms may have incentives to affect permit prices in order to minimize regulation costs. Hahn shows that a firm will exercise monopoly or monopsony power depending on whether its sells or buys permits, on net. The firm will produce less when acting strategically than it would have in a competitive market as long as: $P'(q) \cdot q < \tau'(q) \cdot (qr - \overline{e})$. This holds when permits are allocated $\overline{e} = q^* r$. However, this will not always be the case. As will be discussed below, increasing output may increase the permit price in some cases, but will decrease it in others. In the case of a positive $\tau'(q)$, had the firm been allocated a substantial amount of permits, it would want to produce more in order to drive up the permit price and this inequality would fail. Similarly, in the case of a negative $\tau'(q)$, if the firm had been given very few permits, then the firm would increase production and reduce the permit price (as explained below, by reducing demand for other, dirtier firms' production). This would also result in the failure of the inequality. Another reason firms would have incentives to affect the market price is in order to raise their rivals' costs (Misiolek and Elder, 1989; and Sartzetakis, 1997).

[12] Here, the second order condition for profit maximization is the typical condition for strategic firms and is assumed to hold: $2P'(q) + P''(q) \cdot q - c''(q) < 0$.

[13] Derived demand is nearly completely inelastic for two reasons. First, consumers have no incentive to reduce quantity demanded at higher prices because the regulatory structure of electricity retail markets has kept consumers' rates constant. A few customers have "interruptible" contracts that are exercised when the quantity demanded approaches the capacity of supply, causing customers to curtail electricity demanded. As this does not depend on price, demand shifts but remains completely inelastic. Second, the firms that procure customers' electricity in the wholesale market are mandated to provide the power at any cost.

which is decreasing in production (and therefore in emissions). As consistent with the literature, I model marginal damages from pollution as increasing in emissions. For both types of regulation, namely the tradable permits and tax, the figure displays the optimal policy under the assumption of competitive product markets. When the dominant firm can set the product price, its marginal abatement costs (mca^{mkt_pwr}) again equal the forgone profits:

$$mca^{mkt\_pwr} = \frac{P(q) + P'(q) \cdot q - c'(q)}{r}. \tag{11}$$

As price exceeds marginal revenue, the dominant firm will emit less for a given permit price. However, fringe firms produce more in an imperfect market, which may potentially offset this shift in the market's marginal abatement costs.

With fixed abatement technology, the local pollution implications of introducing strategic behavior will depend solely upon the relative emissions rates of the dominant firm and of the competitive fringe. Note that under a permit system, the reduction in output resulting from the exercise of market power from the dominant firm ($q_m^* - \widetilde{q}_m$) exactly equals the increase in output from the fringe ($\widetilde{q}_f - q_f^*$). Therefore, for a given permit price, the dominant firm reduces emissions by $(q_m^* - \widetilde{q}_m) \cdot r_m$ while the fringe emits more: $(\widetilde{q}_f - q_f^*) \cdot r_f$.

In Figure 2, the dominant firm has a higher emissions rate, $r_m > r_f$, so that the same level of emissions can be achieved with less abatement from firms in other product markets. The aggregate marginal abatement cost function lies below that of the competitive market.[14] For the permit market to be in equilibrium, the reduced demand for permits will result in permit prices falling.

Figure 3 presents the converse case when the dominant firm has a lower emissions rate than the fringe, $r_m < r_f$. At a given permit price, more local pollution occurs when the dominant firm exercises market power. In equilibrium, this increase in demand for permits will result in higher permit prices.

[14] This curve includes the feedback effect that permits have on the product market: firms will alter production decisions when marginal costs change, including permit prices.

1.3 Implications for Policy Choice

Assuming that regulation is set optimally given competitive product markets, almost any deviation in marginal damages or marginal abatement costs will result in welfare loss.[15] One such shock to costs, as shown above, is enabling strategic behavior in product markets. As an application of the theory of the second best, regulators may not want to eliminate this deadweight loss since additional welfare losses also exist in the imperfect product market. In this subsection, I examine the conditions under which permit markets are more robust to market power in product markets in comparison to a tax.

Regulators may fail to account for imperfect product markets for a couple of reasons. First, regulators may be slow to adjust to the introduction of strategic behavior in product markets. As in Weitzman (1974) and in the literature on technological change, important differences arise between policy choices when regulators are slow to react.[16] Another reason why environmental policy may ignore strategic behavior in product markets is the separation of regulatory obligations in the government: the EPA and DOJ have different mandates. For example, the EPA's Integrated Planning Model assumes a competitive electricity industry.[17]

When the dominant firm is dirtier than the fringe, as in Figure 2, exercising market power will reduce local emissions. At the initial permit cap, the marginal damages exceed the new marginal abatement costs. This implies that firms emit more than the new optimal level. This new optimum has less pollution and lower permit prices in comparison to the initial one.[18] Alternatively, had regulators established an initially optimal tax instead, strategic behavior would result in less

[15] In the extreme cases, regulatory mechanisms can mimic society's demand for clean air: if the marginal damages are perfectly inelastic, then a permit system will respond optimally. Alternatively, taxes respond optimally when the marginal damages are perfectly elastic.

[16] For a discussion of the technological change literature, see Jaffe, Newell, and Stavins (2002).

[17] See section 2 of the description of the Integrated Planning Model, written by ICF, on the electricity market (http://www.epa.gov/airmarkets/epa-ipm/).

[18] If a permit market's cap is initially equal to or greater than the optimal emissions level, then the introduction of anticompetitive behavior results in even greater welfare losses in comparison to an initially optimized cap.

pollution as firms abate to the point were marginal abatement costs equal the tax. At that point, the tax exceeds marginal damages, implying emissions are less than socially optimal. The converse arguments can be made when the fringe is relatively dirty, as shown in Figure 3.

However, before policy makers either alter the level of taxes or permit caps or change the type of incentive-based instrument, they may improve welfare by considering how permit prices affect welfare in the economy as a whole. Here, I examine the welfare implications of setting a tax or a tradable permit system under the first best given that environmental regulators either may not consider the welfare implications in the product market, or simply do not know whether there will be more or less pollution after a dominant firm exercises market power in the product market.

Weitzman (1974) shows that uncertainty over the marginal abatement costs imply that taxes and tradable permits are not equivalent but rather depend on the elasticities of marginal abatement costs and marginal damages. The social planner will prefer a tax to a quota system when the slope of marginal damages is less, in absolute terms, than that of marginal abatement costs. In contrast, the quota system will be preferred if marginal damages are steeper. In the special case of equal absolute elasticities, policy makers should be indifferent between the instruments; both cause the same pollution-related welfare losses given a shock to marginal abatement costs, like the introduction of strategic behavior.

Assume that, under perfect competition, regulators are indifferent between a tax and tradable permits that are set such that the tax equals the expected permit price where marginal damages equal marginal abatement costs. This implies that the slope of the marginal damages equals the absolute value of the slope of the marginal cost of abatement. Thus, any shock to costs will result in welfare loss in the market for abatement that will have the same expectation regardless of instrument choice. This is shown in both Figures 2 and 3 by the shaded areas. The gray area is the welfare loss associated with a tradable permit. The black area is the welfare loss associated with a tax.

The additional welfare implication that I want to address is: how does instrument choice affect welfare in the product market? Relative to a tax, permit prices respond to production decisions. The implications on production, and therefore welfare, can be seen by looking at how profits change when the permit price falls.

In the case of perfectly inelastic demand, the dominant firm's residual demand ($P(q_m)$) is defined by the marginal cost of the fringe:

$$P(q_m) = c_f'(q_f) + \tau(q_m) \cdot r_f = c_f'(\overline{q} - q_m) + \tau(q_m) \cdot r_f. \tag{12}$$

Under a permit system, this implies that the slope of the residual demand function will be:

$$P'(q_m) = -c_f''(\overline{q} - q_m) + \tau'(q_m) \cdot r_f \tag{13}$$

The first order condition (8) is modified for the dominant firm as:

$$\begin{aligned} \frac{d\pi(\tau(q_m))}{dq_m} &= [c_f'(\overline{q} - q_m) + \tau(q_m) \cdot r_f] + [-c_f''(\overline{q} - q_m) + \tau'(q_m) \cdot r_f] \cdot q_m \\ &\quad -c_m'(q_m) - \tau(q_m) \cdot r_m - \tau'(q_m) \cdot (q_m r_m - \overline{e}_m) = 0. \end{aligned} \tag{14}$$

Under a tax, the condition (9) is rewritten as:

$$\frac{d\pi(\tau_0)}{dq_m} = [c_f'(\overline{q} - q_m) + \tau_0 \cdot r_f] + [-c_f''(\overline{q} - q_m)] \cdot q_m - c_m'(q_m) - \tau_0 \cdot r_m = 0. \tag{15}$$

At the dominant firm's profit maximizing level of production under a tax ($\widehat{q}_m$), I examine the difference between the first order condition under a permit (14), ($\frac{d\pi(\tau)}{dq}|_{\widehat{q}_m}$), and that condition under a tax (15), ($\frac{d\pi(\tau_0)}{dq_m}|_{\widehat{q}_m}$). (Note that $\frac{d\pi(\tau_0)}{dq_m}|_{\widehat{q}_m} = 0$.)

$$\frac{d\pi(\tau(q_m))}{dq_m}|_{\widehat{q}_m} - \frac{d\pi(\tau_0)}{dq_m}|_{\widehat{q}_m} = [\tau_0 - \tau(\widehat{q}_m)] \cdot (r_m - r_f) + \tau'(\widehat{q}_m) \cdot (\overline{e}_m + \widehat{q}_m r_f - \widehat{q}_m r_m). \tag{16}$$

1.3.1 Relatively Dirty Dominant Firm

If the dominant firm is relatively dirty ($r_m > r_f$) and exercises market power, then permit prices will fall below the level of the tax ($\tau(\widehat{q}_m) < \tau_0$). In this case, $\tau'(q_m) > 0$ and (by assumption) $\overline{e}_m > \widehat{q}_m r_m$. Therefore, at $\widehat{q}_m$, profits are increasing in q_m under a permit and the firm produces more.

As a case in point, consider $r_m = 1$ and $r_f = 0$. Now (16) equals:

$$\tau_0 - \tau(\widehat{q}_m) + \tau'(\widehat{q}_m) \cdot (\overline{e}_m - \widehat{q}_m). \tag{17}$$

Figure 4 depicts the welfare implications of this example by plotting residual demand (a function of the fringe's production costs), the marginal revenue of that function, and four cost curves: marginal private costs ($c'_m(q_m)$), marginal social costs ($c'_m(q_m) + D'(q_m) \cdot r_m$), marginal private costs plus the tax ($c'_m(q_m) + \tau_0 r_m$), and marginal private costs plus the permit price ($c'_m(q_m) + \tau(q_m) \cdot r_m$).

As permit prices fall relative to the tax, the strategic firm produces more. This will reduce the dominant firm's production costs relative to a tax, and production for the strategic firm is greater than it would have been under a tax: $\widetilde{q}_m > \widehat{q}_m$. The welfare loss from a dominant firm facing a tradable permit is the area between the residual demand curve and the marginal social costs from the point where the dominant firm opts to produce ($\widetilde{q}_m$) to the optimal point where the lines intersect q^*_m (the hashed area). A tax would result in addition welfare loss (the gray area), as the dominant firm would produce even less ($\widehat{q}_m$). Section 4 measures these effects.

