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Welfare Effects of Emission Allowance Trading in a Twice-Regulated Industry

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ABSTRACT

Market-based schemes to control environmental quality have long been a favorite of economists. The 1990 Clean Air Act Amendments will institute such a scheme on a national scale for purposes of scaling back sulfur dioxide emissions from coal-fired utility plants. Utilities already face extensive regulatory oversight designed to control their profits to limit monopoly power. This paper analyzes the effects of the joint utility and environmental regulation upon the workings of an allowance market. We build a two-firm model of an electric utility industry whose member firms face rate-of-return regulation and also an environmental constraint. The familiar incentive to overuse capital can be harnessed through the ratemaking treatment of environmental compliance assets. We perform numerical experiments designed to discover the excess demand and supply of allowances. We compare a benchmark command and control regime to the allowance trading regime under study. We find that the allowance market can improve abatement efficiency and augment social welfare. The regulatory treatment of allowances, however, can also get in the way of efficient environmental control. It is optimal for the utility regulator to include allowance assets in the ratebase, but to exclude most of a utility's scrubber capital.

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Abstract

Market-based schemes to control environmental quality have long been favored economists. The 1990 Clean Air Act Amendments will institute such a scheme on a national scale for purposes of scaling back sulfur dioxide emissions from coal-fired utility plants. Utilities already face rate-of-return regulation designed to control their profits to limit monopoly power. This paper analyzes the effects of the joint utility and environmental regulation upon the workings of an allowance market. We build a two-firm model of an electric utility industry whose heterogenous member firms face rate-of-return regulation and also an environmental constraint. The familiar incentive to overuse capital can be harnessed through the ratemaking treatment of environmental compliance assets. We perform numerical experiments designed to discover the excess demand and supply of allowances. We compare a benchmark command and control regime to the allowance trading regime under study. We find that the allowance market can dramatically improve abatement efficiency and augment social welfare. In our model it is optimal for the utility regulator to include allowance assets in the ratebase, but to exclude most of a utility's scrubber capital. The performance of the allowance market depends importantly upon ratemaking decisions by state utility regulators.

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1. INTRODUCTION

Title IV of the Clean Air Act Amendments of 1990, the acid rain title, calls for the creation of a national market in "emission allowances" that will unleash market forces in the effort to achieve ambitious reductions in sulfur dioxide (SO_2) emissions.[1] By the year 2000, national annual emissions are to be reduced by over half to 8.95 million tons. At least since Pigou (1932), economists have recognized the potential benefits of market-based schemes for environmental protection programs. Montgomery (1972) showed formally that in a full-information, competitive setting no alternative regulatory scheme can achieve a given environmental goal at lower cost. Ironically, the industry targeted by Title IV—the U.S. coal-fired electric utility industry—is as perhaps far removed from the competitive ideal as one can go. Member firms are tightly regulated by state public service commissions (PSCs). The objective of this paper is to examine the effects upon the SO_2 allowance market and upon economic welfare of the extra-environmental utility regulation.

The new law will not be described in detail here.[2] It is, however, worth emphasizing that some questions connected with market-based environmental control may be dispensed with in studying the new acid rain legislation. An extensive literature has examined, for example, effects of the precise arrangement of an allowance market—whether the emission or the deposition of a pollutant are controlled.[3] The new acid rain title regulates emissions without regard for ambient air quality. Under Title IV, any two firms in the country may trade without concern for the effects the trade will have upon the geographical incidence of pollution emissions or deposition.[4] The manner in which

[1] The 1990 Amendments introduce the term *allowance* to denote what has long been called an emissions *permit* in the literature. An allowance grants its bearer the right to emit one ton of SO_2 during or after the year in which it is issued.

[2] For a comprehensive treatment of Title IV of the 1990 Amendments, and the various legal, regulatory, and environmental issues surrounding the allowance trading provisions, see Lock and Harkawik (1991).