1.3.2 Relatively Clean Dominant Firm

If the dominant firm is relatively clean, $r_m < r_f$, and exercises market power, then the dirty fringe produces more and permit prices rise relative to a tax, $\tau(\widehat{q}_m) > \tau_0$. Greater permit prices will result in an increase of production costs for *all* firms. *Ceteris paribus*, greater marginal costs for the dominant firm imply that it would increase profits by reducing output. However, what matters is the relative effect. Namely, If marginal revenue increases *even more* than marginal costs, the dominant firm will increase output. Below I discuss the conditions for this to be the case.

Note that when the dominant firm is relatively clean, the increase in the permit price will cause the fringe's production costs to increase even more so than those of the dominant firm. Returning to (16), this has two potentially offsetting effects on marginal revenue. I examine both parts of (16) separately. First, as the permit price exceeds the tax, $\tau(\widehat{q}_m) > \tau_0$, and the dominant firm is relatively clean, $r_m < r_f$, increasing output *improves* profits under a permit relative to a tax:

$$[\tau_0 - \tau(\widehat{q}_m)] \cdot (r_m - r_f) > 0. \tag{18}$$

Second, the more the dominant firm produces, the permit price exceeds the tax by a smaller amount: $\tau'(q_m) < 0$. Therefore, the second term of (16) is negative, $\tau'(\widehat{q}_m) \cdot (\overline{e}_m + \widehat{q}_m \cdot (r_f - r_m)) < 0$, as $r_f > r_m$. When q_m is near zero (and $\tau'(q_m) \cdot \overline{e}_m$ is insubstantial), the first effect is likely to dominate: the marginal revenue under a permit system will exceed that under a tax. Conversely, at the competitive output level q_m^*, the permit price is assumed to be set equal to the tax, $\tau(q_m^*) = \tau_0$, so the second effect dominates. At this competitive outcome, marginal profits are greater under a tax.

Given that (16) is a continuous monotonic function, there exists some $q_m \in (0, q_m^*)$ where these two effects offset and the marginal revenue under the tax is equal to the marginal revenue under the permit system. Permits will result in more production by the dominant firm than a tax ($\widetilde{q}_m > \widehat{q}_m$) and less welfare loss *only if* the permit price does not respond substantially to changes in q_m around $\widehat{q}_m$, meaning:

$$\frac{[\tau_0 - \tau(\widehat{q}_m)] \cdot (r_m - r_f)}{\overline{e}_m + \widehat{q}_m \cdot (r_f - r_m)} > -\tau'(\widehat{q}_m). \tag{19}$$

I examine the implications of this condition using simplifying assumptions: $r_m = 0$ and $r_f = 1$. Also, I assume that the clean dominant firm will not be allocated permits: $\overline{e}_m = 0$. Now the condition (19) can be written:

$$(\frac{\tau(\widehat{q}_m) - \tau_0}{q_m^* - \widehat{q}_m}) \cdot (\frac{q_m^* - \widehat{q}_m}{\widehat{q}_m}) > -\tau'(\widehat{q}_m). \tag{20}$$

The left-hand side of this equation equals the average increase in the permit price from reducing output from the competitive level multiplied by a ratio. The ratio, which is the amount of output reduced over the amount the dominant firm produces, is bounded by zero and one assuming positive marginal costs. The right-hand side is the marginal increase in the price from further reducing output. If the average impact is substantially greater than the marginal effect, then permits are welfare improving. In other words, this constraint will hold if $\tau(q_m)$ is concave.

Figure 5 provides an example of the welfare implications. As in the previous case, the strategic firm produces where marginal revenue equals marginal cost. This figure has four residual demand curves based on the fringe's costs in these cases: marginal private costs ($c_f'(\overline{q} - q_m)$), marginal social costs ($c_f'(\overline{q} - q_m) + D'(q_m) \cdot r_f$), marginal private costs plus the tax ($c_f'(\overline{q} - q_m) + \tau_0 r_f$), and marginal private costs plus the permit price ($c_f'(\overline{q} - q_m) + \tau(q_m) \cdot r_f$). I have drawn the marginal revenue curves for the two policy instruments. I have shown the case when the residual demand with the permit price lies above that with the tax at $\widehat{q}_m$. Therefore, for a given fringe emissions rate, the marginal revenue for the residual demand with permits is greater than that with taxes, implying more welfare loss under the tax (the same area shading is used as in the previous figure).

In both cases, the dominant firm produces more and, therefore, reduces welfare loss. This finding suggests that more consideration should be given to permit markets, even when the marginal damages and marginal abatement costs have different absolute elasticities. Another important consideration is that transaction costs imply improved welfare from using a tax instead of a tradable permits system (Stavins, 1995). All else equal, I find that given the presence of strategic firms in product markets, welfare losses will be reduced if environmental policy makers opt for tradable permit systems in comparison to pollution taxes.

1.4 Application to Restructured Electricity Markets

While regulators had hoped to spur more efficient production and investment than had resulted under rate-of-return regulation, electricity markets have proven to be especially susceptible to the exercise of market power.[19] Many electricity markets consist of a few strategic firms and a competitive fringe facing perfectly inelastic demand. If plants' emissions rates are fixed, only technology substitution yields pollution effects. For example, emissions will fall if strategic firms reduce output from dirty power plants and a competitive fringe meets demand using cleaner technology. Further, if marginal costs are monotonically increasing or decreasing in emissions rates, then direction of the pollution effects of imperfect markets depend only upon the sign of this correlation. When expensive plants pollute more than cheap plants, market power increases local emissions. Conversely, when cheap plants pollute more, strategic behavior results in less local pollution. These environmental impacts will be exacerbated if strategic firms are more concentrated in low-cost technology.

To further elucidate this point, I compare the different implications of this model for the California and the PJM electricity markets. A firm choosing to exercise market power will opt to restrict output from its most expensive power plants. While California generators primarily use hydroelectric, nuclear, and natural gas to produce electricity, strategic firms' plants on the margin almost always burn gas. Therefore, firms opting to exercise market power will do so by restricting output from gas-fired plants. As a result, more expensive gas-fired plants owned by the fringe must operate in order to meet demand (in lieu of cheaper ones owned by the strategic firms). High-cost gas plants tend to be older, less efficient, and more polluting. Thus, in California, we observe marginal costs (including pollution permits) increasing in emissions. Therefore, exercising market power in California will likely increase local emissions (or the permit price if emissions are capped).

[19] Numerous studies find large, positive price-cost margins in England (Wolak and Patrick, 1997; Wolfram, 1998; Wolfram, 1999), California (Borenstein, Bushnell, and Wolak, 2002; Puller, 2000; and Joskow and Kahn, 2002), New England (Bushnell and Saravia, 2002), and PJM (Mansur, 2004a).

Typically, exercising market power in electricity markets will increase pollution when strategic firms and fringe producers use the same fuel type; variation in "heat rates" (a measure of efficiency) leads to a positive correlation between marginal costs and emissions rates.

In contrast, strategic firms in PJM will reduce output from coal, natural gas, or oil plants, depending upon the level of demand. When demand ranges from low to medium levels, a firm considering exercising market power will have coal-fired power plants on the margin. Coal plants tend to be substantially dirtier and cheaper, even including permit prices, than natural gas plants. Therefore, restricting output with coal leads to more production by gas plants. On net, there will be less local pollution than under perfect competition. Hence, firms exercising market power in California will likely cause pollution to *increase* due to within-technology substitution. The effect in PJM will depend on the relative size of the across-technology substitution that reduces pollution and the within-technology substitution that increases it. (The remaining sections of this paper will examine the environmental impacts of strategic behavior in PJM.)

With regard to the policy implications, when firms exercise market power in PJM, less pollution occurs locally and permit prices fall. This will reduce the marginal costs of strategic and fringe firms. However, since strategic firms emit more pollution, their marginal costs will be more affected. In the case of California, the marginal costs and emissions rates tend to be positively correlated. Firms exercising market power will increase local pollution and permit prices. Here, the marginal costs of the strategic firms are less affected: higher permit prices increase marginal costs for the strategic firms, but the marginal cost of fringe firms increases even more. Had a subsidy been placed only on the strategic firms' output, the effects would be similar.[20] In both cases, the strategic firms will produce more under a permit system than under a tax.[21]

[20] As depicted in the cases of PJM and California, an expensive fringe will either be cleaner or dirtier than the dominant firms. If the fringe is cheaper, it will not produce more in an imperfect market; the dominant firms will reduce output from more expensive units.

[21] Welfare benefits of a permit system may not be politically feasible when high prices result. For example, consider the Regional Clean Air Incentives Market (RECLAIM) tradable permit system that regulates pollution in the Los

2 Environmental and Economic Regulation

Given these general theoretical findings, I now examine the case of PJM and ask whether restructuring that electricity market had environmental implications. Over the past fifteen years, several countries and U.S. regions – such as California, New England, New York, PJM, and Texas – have restructured their electricity markets. Historically, in these U.S. markets, many regulated utilities made inefficient investments in generation, particularly in nuclear power plants, and signed expensive long-term contracts with independent power producers. In many cases, these costly decisions resulted in retail electricity rates that were substantially above the national average. Policy makers believed that restructuring would impose market discipline and thus lead to more efficient investment in new generation and lower production costs at existing generating units.

Unfortunately, the promises of restructuring have not been realized in many markets. Thus far, restructured markets in the Eastern U.S. have experienced greater success than the California market. Some argue that the market design of the Eastern markets has reduced price volatility and limited the degree to which firms exercise market power. Nevertheless, these markets also appear to have experienced market imperfections and high prices. For example, in the summer of 1999, PJM's prices exceeded the marginal cost of the most expensive power plant almost three times as often as in the previous summer, when prices were regulated.

Restructuring may have led to market imperfections, including oligopoly behavior, that caused production inefficiencies and reduced pollution.[22] Mansur (2004a) finds evidence of firms exercising market power during the first summer following the restructuring of PJM. Furthermore, Mansur

Angeles basin. In the summer of 2000, RECLAIM NO_x prices skyrocketed partially because of reduced permit supply. Production inefficiencies may have also increased permit demand. Regulators responded by effectively replacing the permit system with a tax lower than the permit price. As of May 2001, electricity generators in the RECLAIM region are guaranteed permits at fixed prices far below the prices for which permits had been selling. This might have increased welfare losses if marginal damages and marginal abatement costs had similar elasticities; however, regulators may have been more concerned with reducing the substantial wealth transfers.

[22] In addition to market power, inefficiencies could also be caused by non-strategic firm behavior (*e.g.*, misunderstanding marginal costs) or by the market maker, PJM (*e.g.*, flaws in the pricing algorithm). Note that the environmental impacts of restructuring hold regardless of why the production efficiencies occurred.

(2004b) provides evidence that firms distorted production decisions. Given the variation in emissions rates of these firms, the cross-firm production inefficiencies may have impacted local pollution levels, and therefore, the permit prices of the regulating markets.

To test for these impacts in PJM, I begin by discussing the incentive-based environmental regulations and electricity regulation during 1998 and 1999. Electricity generation in the PJM region was subject to two incentive-based environmental regulations in the summer of 1999. One had just been introduced that summer, the Ozone Transport Commission (OTC) NO_x tradable permit regulation. In contrast, the Acid Rain Program had been in effect for a number of years but affected a smaller number of power plants at that time.

2.1 OTC Permit Regulation

Twelve Northeastern states comprising the OTC established a tradable permits program for summer NO_x emissions. For each ton of NO_x emitted from May through September, power plant owners must procure an allowance. If the permits are not used, they may be 'banked' (in a limited manner) for use in future years. In 1999, Phase II of this program called for substantial reductions: greater than 50 percent reduction from 1990 emission levels of 490,000 tons. Eight states participated in 1999 (CT, DE, MA, NH, NJ, NY, PA, and RI). Sources may be constrained by other federal and state environmental regulations.