[3] Tietenberg (1985), McGartland and Oates (1985), and others have studied the differences between ambient permit systems and emission permit systems. Montgomery (1972) also drew such a distinction.

[4] The sequential trading procedure studied by Atkinson and Tietenberg (1991) does not figure into the new law. There is no requirement that any allowance trade conform to air quality standards at a set of receptor sites. An Ohio valley plant is free to purchase allowances from a utility in New Hampshire, thereby emitting sulfur dioxide that is deposited in New Hampshire.

allowances should be distributed to participating firms has also received considerable attention.[5] With the exception of a relatively modest auction provision for so-called bonus allowances, under Title IV allowances will be issued to firms at zero cost in amounts based upon historical generating levels. Likewise, comparisons between effluent charges and trading schemes, as studied by Spulber (1985) and Kolstad (1986) among others, do not play a role.

This paper considers the behavior of a firm facing multiple regulatory constraints, here at the hands of an environmental and a utility regulator.[6] Less has been said about this matter than one might expect, given the vast regulatory literature. Hahn (1989) models the effects of multiple regulatory objectives sought by a single regulatory authority. Lave (1984) finds that if two or more agencies are involved, their goals in applying multiple regulatory constraints may conflict. The interaction between two regulators with possibly contradictory objectives is also studied by Baron (1985), whose information-based bargaining model examines the strategic interaction between an environmental regulator (the EPA) and a utility regulator. The fact that the environmental goal, a strategic variable for Baron's EPA, is fixed in the law, removes any scope for strategic interaction between the EPA and the PSC.

The model of this paper is of a two-firm utility industry whose member firms face an emissions constraint. Each firm is a rate-of-return (ROR) regulated monopolist that uses a variable input and productive capital to produce electricity for a distinct output market. The firms also produce SO_2, in amounts that depend both on output and on the level of employment of *scrubber* or *abatement* capital (we use these two terms interchangeably throughout). Firms are heterogenous in their pollution technologies—one is dirty and the other clean. The model is similar in some respects to one developed by Bohi and Burtraw (1992), who model explicitly the effects, in the presence of allowance trading, on over-time capital investment plans of rate-making treatment. They draw interesting conclusions about how the PSC should treat allowances in their regulatory decisions, but their model does not capture the important output effects of regulatory policy that we examine. Cronshaw and Kruse (1992) also consider the dynamic nature of allowance trading, looking at the effects of banking of allowances for use in the future. Hahn (1992) considers the

[5] See, for example, Lyon (1986), Oehmke (1987), and Borenstein (1988), all of whom study the effects of various initial allotment schemes, including auctions, upon markets. See also Tripp and Dudek (1986).

[6] In actual practice, the environmental regulator is a federal agency, while the utility regulator is a state agency. This fact alone presents a number of interesting and knotty problems. See Stalon and Lock (1990).

response of regulated firms to joint environmental and rate-of-return (ROR) regulation, but is interested in the effects of various taxation policies. Ours is an equilibrium-based model in which the equilibrium allowance price is endogenous. The simulation exercises presented below, in which firms' equilibrium behavior is investigated, appear to be novel.

We consider two alternative environmental policy regimes: an allowance market and a benchmark command-and-control (CAC) regime. Aggregate pollution, and thus environmental quality, are assumed to be identical under the two regimes.[7] Under the CAC scheme, the PSC must decide whether scrubber capital is to be allowed in the ratebase. Under the allowance scheme a firm may choose from two compliance strategies: use of allowances and use of scrubber capital. The PSC in this case must decide whether these two compliance inputs are included in the firm's ratebase. (Increases in the ratebase generally, though not always, increase the firm's profit levels.) It is upon this rate-making decision by the PSC that our study centers.