The permit market had a substantial impact on the marginal cost of production for many power plants in the Northeast. When the permit market started, in May of 1999, the permit price was \$5244/ton. This increased the marginal costs of some coal plants by 50 percent in comparison to the previous summers' costs. Many in the industry were concerned about firms 'hoarding' permits and the lack of announced equipment retrofits. However, the permit prices fell over the summer and reached \$1093/ton by mid-September. Just after the regulatory period the bankable permits traded at $825/ton.[23]

2.2 The Acid Rain Program

Title IV of the 1990 Clean Air Act Amendments, the Acid Rain Program, established a national tradable permits system for annual sulfur dioxide (SO_2) emissions. As a result, power plant emissions have been reduced to approximately 50 percent of 1980 levels. A firm can opt to purchase permits, switch to low sulfur coal, or install a scrubber. Excess permits can be traded to other firms or held for future use by banking them. Phase I began in 1995, regulating the 398 dirtiest "generating units" in the U.S. In 2000, Phase II brought over 2,300 fossil fuel units into compliance. The increase in the scope of regulated firms was accompanied by an increase in permits, while overall, Phase II requires more abatement.

Twenty-three units at ten plants in PJM were regulated by Phase I. Two generators at the Conemaugh plant, owned by GPU, installed scrubbers in 1994 and 1995. The others either switched to low sulfur coal or purchased permits from the market. Regardless of how these units complied with the regulation, the price of the permit is the opportunity cost of polluting. During the summer of 1999, the price of these allowances was about $200 per ton. For the median coal unit regulated by Title IV, this corresponds to about three dollars per MWh. The average Phase II unit is cleaner with an expected marginal cost of approximately one dollar per MWh at these prices.[24]

Note that one possible explanation for the reduction in emissions from 1998 to 1999 is that some of the firms may have invested in improved abatement technology. For this reason, the analysis below uses data on annual emissions rates. Firms may have been preparing for the tightening of the national SO_2 permit market in 2000. However, no power plant in PJM installed a scrubber in

[23] The price remained around $1000 since that first summer. For more information on the OTC, see http://www.epa.gov/airmarkets/otc/.

[24] In Phase I, the median "heat rate" was 10,179 BTU/kWh (a measure of how efficient the unit is in converting fuel into electricity) and the median emissions factor was 2.93 lbs. of SO_2/mmBTU. In Phase II, I assume a heat rate of 12,000 BTU/kWh and an emissions factor of 1.2 lbs. of SO_2/mmBTU.

1999. Even with the new NO_x market, only a few plants installed NO_x abatement technology from 1998 to 1999.[25] In general, PJM firms' emissions rates did not change significantly over this time period.[26]

2.3 The PJM Electricity Market

In 1998 and 1999, the whole of New Jersey, Delaware and the District of Columbia, the majority of Pennsylvania and Maryland, and part of Virginia comprised the PJM Interconnection market's regulatory bounds. PJM facilitates trade among regulated utilities and independent producers involved in the generation, transmission, and distribution of electricity. In doing so, the wholesale market attempts to lower utilities' costs of providing power to customers.

In 1998, the PJM wholesale electricity market established a new pricing network to facilitate inter-utility trading.[27] PJM required firms to offer non-binding bids to supply electricity from each generating unit into a day-ahead uniform-price auction. In the first year of the market, PJM mandated that bids equal marginal costs. Years of regulation rate hearings resulted in well understood cost measures. In April 1999, the market operators restructured the market again by allowing for competition in the wholesale electricity spot market. The Federal Energy Regulatory Commission granted most firms the right to switch from "cost-based" bidding to unregulated, "market-based" bidding, subject to a \$1000/MWh cap.

Figure 6 plots the market supply curve that consists of a mix of nuclear, hydroelectric, coal,

[25] From 1998 to 1999, Delmarva installed low NOx burners at two boilers at its Indian River plant. Baltimore Gas & Electric installed oven fired air controls at two boilers at its C.P. Crane plant. It also installed low NOx burners at a boiler in its Gould Street plant and in a boiler at its H.A. Wagner plant. Finally, PECO installed biased firing alternate burners at two boilers at its Eddystone plant and low NOx burners at two other boilers at the same plant. This is based on EIA form 767.

[26] The EPA compiles data on electricity generators in the Egrid data set. Egrid includes data on the annual average emissions rate of SO_2, NO_x, and carbon dioxide (CO_2) for each power plant in the U.S. For the plants in PJM, I calculated the change in plant emissions rates from 1998 to 1999 and regressed this on a constant. Changes in emissions rates from technological adoption are decided jointly at the level of the firm. Therefore, the standard errors were corrected for common shocks within a utility using Stata's cluster command. Rates were lower in 1999 but none of the changes were significant at the five percent level. SO_2 rates fell 0.76 lbs. per MWh (with a standard error of 0.37), NO_x rates fell 0.74 lbs. per MWh (s.e. of 0.76), and CO_2 fell 0.057 tons per MWh (s.e. of 0.046).

[27] PJM accommodates transmission constraints by using what is known as "nodal" pricing. Each of the over 2000 nodes is a point of energy supply, demand, or transmission.

natural gas, and oil energy sources.[28] Panel A of Table 1 shows the eight largest firms' capacity by fuel type.[29] The four largest firms–Public Service Electric, PECO, GPU, and PPL–account for two thirds of the market's 57,000 megawatts (MW) of capacity and use all these energy sources. Nuclear and coal plants provide baseload generation capable of covering most of the demand. Nuclear power comprises 45 percent of generation but only 24 percent of capacity. In contrast, natural gas and oil burning units provide over 35 percent of the market's capacity, yet they operate only during peak demand times. These differences in production result from heterogeneous cost structures. Baseload units have low marginal costs but are expensive to start and slow to increase production. In contrast, the relatively flexible peaking units are more expensive to operate.

Emissions rates vary substantially both within and across fuel types. Figure 7 shows the SO_2 emissions rates, which correspond to the units in Figure 6, using data from the EPA's Continuous Emissions Monitoring System (CEMS).[30] Coal units tend to emit more SO_2 than oil units while natural gas only has trace amounts of SO_2. Table 2 provides the summary statistics of emissions rates by fuel type using CEMS data for 1998. Coal units' average SO_2 emissions rate of 20.3 lbs per MWh is approximately three times that of oil units (7.0) and vastly higher than gas units (0.0). For NO_x emissions rates, coal units' rates are, on average, 5.8 lbs. per MWh. This average is greater than the average for oil (3.5) or gas (0.9) but not as dramatically different as SO_2 emissions rates. Carbon dioxide (CO_2) emissions rates vary the least across fuels (coal is 2198, oil is 1790, and gas

[28] The data are for marginal costs on April 1, 1999. See Mansur (2004a) for a discussion of how this was calculated.

[29] The capacity data are from EIA Form 860 for 1999.

[30] In order to comply with the 1990 Clean Air Act, fossil-fuel generating electric producers are required to report hourly emissions and electricity production by unit. Regulation affects units of 25 MW capacity plus new units under 25 megawatts that use fuel with a sulfur content greater than 0.05% by weight. CEMS records hourly gross production of electricity, heat input, and emissions of SO_2, NO_x, and carbon dioxide for most fossil units in the country. During the summers of 1998 and 1999, CEMS monitored 234 units that accounted for over 97 percent of PJM's fossil fuel capacity. Gross generation includes the electricity generated for sales (net generation) as well as the electricity produced to operate that power plant. Typically net generation is approximately 90 to 95 percent of gross generation. I define emissions rates as the ratio of the aggregate summer pollution over the aggregate summer gross generation. CEMS data are highly accurate and comprehensive for most types of fossil units (Joskow and Kahn, 2002).

is 1423) or even within fuels.[31]

In PJM, the large firms are vertically integrated in generation, transmission, and distribution. They sell electricity into the wholesale market, but also must procure electricity to sell to retail customers, called "native load." The rate that the firms can sell to their customers was fixed by regulators. Therefore, Panel B of Table 1 reports each firm's market share of capacity, generation, and peak demand of its customers' native load.[32] On average, the generation of PECO and PPL exceeded their native load. As shown in Mansur (2004a), PECO and PPL reduced output relative to the behavior of other firms.[33]

Table 3 provides descriptive statistics about demand, fossil unit generation, electricity prices, and input prices during the summers of 1998 and 1999.[34] Demand rose three percent while fossil unit generation increased only one percent, causing a greater dependence on imports. The market price was 46 percent higher in 1999, in part because of higher input prices for oil, natural gas, and SO_2 permits. The introduction of the OTC NO_x trading program had the largest impact on costs.

Firms did not respond to these input costs symmetrically. Table 4 reports on the fraction of total capacity used for generation across firm and fuel type during the summers of 1998 and 1999.[35] The behavior of the strategic firms, PECO and PPL, is compared with that of the fringe by fossil fuel type: "dirty" (high SO_2 emissions rate) coal, "clean" (low SO_2 emissions rate) coal, natural

[31] To compare variation in rates within a fuel type, I calculate the coefficient of variation (standard deviation over mean) for each fuel and pollutant. The coefficients of variation for SO_2 rates are: 0.45 for coal; 1.36 for oil; and undefined for gas. The coefficients of variation for NO_x rates are: 0.50 for coal; 0.77 for oil; and 0.89 for gas. The coefficients of variation for CO_2 rates are: 0.14 for coal; 0.26 for oil; and 0.15 for gas.

[32] The generation shares are calculated over April 1 to September 30, 1999, using EIA Form 759 data.

[33] See Mansur (2004a) for greater discussion on the PJM market and an examination of the importance of vertical integration in understanding firm behavior.

[34] Electricity price and quantity data are from PJM Interconnection: www.pjm.com. Natural gas prices at Transco Zone 6 non-New York data are from Natural Gas Intelligence. No. 2 heating oil sold at New York Harbor data are from the EIA. EPA reports monthly average prices of SO_2 permits at two brokerage firms (Cantor Fitzgerald and Fieldston). NO_x costs are from Cantor Fitzgerald's monthly price index.

[35] The fraction of total capacity equals ratio of total summer gross generation over potential gross output. The potential output equals the capacity, which I define as the maximum observed gross output, times the number of hours. Given the possibility of forced outages, I derate the capacity by multiplying it by one minus the forced outage rate.

gas, dirty oil, and clean oil.[36] Dominant and fringe firms had similar production rates in 1998 for most fuel types. In 1999, PECO and PPL production dropped for all fuel types in the sample. The fringe also reduced output from dirty units, however to a lesser degree than did PECO and PPL.

Either cost or incentive asymmetries could cause this disproportional reduction in output by PECO and PPL. If the dominant firms owned units with relatively high NO_x emissions rates, one might expect the OTC program to have affected these firms more so than others. Alternatively, one could presume that PECO and PPL produced inefficiently in exercising market power. In order to separate out these explanations, the following section accounts for cost increases and measures the environmental effects of exercising market power.

3 Measuring Environmental Implications

This section measures the environmental implications of strategic behavior in the PJM wholesale electricity market. For both the summer of 1998 and the summer of 1999, I compare observed emissions (E_j) with emissions from a model of perfectly competitive behavior (E_j^*). The environmental implications of firms exercising market power will depend on dominant firms' reduced emissions and increased emissions from the fringe firms in PJM. Furthermore, as strategic behavior increases prices, there will be greater emissions from imports.

I now calculate the change in SO_2, NO_x, and CO_2 emissions. For T time periods and N units, the change in emissions can be written as:

$$E_j - E_j^* = \sum_{t=1}^{T} \sum_{i=1}^{N} E_{ijt} - \sum_{t=1}^{T} \left[\sum_{i=1}^{N} r_{ij} q_{it}^* + r_{jt}^{imp} \cdot \left(q_t^{imp}(p_t) - q_t^{imp}(p_t^*) \right) \right], \tag{21}$$

where E_{ijt} is actual emissions for unit i, pollutant j, and time t. That unit's emissions rate is r_{ij}. As in section 1, q_{it}^* is unit i's output in a competitive market. Imports (net of exports), q_t^{imp},

[36] High emission rates are defined as those with rates above a pound of SO_2 per mmBTU using emission rates from CEMS. This level was the median emission rate for oil and coal units in the sample. Similar findings result from using NO_x emission rates to stratify unit types.

are a function of price, either actual (p_t) or the competitive simulation (p_t^*). The emissions rate of import supply is r_{jt}^{imp}.

The CEMS data report actual emissions, E_{ijt}, by unit, pollutant, and hour. I aggregate these emissions to compute the total tons of SO_2, NO_x, and CO_2 for each summer. For the competitive counterfactual, I calculate each unit's summer average emissions rates, r_{ij}, using the CEMS data.[37] Below, I discuss the methodologies for estimating q_{it}^*, q_t^{imp}, and r_{jt}^{imp} and then I report and discuss the results of calculating (21).

3.1 Competitive Production Model

I use predictions of competitive behavior, q_{it}^*, that are described in Mansur (2004a). This method has been used to calculate competitive equilibrium in many markets. Two notable papers are by Wolfram (1999) on the England and Wales market and by Borenstein, Bushnell, and Wolak (2002) on the California market.

For each hour t, the model solves for the equilibrium price of a competitive market. Electricity is supplied by some technologies that are capable of responding to prices like fossil units (q_t^f). Mansur (2004a) assumes that other technologies do not respond to prices, like hydroelectric (q_t^h) and nuclear generation (q_t^n). The residual demand that firms in PJM face is equal to the market demand ($\overline{q}_t$), which is perfectly elastic, minus the production from importers (net of exports) into PJM (q_t^{imp}). The equilibrium price, p_t^*, is such that the amount supplied equals the amount demanded:

$$q_t^f(p_t^*) + q_t^h + q_t^n = \overline{q}_t - q_t^{imp}(p_t^*). \tag{22}$$

[37] The emissions rates are equal to the total summer emissions divided by the total summer gross generation. The rates are merged, by unit, with the competitive simulation model described below. That model uses data from PROSYM (Kahn, 2000). The identification of the units in CEMS and PROSYM did not match exactly. For some of the PROSYM units, there were no CEMS emissions rates. For these units, the PROSYM emissions rates were used. As most units were close but not exact matches, the averages of the CEMS and PROSYM rates were used. For CO_2 emissions, only CEMS rates were available. Any missing rates were replaced with technology specific averages.

Mansur (2004a) estimates the supply curve of net imports as a function of actual price (p_t):

$$q_t^{imp} = \beta_1 \ln(p_t) \cdot Peak_t + \beta_2 \ln(p_t) \cdot (1 - Peak_t) + X_t\gamma + \varepsilon_t, \tag{23}$$

where $Peak_t$ indicates hours between 11 AM and 8 PM on weekdays and X_t includes temperature and indicator variables.

The fossil units are modeled as producing at capacity (K_i) whenever price equals, or exceeds, its marginal cost (c_{it}). Mansur (2004a) uses data on daily input prices for fuels (W_{it}^{fuel}), SO_2 permits ($W_t^{SO_2}$), and NO_x permits ($W_t^{NO_x}$). Costs also depend on unit-specific characteristics of efficiency (*i.e.,* heat rate HR_i), SO_2 emissions rates ($r_i^{SO_2}$), NO_x emissions rates ($r_i^{NO_x}$), and variable operating and maintenance costs (VOM_i). Marginal costs are measured using a formula from historic regulatory rate hearings:

$$c_{it} = VOM_i + HR_i \cdot (W_{it}^{fuel} + W_{it}^{SO_2} r_i^{SO_2} + W_{it}^{NO_x} r_i^{NO_x}). \tag{24}$$

Whenever a firm attempts to generate using unit i, their is some probability, f_i, that the unit will not be able to operate. The model accounts for these "forced outages" by using Monte Carlo simulations. For each hour in the sample, outages are simulated by drawing ξ_{it} from a $[0,1]$ uniform distribution. If ξ_{it} is less than f_i , the unit cannot operate. Therefore, the fossil unit production in a competitive model is:

$$q_{it}^*(P_t^*) = \{ \begin{array}{ll} K_i \text{ if } p_t^* \geq c_{it} \text{ and } \xi_{it} > f_i \\ 0 \qquad \text{otherwise.} \end{array} \tag{25}$$

A competitive price and output for each unit are calculated for each hour and Monte Carlo simulation. A unit's hourly production, q_{it}^*, equals the mean of 100 simulation draws.

3.2 Import's Emissions

When PJM firms exercise market power, generating units throughout the Eastern grid must produce more to satisfy PJM demand. This section estimates the emissions associated with the import supply curve. I calculate the correlation during the summer of 1999 between PJM net imports and production throughout the East. Production data are available from CEMS. Import firms produce based on prices in PJM and their local areas outside of PJM. I use temperature variables to proxy for local prices in other regions. The correlation between a unit's production and total PJM imports is directly examined rather than measuring the impact of PJM price on a unit's production and then imposing that prices affect the aggregate production of firms exactly the same as they affect measured imports. For each unit *i not in PJM*, the following equation is estimated:

$$q_{it} = \alpha_i + \delta_i q_t^{imp} + \phi_{1,i} T_{it} + \phi_{2,i} {T_{it}}^2 + \varepsilon_t, \tag{26}$$

where q_{it} is hourly production, q_t^{imp} is PJM imports (net of exports), and T_{it} is the unit i's state daily mean temperature. The estimated $\widehat{\delta}_i$ coefficients are calibrated to sum to one, imposing that the total change in imports equals the total change in production outside of PJM:

$$\widetilde{\delta}_i = \widehat{\delta}_i / \sum_{j=1}^{M} \widehat{\delta}_j, \tag{27}$$

where M is the sample of units in the Eastern grid not in PJM. The implied emissions from imports equal $q_t^{imp} \cdot (\sum_{i=1}^{M} \widetilde{\delta}_i r_{ij})$, where r_{ij} is the emissions rate for unit i and pollutant j. Estimates of imports in the competitive scenario are measured in Mansur (2004a).[38] Over the summer of 1999, actual imports were greater than those predicted by the competitive model by a total of 463,587 MWh.

3.3 Results

Table 5 reports total summer emissions in PJM using actual and predicted data from the competitive model in Mansur (2004a). From the summer of 1998 to the summer of 1999, actual emissions fell substantially. SO_2 emissions fell from 631,898 tons in 1998 to 539,602 tons in 1999. This is a

[38] The simulation of competitive imports results from actual prices (p_t) exceeding the competitive price estimates (p_t^*). For these hours, the competitive imports would be less than actual imports by the amount $\beta_l \cdot [\ln(p) - \ln(p^*)]$ where β_l is estimated in Mansur (2004a) and differs by l for peak and off-peak hours.

15 percent reduction. NO_x emissions had an even larger percent drop of 21 percent between these summers. CO_2 emissions fell 6,976,420 tons, or nine percent.

The competitive model's predictions of changes in emissions are smaller than those observed. I find that the implied reduction in PJM emissions explained by cost and demand shocks was only 41,883 tons of SO_2, which is a reduction of eight percent. NO_x emissions decreased 14 percent, or by 26,024 tons. CO_2 emissions were reduced by 5,132,820 tons (six percent). Note that for 1998 the model predicts fewer SO_2 emissions but greater NO_x and CO_2 emissions than actually occurred. Actual and simulated emissions may differ because of production complexities that the simulation does not take into account.[39] I assume that these differences do not change over time.

In addition, strategic behavior increases imports relative to a competitive model. This results in more pollution in other areas. I use CEMS data on r_{ij} and the $\widetilde{\delta}_i$ to calculate the increased emissions from imperfect behavior in PJM for the summer of 1999. I find that importing regions increased emissions by 1637 tons of SO_2 emissions, 722 tons of NO_x emissions, and 339,018 tons of CO_2 emissions. As these emissions would not have occurred in a competitive market, I subtract them from the competitive estimates.

The changes in competitive estimates are between a half and two thirds of the changes in actual emissions. These estimates account for the emissions from imports. The competitive estimates predict a reduction of nine, 13, and six percent for SO_2, NO_x, and CO_2 emissions, respectively. I attribute the difference between these percentages (six, eight, and three percent, respectively) to market imperfections such as firms setting prices.[40]

This suggests that, of the observed reduction in SO_2 emissions from 1998 to 1999, 42 percent resulted from market imperfections. For NO_x emissions, I attribute 36 percent of the actual reduc-

[39] Cost non-convexities arise because of intertemporal constraints, or unit commitment problems, such as start up costs and ramp rates. When a firm starts a unit, it incurs large costs. This will alter how actual units are used relative to the competitive model in Mansur (2004a). See Mansur (2004b) for a discussion of how these costs may impact welfare calculations.

[40] As discussed in section 1, these environmental effects will be overstated if permits are endogenous.

tion to imperfections. Finally, for CO_2 emissions, 33 percent of the actual reductions are attributed to strategic behavior and other market imperfections.

3.4 Discussion

This section discusses the environmental implications of restructuring. In particular, I determine the value of the pollution reductions that resulted from firms exercising market power in PJM. Under tradable permit systems, production distortions *cannot* affect aggregate emissions. These systems place system-wide caps on the total amount of pollution emitted. The firms can trade permits for the right to pollute so long as the total cap is not exceeded. Reducing demand for permits in one part of the system allows for increased pollution elsewhere. Although aggregate emissions will be unaffected, the distribution of pollution may change as a result of firms exercising market power. This emission distribution could be of potential importance if environmental and health damages depend on spatial and temporal factors.[41]

However, if the imports came from outside of the OTC region, such as from Ohio, then exercising market power would increase the overall NO_x emissions. Any emissions reduction in Delaware, New Jersey, or Pennsylvania will be offset by increases within the OTC region, either across space or time, due to the trading and banking nature of the pollution cap. Thus, importing electricity from Ohio will result in even more emissions. This may not be the case for SO_2, as only some firms were regulated by Phase I, or for unregulated CO_2.

Even if no health or environmental effects resulted from restructuring the PJM electricity market, the reduction in local pollution has economic effects. Since less pollution occurred in PJM, there are temporarily more unused permits available. Firms elsewhere in the OTC tradable permit market, like in New York, can now purchase these permits. The total pollution level will be the same in equilibrium, but now the firm in New York no longer needs to install expensive abatement

[41] However, the issue of distributional effects is one of the optimal size of a permit system's region.

technology as it would have done without the excess permits from PJM. In other words, society forgoes expenditures on abatement technology, reducing the overall cost associated with complying with environmental regulation.

In order to measure the economic consequences of the pollution reductions, I make the following assumptions for this section only. I assume that the SO_2 and NO_x permit markets are competitive, implying that the permit prices accurately reflect the marginal cost to society of abating pollution. Furthermore, I assume that permit prices are exogenous to firm behavior. I also assume that the permit price reflects the marginal damages to society. If a firm not under an environmental regulation changes its emissions, then society values changes at the permit price. Finally, this paper does not put a monetary value on the CO_2 reductions. The value of SO_2 and NO_x emission reductions equals the permit prices times the amount of pollution that is reduced.