The theoretical model is transformed, by the selection of functional forms for the various relationships, into a numerical counterpart. The numerical experiments build in three steps. First, the CAC case is developed, with the fraction of scrubber capital that appears in the ratebase ranging from zero to one. In this example, without allowance trading, profits and economic welfare are maximized when all abatement capital is included in the ratebase.[8] Second, with ratemaking treatment of scrubber capital held constant at three levels (0, 0.5, and 1.0), the fraction of *allowances* that appears in the ratebase ranges from zero to one. In this example we find that for any treatment of scrubbers, welfare is maximized when allowances are included fully. Third, with the treatment of allowances fixed at this optimal level and also at zero, we let the scrubber fraction again range from zero to one, and we find that it is optimal for PSC to *exclude* most scrubber capital from the ratebase.

Two of our primary findings accord with widely-held views concerning market-based environmental schemes. First, allowance trading yields welfare gains compared to the command and control scheme. Second, total abatement costs are reduced with allowance trading. Both of these results must be qualified, however, by noting that they can be reversed under some ratebase policies.

[7]Oates, *et. al.* (1989) consider the possibility for a CAC scheme, as a result of overcompliance, to cause environmental gains that do not accrue when an incentive-based scheme meets the overall standard precisely. Our model does not address this question.

[8]This finding neatly matches reality: in 49 of the states, the PSC *does* include scrubbers in the ratebase (NARUC 1990).

2. The Theoretical Model

Consider a single-period model of a two-firm (ROR) regulated industry whose heterogenous member firms each own two technologies, a *production technology* and an *emission technology*. The ith firm's production technology is given by $q_i = f_i(x_i, k_{1i})$, which relates electricity output q_i to the firm's use of a variable input x_i (say, coal) and a productive capital input k_{1i}. Each f_i is assumed to be differentiable and concave, and to have strictly positive first partial derivatives: $f_x > 0$ and $f_{k_1} > 0$, where f_x denotes partial differentiation of f with respect to variable x. Inputs are purchased in competitive markets at prices w and r, respectively. (Without loss of generality, we assume that the acquisition cost of capital is unity.)

The ith firm's emission technology is given by $e_i = h_i(q_i, k_{2i})$, a differentiable function that relates emissions e_i of a single pollutant to q_i and to k_{2i}, an emission-reducing capital variable that will be called "scrubber capital."[9] We assume that k_{2i} is a perfectly divisible input, and that emissions are uniformly mixed in the airshed. Emissions increase with output and decrease with scrubber use: $h_{q_i} > 0$ and $h_{k_{2i}} < 0$. A second-order restriction is also placed on h_i: $\partial^2 h_i / \partial q_i \partial k_{2i} < 0$, which means that as output increases the effectiveness of an additional unit of abatement capital also increases.[10] This ensures that for any fixed level of emissions E_i, the level of abatement capital k_{2i} can be expressed as a function of q_i. Let this function be denoted $k_{2i} = g_i(q_i; E_i)$, where $g_i'(q_i; E_i) > 0$.

Each firm is a monopolist in its output market, facing the downward-sloping demand function $p_i = p_i(q_i)$. The two output markets are completely distinct. Firm i's profits are given by $\pi_i = p_i(q_i)q_i - wx_i - r(k_{1i} + k_{2i})$. In the absence of environmental restrictions, a ROR-regulated firm maximizes profits subject to a constraint placed directly upon profits. This constraint takes the form $\pi_i \leq (s - r)k_{1i}$, a formulation due to Averch and Johnson (1962). In the simple version, where tax treatment and depreciation are neglected, k_{1i} is the firm's *ratebase*, and $s > r$ is the allowed rate of return. The choice of s is the responsibility of the PSC.[11] It is well known that in this

[9] This function is akin to that used by Bohi and Burtraw (1992). Spulber (1985), on the other hand, assumes that the production of output and of pollution are inseparable in that a single functional relationship exists between inputs, output, and pollution. The fact that emissions do not depend in any way upon the choice of fuel is a strong assumption. In fact, switching from high- to low-sulfur coal is an important compliance option, one that we defer to a later study.