These assumptions lead to the following welfare implications. In the summer of 1999, I estimate that actual SO_2 emissions were 41,883 tons below my competitive estimates. This amount equals less than one percent of the total reductions mandated by the Clean Air Act Amendments. Multiplying daily SO_2 permit prices and emission reductions and aggregating over days yields a value of \$10.4 million. That summer's NO_x emissions were 26,024 tons below my competitive estimates. This amount equals about a third of the system's mandated reductions and corresponds to \$30.0 million. Therefore, over a single summer, the total value of reduced pollution in PJM is \$40.4 million.

Ignoring any responsiveness of permit prices to PJM firm behavior will lead to estimates that overstate welfare losses and understate compliance cost savings. To influence permit prices, firms need to be relatively large in comparison to the permit market. PJM firms have historically emitted a substantial 68 percent of the NO_x emissions in the OTC market. The two firms that likely exercised market power, PECO and PPL, account for 14 percent of the OTC region's emissions.

These dominant firms may be capable of affecting the NO_x permit price, depending on the price elasticity of abatement.[42] The following section simulates how NO_x permit prices respond to market power in the PJM electricity market and quantifies the welfare impacts of policy choices.

4 Simulation of Prices versus Quantities

Section 1 discussed the theoretical impacts of environmental regulation on welfare when firms exert market power in a product market. In this section I measure the economic significance of this consideration. Specifically, the question I ask is: what would be the *additional* deadweight loss in the PJM electricity market had a tax been implemented instead of a permit system? As argued above, I assume the tax would have been set optimally assuming competitive behavior. Recall that the strategic firms in PJM are dirtier than those in the fringe. So, exercising market power will result in decreased demand for permits. The permit price would fall relative to a tax. This lower permit price gives incentives for the strategic firms to produce more than they would under a tax, and therefore, cause less distortion to the economy. Again, I assume that the slopes of the marginal benefits and marginal costs of abatement are equal so that the welfare implications are solely a function of the impacts on the electricity market.

The estimation of the welfare implications requires modeling the regulators tax level decision and the strategic firms' production behavior under this scenario. This requires a permit supply model for firms outside PJM and a model of firm behavior in the PJM electricity market. The strategy is first to determine what the permit price would have been had the firms in PJM behaved competitively. In equilibrium, the increase in emissions in PJM as the market changes from a strategic "regime" to a competitive one must equal the increase in abatement by firms outside of PJM. Given the equilibrium price, I assume that regulators would have set the tax at this intended

[42] Even if no single firm exercises market power in the permit market, a shift in the marginal abatement cost function caused by firms exercising market power in the electricity market may affect permit prices.

level and then simulate how strategic firms would have produced. As demand is assumed to be perfectly inelastic, the welfare effects of a tax are the extra production costs. These costs include the environmental externality that is valued at the tax level. This assumes optimal regulation whereby the tax equals the marginal external cost.

The section begins by describing the model of abatement supply outside of PJM. Then I model firm behavior in the PJM electricity market for both the competitive and strategic regimes. Finally, the simulation method is discussed and the results are presented.

4.1 Model of Permit Supply

From May to September, the OTC NO_x permit market regulates firms in PJM, New England, and New York. During 1999, OTC did not apply to firms in Maine, Maryland, Vermont, Virginia, and Washington, D.C. The number of permits are fixed. If the PJM firms pollute more, the other firms in New England and New York must abate an equal amount.[43] To clear the PJM firms' demand for extra permits with these non-PJM firms' supply, the permit price will rise.

The degree to which the price rises depends, in part, on the elasticity of the non-PJM firms' supply of abatement. NO_x pollution can be abated by installing technologies such as "SCR" and "NSCR," by reducing the burning efficiency of a power plant, and by improving the monitoring of the production process. Some of this technology was installed in preparation for this regulation. I assume that these capital investments are fixed in the short run and that firms could not change these investment decisions during the first summer of the regulation. In the short run, firms can abate pollution by not operating. The firm forgoes profits but no longer needs to purchase or to hold on to a pollution permit. It is this trade-off of profits for permits that determines my abatement supply curve.

In order to construct this curve, I model the permit market and the New England and New

[43] This market allows firms to bank permits for future summers. However, this feature would be extremely complex to model as it would require considering multiple years of permit supply and demand.

York electricity markets as competitive. Recall from (10), the short run marginal cost of abatement (MCA) of a firm taking prices as given is equal to the rents ($P - c'(q)$) divided by the emissions rate (r). For the period of May to September, I construct an abatement supply curve by measuring the hourly MCA for each power plant regulated by OTC but not in PJM. To measure the market price (P), I use the hourly system-wide price from the New England ISO for the New England firms. New York did not restructure until the following winter. Therefore, I use the New England price as a proxy for the New York electricity price. The price is assumed to be exogenous to individual cost shocks. Further, I do not model the New England electricity price as a function of the permit price. Note that if electricity prices are endogenous, then more abatement will mean higher permit prices and higher electricity prices. This will increase the slope of the abatement supply curve. As will be shown below, my assumption leads to a conservative estimate of the welfare impacts.

The EPA's Egrid database includes information on a power plant's heat input, electricity output, capacity, emissions, primary fuel source, and regulations. Fuel costs are determined from three sources: the New York city gate natural gas spot market; the EIA's form 767 spot coal prices by power plant; and the New York oil spot market.[44] The daily marginal costs ($c'(q)$) are defined as the sum of fuel costs, variable operating and maintenance costs, and SO_2 pollution costs.[45] These costs do not include the costs of the NO_x regulation.

From these data, I construct the abatement supply curve. If the hourly price equals or exceeds a plant's marginal cost, then that plant can abate up to its capacity times its emissions rate that hour. I sort the quantity of abatement by the plant-hour's MCA. Then I calculate a cumulative abatement function, assuming a linear fit of abatement for observations with MCA below \$5000/ton. An OLS regression implies that for every additional ton abated by firms outside of PJM, the permit price will increase by \$0.1053/ton.

[44] Mansur (2004a) discusses the oil and natural gas data. Keohane (2002) uses the coal data.

[45] Data on variable O&M costs are not readily available so I assume them to be \$2/MWh for all power plants. The SO_2 pollution costs apply to power plants regulated by Phase I of the 1990 Clean Air Act Amendment's Title IV.

4.2 Model of Competitive and Strategic Behavior

This subsection adapts a model of competition and Cournot behavior from Bushnell, Mansur, and Saravia (2004, henceforth BMS). As noted in Mansur (2004a), some firms in PJM had incentives to increase prices as they sold a substantial amount of energy, q, in the wholesale market. Other firms had obligations to serve large amounts of electricity, or native load, (q^c) to retail customers at fixed rates. These firms may have benefited from lower wholesale prices. The difference between a firm's production of q and retail obligations of q^c, or "net positions," affect firms' incentives. The first order condition is a modification of (8):

$$P(q) + P'(q) \cdot (q - q^c) = c'(q) + \tau(q) \cdot r + \tau'(q) \cdot (qr - \overline{e}), \tag{28}$$

where now firms profit from higher prices only on the amount sold in the market net of the contracts. BMS discuss and account for these net positions. That paper's model uses a firm's first order condition of profit maximization to solve for equilibrium in the PJM electricity market.

As discussed above, Hahn (1984) and others have examined the importance of firms exercising market power in permit markets. If the allocation of permits, $\overline{e}$, is similar to the amount emitting by a strategic firm, then the term last term of (28), $\tau'(q) \cdot (qr - \overline{e})$, will be small. Recall from the discussion of Panel B of Table 1 that the two firms likely to set prices in the wholesale electricity market are PECO and PPL. These firms emitted 120 and 74 percent as much NO_x as they were allocated in permits, respectively.[46] For this section, I assume that firms did not behave strategically in the permit market and focus on the impact of policy choice on welfare in the product market. For a given permit price, I simulate how much each firm in PJM would have produced under both the competitive and Cournot regimes.

[46] Using CEMS data, I calculate that during the period of OTC regulation, PECO emitted 3554 tons of NO_x. In contrast, the firm was allocated permits for 2939 tons of NO_x (See http://www.pacode.com/secure/data/025/chapter123/s123.121.html). PPL emitted 14,785 tons and was allocated permits for 20,027 tons.

Regardless of whether firms take prices as given or act strategically, they will produce a given amount using their least costly generating units. The BMS model includes data on marginal costs, capacity, and emissions rates for all polluting units. I use these data to determine each firms' hourly emissions. This allows me to compare aggregate emissions across regimes and permit prices.

4.3 Simulation Results

The simulation is solved in several steps. I begin by modeling the permit price assuming firms actually behave as Cournot firms in the PJM electricity market. BMS find supporting evidence of this assumption. The actual permit price was volatile during the summer of 1999; the price started near \$5000/ton and eventually settled around \$1000/ton. In comparison, a tax would have been constant throughout this period. It would be difficult to interpret the effects of a volatile permit price relative to a tax. Therefore, I model the permit price as a constant equal to the price that permits were trading at in late September. This is when firms had to demonstrate compliance. I model the permit price as equal to \$1000/ton.

Second, I use the BMS model to estimate firm behavior in PJM when OTC was in effect. From May 1 to September 30, 1999, the Cournot model simulation predicts that the firms regulated by OTC emit 88,222 tons of NO_x (see Table 6). In contrast, these same firms would have emitted 100,936 tons, an increase of 11 percent, if they had taken prices as given. Therefore, PJM firms in a competitive regime would have demanded 12,713 more permits than those in a Cournot regime. This increase in demand for permits results in a higher permit price. If the firms in PJM behaved the same regardless of the permit price, then based on the permit supply estimates above, the price would have been \$2338/ton.[47] However, the PJM firms do change their production decisions as the permit price increases.

I solve this simultaneity problem by iterating between the two models discussed in subsections

[47] That is, the initial \$1000/ton plus the slope of \$0.1053/ton times the change in emissions of 12,713 tons.

4.1 and 4.2. I begin by picking a permit price. Then I measure the quantity of abatement, or number of permits, supplied by firms outside of PJM at that price. Next I determine the amount of permits demanded by competitive firms in PJM at that price and compare that level with the amount demanded in the benchmark case: *Cournot firms at the $1000 price.* I vary the permit price until one is found that equates supply and demand. At the equilibrium price of $1934/ton, the firms in the competitive market emit 97,096 tons, which is 8874 more than the Cournot equilibrium emissions. To meet this extra demand for permits, the permit price rises by 93 percent, a level well within the range firms actually faced during that summer.

I assume that the marginal external cost of NO_x emissions equals $1934/ton. In an attempt to optimize welfare, regulators who assume a competitive PJM market would set the tax at this amount.[48] As discussed in section 1, deadweight loss is greater under such a tax than under a permit system when firms behave strategically. To quantify this effect, I measure the total variable social cost in the PJM market including the environmental externalities of NO_x pollution. Over the summer of 1999, the variable social costs for the competitive regime totaled $1452 million. This is the case for both a permit system and a tax because the permit price equals the tax of $1934/ton when PJM is a competitive market. The Cournot model predicts costs of $1565 million given the permit price of $1000/ton. This simulation predicts that firms exercising market power in PJM cause deadweight loss equal to $113 million, or 7.8 percent of the variable social costs.

Next, the total variable social costs are estimated assuming a tax. As mentioned, the competitive model costs are the same as above since the tax and permit prices equate. With a tax, the strategic firms distort production even more. The variable social costs, *including* the externality, equal $1573 million. The higher price of pollution resulted in 2002 fewer tons, a reduction of 2.7 percent. The value of this pollution reduction is $4.4 million. The benefit of these externalities have been taken into account in the simulation's measure of total cost. In other words, the costs to the firms are

[48] This first best solution ignores any tax interaction effect (see Goulder, Parry, and Burtraw, 1997).

$12.7 million greater under the tax in comparison to the permit system, but society also values the cleaner air under a tax. Thus, relative to a permit system, social costs in PJM have increased by $8.3 million under a tax even though there is less pollution.

In addition, the equilibrium price under the tax is greater than that under the permit system. The higher prices imply greater imports of electricity, which are costly. I assume that electricity imports are competitive. The area under the import supply curve between the electricity price with the permit and that with the tax represents additional variable costs. These costs total $3.0 million.

Therefore, a tax would have increased the deadweight loss in PJM by $11.3 million in one summer. This is equal to 7.4 percent of the total welfare loss associated with strategic behavior in this market. In addition to these welfare effects, retail customers pay more for electricity under a tax. The simulated electricity price for the Cournot regime averages $52.85/MWh under a tax, slightly more than the $51.89/MWh average under a tradable permit system. If all electricity traded at these prices, then the procurement costs of buyers in the wholesale market would have increased by $102.4 million under a tax relative to a permit system. Recall these costs are for one market and one summer only. If similar margins exist in other pollution regulations, the overall impacts on welfare and transfers may be substantial.

5 Conclusions

Policy makers developing incentive-based environmental regulation should consider the consequences of firms exercising market power in product markets. When dominant firms are dirtier than the fringe, exercising market power reduces pollution from the product market and lowers prices in permit markets. The optimal pollution cap is lower than under perfect competition. When dominant firms are cleaner than the fringe, the opposite conclusions are drawn. However, altering the environmental regulation could increase welfare loss in the product market. In this second best setting, the overall welfare effects must be considered.

Market conditions influence whether a permit system increases welfare in comparison to a tax. In this paper, I suppose that the environment policies optimize welfare assuming perfect competition in all markets. This may result from regulators being slow to adjust to the introduction of strategic behavior. Alternatively, environmental policy makers may ignore issues of competition because of regulatory jurisdiction.

Tradable permits may be preferable to taxes when firms set prices in product markets.[49] When the fringe has lower emissions rates than the dominant firms, permit prices fall as market power is exercised. A permit system will be preferable to a tax if dominant firms' marginal costs decrease by more than their marginal revenues (which depend on the fringe's marginal costs). In the case in which the fringe is dirtier, strategic behavior increases the permit price. This may increase the dominant firms' marginal revenue more so than its costs. As an application of the theory of the second best, when regulators initially determine optimal environmental policy assuming competitive product markets, the presence of strategic behavior in product markets may make tradable permits preferable to a tax.

In the summer of 1999, firms in the PJM wholesale electricity industry exercised market power and caused production inefficiencies. I measure the impacts of market power on pollution emissions by comparing observed behavior with estimates of competitive production choices. Between the summers of 1998 and 1999, actual SO_2 emissions fell 15 percent, NO_x emissions fell 21 percent, and CO_2 fell nine percent. Using a model of competitive behavior, I account for approximately 58 percent of the SO_2 emission reductions typically attributed to new environmental regulation. The remaining 42 percent may be ascribed to market imperfections. For the NO_x and CO_2 emission reductions, I attribute 36 and 33 percent of the reductions, respectively, to strategic behavior.

[49]If marginal damages and marginal abatement costs have similar elasticities, Weitzman (1974) argued that these policies would have the same expected welfare loss. Relative to this baseline, I argue that permits are less distortionary.

From a policy perspective, these emission reductions have both environmental and cost implications. In the case of CO_2, which does not have a cap limiting total emissions, these findings imply lower environmental damages. When pollution markets exist, these findings imply lower costs of abatement for firms overall. Since less NO_x pollution occurred in PJM, to clear the market the extra permits from PJM will be sold at a lower price to firms elsewhere in the OTC tradable permit market. The total pollution level will be the same in equilibrium, however, now firms in New England and New York no longer need to abate as much as they would have done without the excess permits from PJM. For example, these firms may forgo installing expensive abatement technology. For SO_2, Phase I of the Acid Rain Program capped total pollution only for some power plants. Therefore, market power may reduce both SO_2 pollution and permit prices. Holding prices fixed, the reduced demand for NO_x and SO_2 permits resulted in compliance cost savings of $40 million.

Finally, I examine the welfare implications of environmental policy choice when firms are strategic in product markets. I simulate the permit market and firm behavior in the PJM electricity market. This simulation predicts that strategic behavior in PJM dampened the permit price. Had the market been competitive, the permit price would have been 93 percent greater. I then estimate and compare the welfare effects of Cournot behavior at the observed permit price and under a tax. I model regulators as setting the tax optimally given an assumption of competitive behavior in all markets. The deadweight loss from oligopoly behavior would have increased by seven percent if regulators had chosen a tax rather than a tradable permit system.

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Figures and Tables

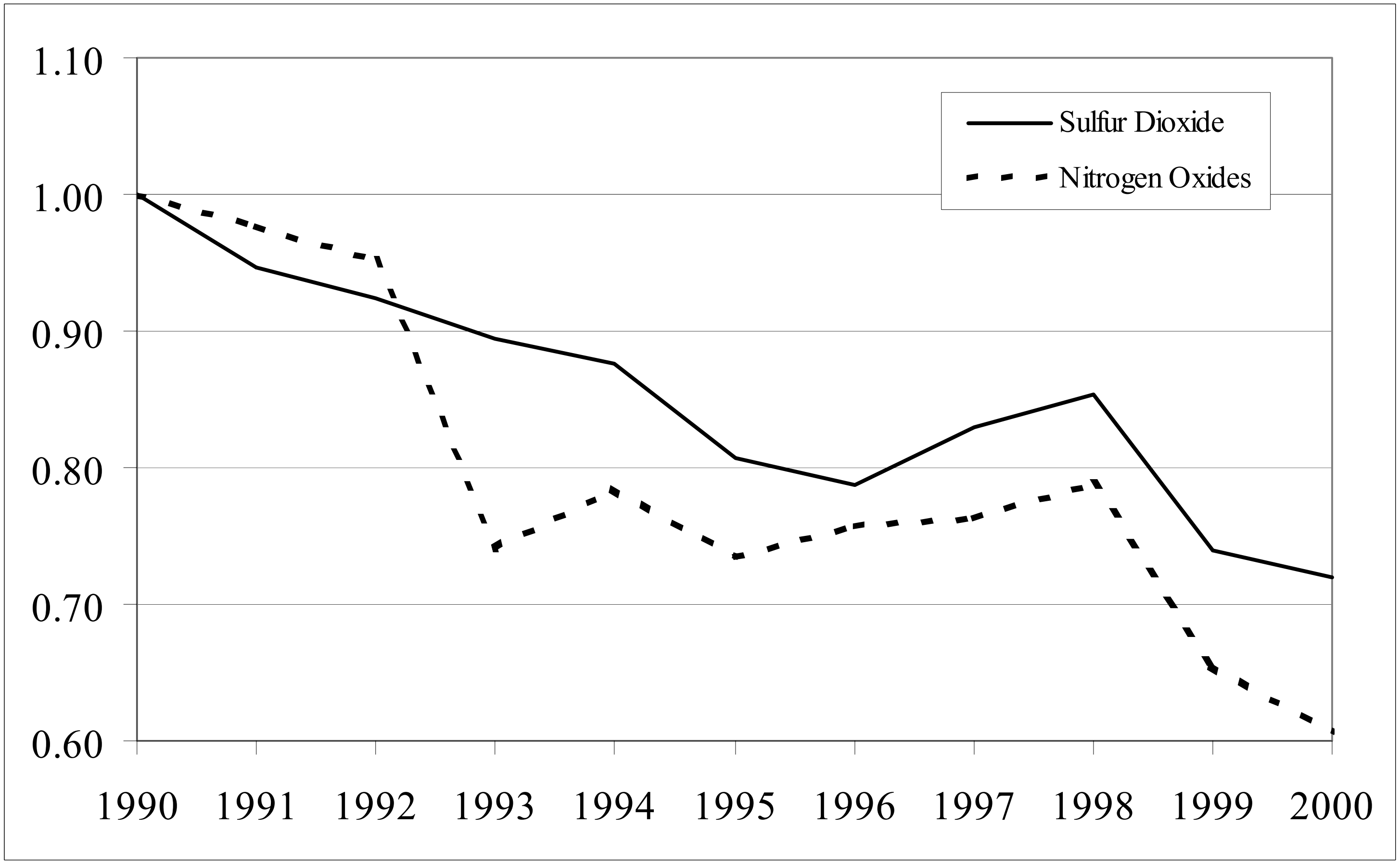

Figure 1: Annual SO_2 and NO_x Emissions from Electricity Generation in the Mid-Atlantic (Pennsylvania, New Jersey, Maryland, and Delaware). Emissions are normalized to 1990 levels: 1,686,000 SO_2 tons and 544,000 NO_x tons.

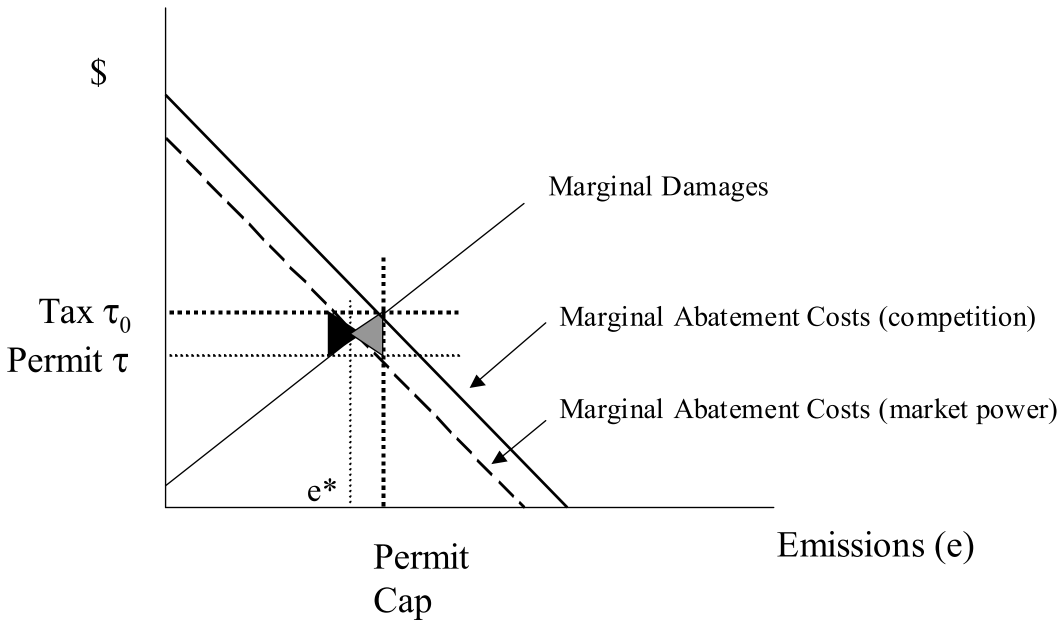

Figure 2: Emissions Implications of Imperfect Product Market Under Pollution Tax versus Tradable Permit System: Case A of a polluting dominant firm.

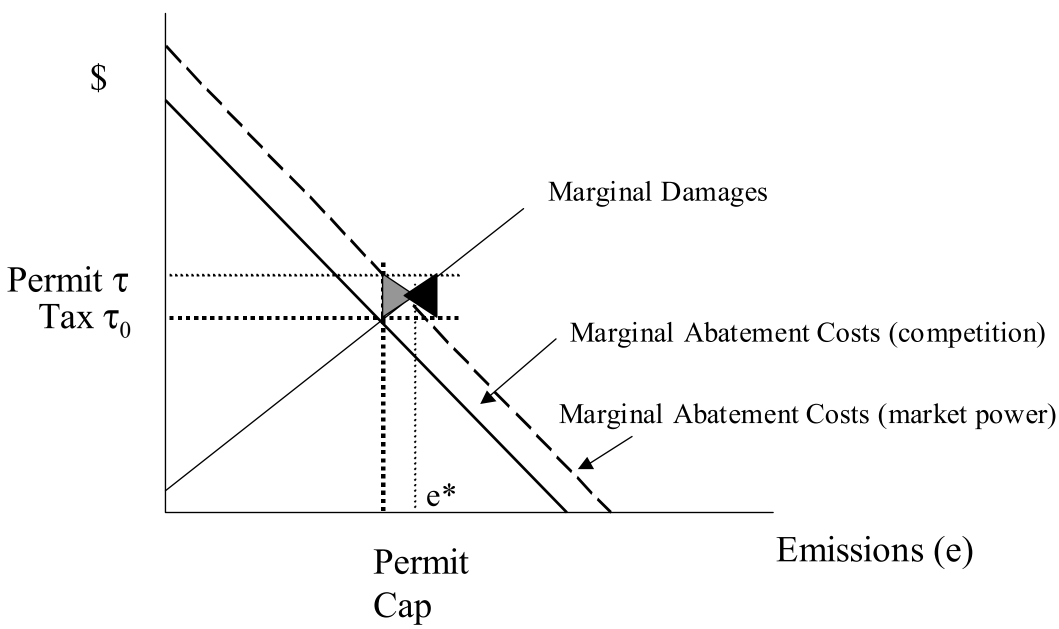

Figure 3: Emissions Implications of Imperfect Product Market Under Pollution Tax versus Tradable Permit System: Case B of a polluting competitive fringe.

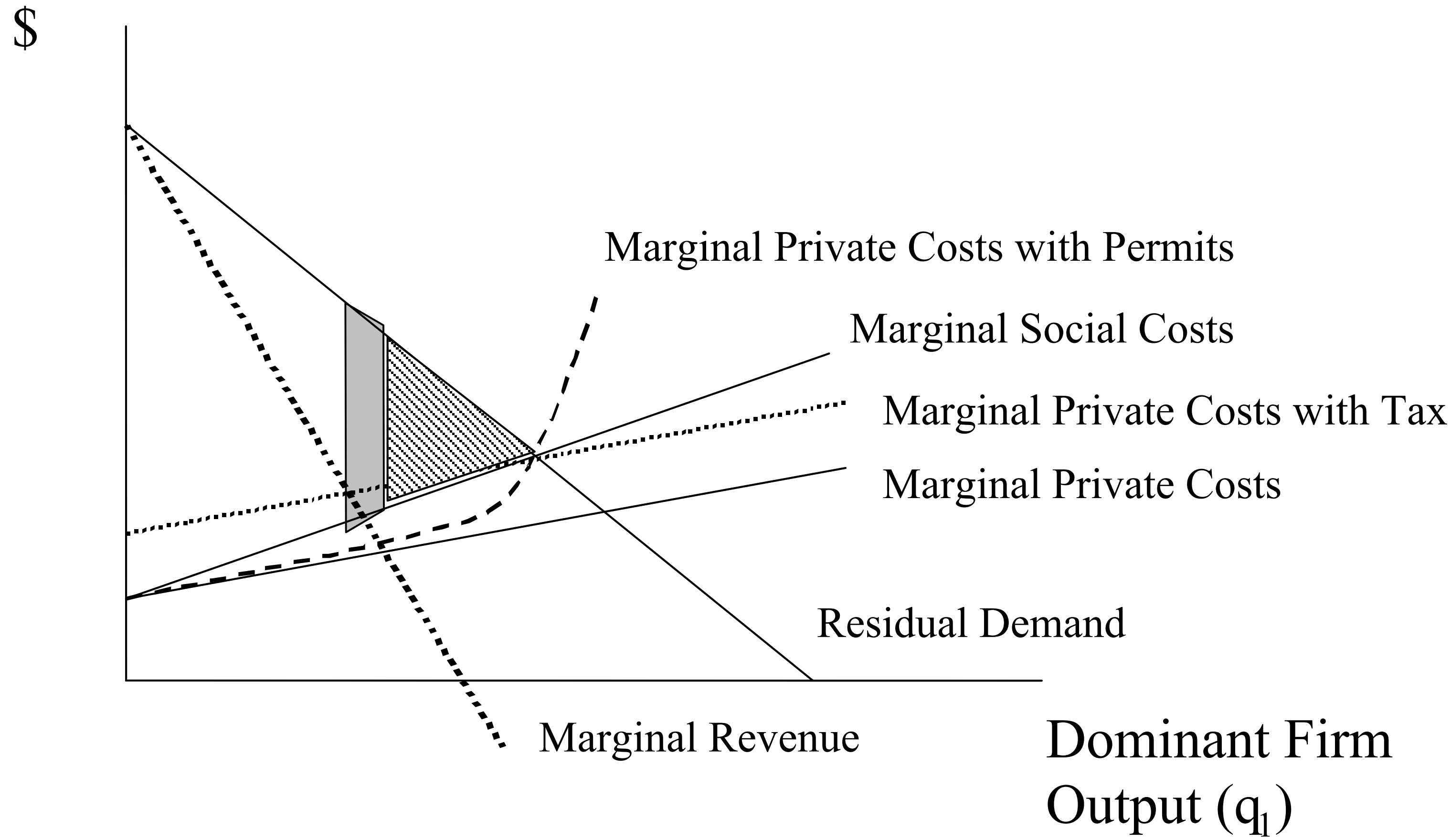

Figure 4: Production Implications of Imperfect Product Market Under Pollution Tax versus Tradable Permit System: Case A of a polluting dominant firm.

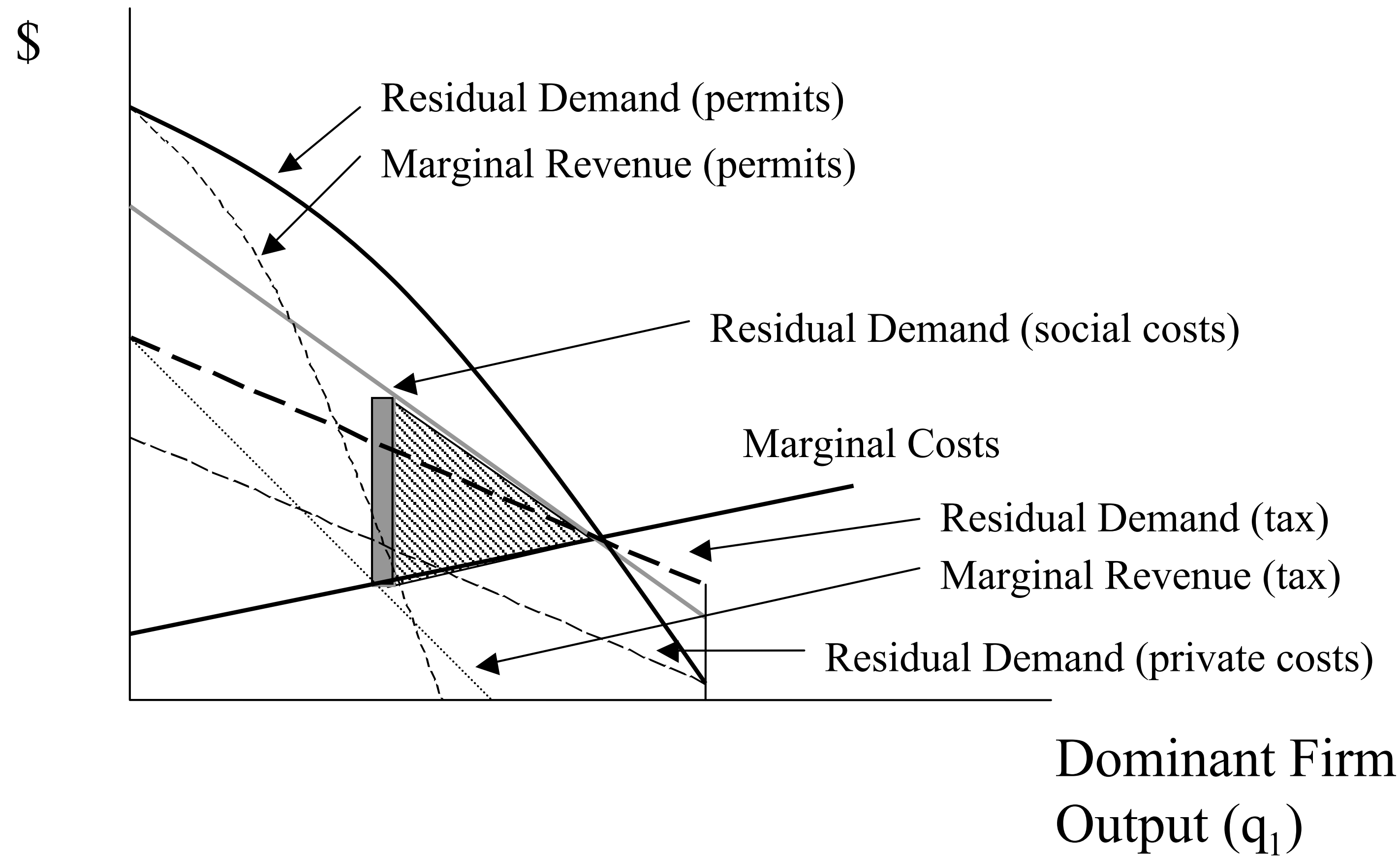

Figure 5: Production Implications of Imperfect Product Market Under Pollution Tax versus Tradable Permit System: Case B of a polluting competitive fringe.

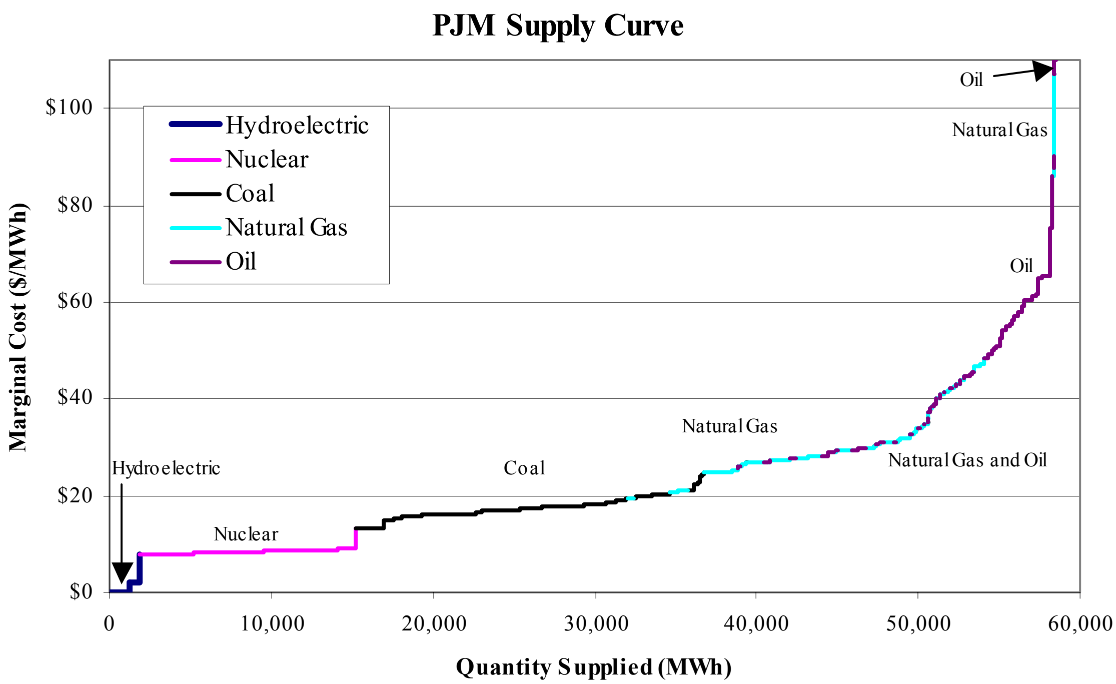

Figure 6: PJM Supply Curve.

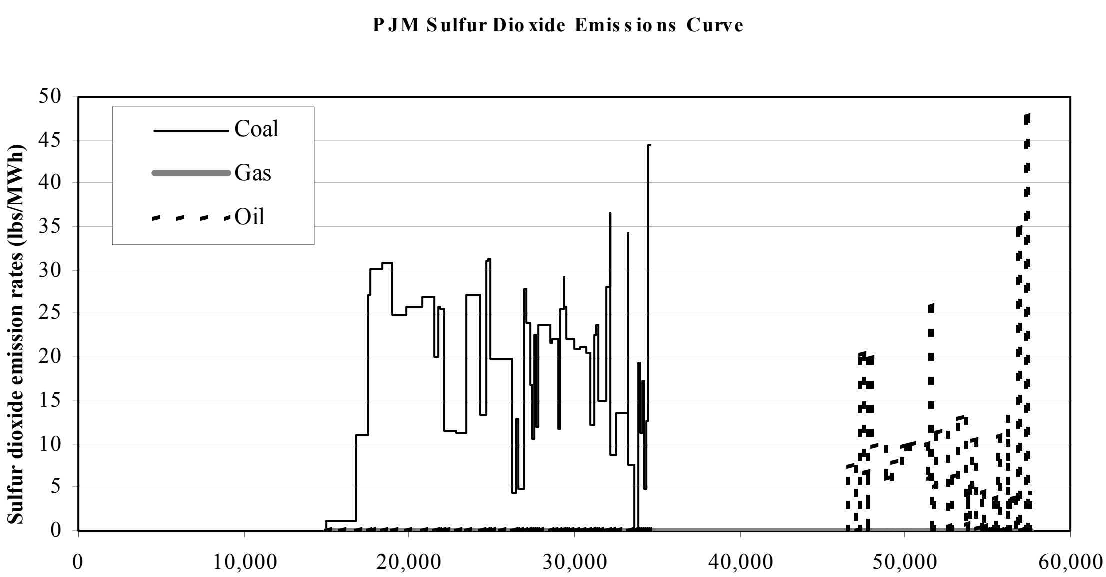

Figure 7: SO_2 emission rates varying along the supply curve.

Table 1

PJM Firm Characteristics

Panel A: Generation Capacity by Firm and Fuel Type in 1999[a]

Firm	Coal	Oil	Gas	Water	Nuclear	Total
Public Service Electric [b]	1,607	1,842	3,311	-	3,510	10,269
PECO	895	2,476	311	1,274	4,534	9,490
GPU, Inc.	5,459	1,816	203	454	1,513	9,445
PPL Inc.	3,923	478	1,701	148	2,304	8,554
Potomac Electric Power	3,082	2,549	876	-	-	6,507
Baltimore Gas & Electric	2,265	925	755	-	1,829	5,773
Delmarva Power & Light	1,259	888	311	-	-	2,458
Atlantic City Electric	391	436	482	-	-	1,309
Other[c]	2,087	353	-	439	-	2,880
Total	20,967	11,762	7,949	2,316	13,690	56,685
Market Share	37%	21%	14%	4%	24%	

Panel B: Market Shares of Capacity, Generation, and Demand by Firm in Summer of 1999

Firm	Capacity	Generation	Demand Served[d]
Public Service Electric	18.1%	14.0%	17.3%
PECO	16.7%	17.8%	8.8%
GPU, Inc.	16.7%	19.8%	14.7%
PPL Inc.	15.1%	15.9%	9.9%
Potomac Electric Power	11.5%	10.1%	10.4%
Baltimore Gas & Electric	10.2%	12.5%	11.2%
Delmarva Power & Light	4.3%	3.2%	6.0%
Atlantic City Electric	2.3%	1.1%	4.3%
Other	5.1%	5.6%	17.4%

Notes:

a) Capacity, in megawatts (MW), is listed by primary fuel type used in each generating unit at a power plant, as determined by the EIA. Coal includes anthracite, bituminous coal, and petroleum coke. Oil includes No. 2, 4, and 6 fuel oil and kerosene. The other categories are natural gas, hydroelectric, and nuclear.

b) In 1999, the GPU parent company owned Jersey Central, GPU Nuclear, Metropolitan Edison and Pennsylvania Electric.

c) “Other” includes the following utilities: Safe Harbor Water Power, Easton Utilities, UGI Development, Allegheny Electric Coop, A&N Electric Coop, and cities of Berlin, Dover, Lewes, Seaford, and Vineland.

d) Demand served is share summer peak demand less direct access customers. On July 6, 1999, the system-wide demand reached a peak of 51,700 MW. Source: EIA Form 861, 1999. In 1999, many Pennsylvania customers switched to alternative providers, leaving GPU (3.4 percent of total market demand), PECO (5.6 percent), and PPL (2.5 percent). “Other” demand includes direct access customers. Source: www.oca.state.pa.us.

Table 2

Summary Statistics on Emission Rates (lbs. per MWh) by Fuel

Fuel Type	Emission	Obs.	Mean	Std. Dev.	Min	Max
Coal	SO_2	60	20.3	9.2	1.2	44.6
	NO_x	60	5.8	2.9	2.6	18.9
	CO_2	60	2197.9	307.7	1797.9	3382.6
Gas	SO_2	16	0.0	0.0	0.0	0.0
	NO_x	16	0.9	0.8	0.2	3.1
	CO_2	16	1423.3	216.1	1137.0	1902.7
Oil	SO_2	48	7.0	9.5	0.0	47.8
	NO_x	48	3.5	2.7	0.2	16.3
	CO_2	48	1789.5	468.2	383.8	2990.1
All	SO_2	124	12.5	11.7	0.0	47.8
	NO_x	124	4.3	3.1	0.2	18.9
	CO_2	124	1939.9	459.2	383.8	3382.6

Table 3

PJM Market Summary Statistics During Summers of 1998 and 1999

Panel A: Summer of 1998

Variable	Units	Mean	Std. Dev.	Min	Max
Quantity demanded hourly[a]	MWh	29,650	6,482	17,461	48,469
Electricity price[a]	$/MWh	$26.04	$43.46	$0.00	$999.00
Natural gas price[b]	$/mmbtu	$2.33	$0.25	$1.80	$2.81
Oil price[c]	$/Barrel	$16.30	$1.36	$13.99	$19.17
SO_2 permit price[d]	$/Ton	$172.44	$24.40	$136.50	$198.50
NO_x permit price[e]	$/Ton	N/A	N/A	N/A	N/A

Panel B: Summer of 1999

Variable	Units	Mean	Std. Dev.	Min	Max
Quantity demanded (hourly)	MWh	30,459	7,156	17,700	51,714
Electricity price[a]	$/MWh	$37.97	$100.99	$0.00	$999.00
Natural gas price[b]	$/mmbtu	$2.60	$0.27	$2.08	$3.28
Oil price[c]	$/Barrel	$20.56	$2.91	$16.55	$26.04
SO_2 permit price[d]	$/Ton	$202.71	$9.23	$188.00	$211.50
NO_x permit price[e]	$/Ton	$2,406	$1,756	$0	$5,244

Table 4

Fraction of Capacity Used for Generation by Ownership, Fuel Type, and Emissions Rate

Panel A: Fringe Producers

Fuel Type	Summer of 1998	Summer of 1999	Change
Coal (High Emis Rate)	0.820	0.813	-0.008
Coal (Low Emis Rate)	0.814	0.811	-0.003
Gas	0.632	0.578	-0.054
Oil (High Emis Rate)	0.518	0.550	0.032
Oil (Low Emis Rate)	0.606	0.596	-0.010
Total	0.769	0.756	-0.013

Panel B: PECO

Fuel Type	Summer of 1998	Summer of 1999	Change
Coal (High Emis Rate)	0.169	0.117	-0.051
Coal (Low Emis Rate)	0.738	0.671	-0.068
Gas	0.005	0.170	0.165
Oil (High Emis Rate)	0.171	0.113	-0.058
Oil (Low Emis Rate)	0.644	0.503	-0.141
Total	0.645	0.564	-0.082

Panel C: PPL

Fuel Type	Summer of 1998	Summer of 1999	Change
Coal (High Emis Rate)	0.749	0.746	-0.003
Coal (Low Emis Rate)	0.759	0.659	-0.100
Gas	0.049	0.138	0.090
Oil (High Emis Rate)	0.640	0.487	-0.153
Oil (Low Emis Rate)	0.671	0.626	-0.044
Total	0.725	0.675	-0.050

Table 5

PJM Summer Emissions

	Summer of 1998	Summer of 1999	Change	Percent Change
SO_2 Emissions (tons)				
Actual	631,898	539,602	-92,295	-14.6%
PJM competitive estimates	513,780	471,897	-41,883	-8.2%
Change in import emissions	0	1,637	1,637	
Total competitive estimates	513,780	470,260	-43,520	-8.5%
Difference	-118,118	-69,343	-48,775	-6.1%
Percent difference				42.0%
NO_x Emissions (tons)				
Actual	174,063	138,014	-36,049	-20.7%
PJM competitive estimates	202,919	176,895	-26,024	-12.8%
Change in import emissions	0	722	722	
Total competitive estimates	202,919	176,172	-26,746	-13.2%
Difference	28,856	38,159	-9,303	-7.5%
Percent difference				36.4%
CO_2 Emissions (1000s tons)				
Actual	74,704	67,728	-6,976	-9.3%
PJM competitive estimates	87,981	82,848	-5,133	-5.8%
Change in import emissions	0	339	339	
Total competitive estimates	87,981	82,509	-5,472	-6.2%
Difference	13,276	14,781	-1,505	-3.1%
Percent difference				33.4%

Notes: Had PJM been competitive, where competitive prices are below actual prices, firms would have imported less into PJM than they actually did. The corresponding changes in emissions are calculated for the summer of 1999. The summer of 1998 is assumed to be competitive. The total competitive estimates equal the sum of the competitive estimates in PJM and the change in the emissions from imports. The difference equals the total competitive estimates minus actual emissions. The percent difference is the ratio of this difference over actual emissions.

Table 6

Simulation of Policy Choice Effects on Emissions and Welfare

	Permit System	Tax	Difference	Percent Difference
Marginal private cost of a ton of NO_x pollution	\$1,000	\$1,934	\$934	93%
NO_x emissions (tons)				
Cournot	88,222	85,923	2,300	2.7%
Competitive[a]	100,936	97,096	3,839	4.0%
Difference	12,713	11,174		
Percent difference	11%	12%		
Additional permits[b]			8,874	10.1%
Variable costs (\$ millions)				
Cournot	1,565	1,573	8.3	
Competitive	1,452	1,452	0	
Welfare loss				
Emissions component			-4.4	
Firm cost component			11.7	
PJM total	113	121	8.3	7.4%
Percent loss	7.8%	8.3%		
Change in Imports			3.0	
Total			11.3	10.0%
Percent loss				

Notes:

a) Under a permit system, the competitive regime's permit price would equal \$1934/ton. The first column holds the price at \$1000/ton (the Cournot regime's permit price) for comparison purposes only.

b) "Additional permits" compares the Cournot regime's emissions at a \$1000/ton permit price with the competitive regime's emissions at a \$1934/ton permit price or tax.