[10] The derivative $\partial h_i / \partial k_2$, which is negative, becomes *more* negative as q increases: the scrubber becomes more effective. In the relevant range, our assumption says, a given scrubber will remove more sulfur dioxide when the plant is at full capacity than when it is nearly idle.

[11] We assume that the ratebase coincides with k_{1i}. In practice, decisions concerning the inclusion of assets in

regulatory setting a utility feels an incentive to over-use capital. Specifically, for any given output level, a firm in the A-J model uses more capital than it would at the cost-minimizing input bundle. At the margin the firm has an incentive to make the ratebase too large. The regulatory tradeoff is thus between the benefits of reducing the deadweight costs due to monopoly and the harmful effects of inefficient input use that the regulation itself fosters.[12]

The firm may use capital inefficiently, but for any given (k_{1i}, q_i) pair it will always choose a cost-minimizing level of x_i. Therefore, following Diewert (1981), the firm's decision problem is here decomposed into two parts. The firm first chooses the cost-minimizing value of x_i as it depends on q_i and k_{1i}. The cost of purchasing x_i is given by the variable cost function $C_i(w, q_i, k_{1i})$, defined as

$$C_i(w, q_i, k_{1i}) = \min_{x \geq 0} \quad \{wx \mid q_i \leq f_i(x_i, k_{1i})\}.$$

Then, given the function $C_i(w, q_i, k_{1i})$, it selects q_i and k_{1i} to maximize profits subject to its ROR constraint.

Up to this point there is nothing in the problem that bears upon the utility's environmental requirement. It is to this complication that we now turn, developing first the command and control version, and then adding a market for emission allowances.

Command and Control Regime. Under the CAC regime, each firm must emit no more than E_i, a fixed emissions cap chosen exogenously by an environmental authority.[13] Let industry-wide emissions be given by $E = \sum_i E_i$. The PSC must now make a choice that it does not face in the absence of environmental restrictions. The firm will seek to have k_{2i} included in its ratebase, thereby increasing its profit opportunities. If this request is granted, use of k_{2i} will increase at the margin. Though it appears that allowing the monopolistic firm to increase its ratebase will reduce economic welfare, two benefits may attend placing k_{2i} in the ratebase. First, the firm will now tend to substitute k_{2i} for k_{1i} in satisfying its urge to inflate its ratebase. As a result, it will move toward

the ratebase are generally as contentious as is the choice of s. It is the ratebase decision over pollution abatement capital to which we turn shortly.

[12] For a review and extensive development of the implications of this model see Baumol and Klevorick (1970). Greenwald (1984) investigates the equity and efficiency effects of different ratebase selection rules upon a regulated firm. Averch and Johnson's primary result—that regulated utilities will use more than the cost-minimizing quantity of the capital input—has become known as the "A-J effect." Though Spann (1974) and others have detected an A-J effect, Joskow (1974) finds that utilities do not have an incentive to overcapitalize during times of inflation and when regulatory review is uncertain. (Joskow and Rose 1989 review the literature along these lines.)

[13] We assume perfect, costless enforcement of the emissions constraint. Keeler (1991) and Fuller (1987) explore the effects of facing firms with the decision whether to cheat, exceeding the constraint while risking penalties if they are audited. In both the CAC and the allowance trading regimes, it will be assumed that the environmental constraint is binding.

the efficient input mix, lessening the inefficiency due to the A-J bias. Second, if reductions in production cost associated with the input mix are sufficiently large, the firm may increase output, resulting in a reduction in electricity prices and an increase in consumer welfare. In short, adding k_{2i} to the ratebase adds to firm profits, but might increase consumer surplus at the same time.

The PSC's ratemaking decision regarding scrubber capital is assumed to be continuous. Let $\varphi \in [0,1]$ denote the share of k_{2i} that is placed in the ratebase. Thus, for example, if $\varphi = 1$, then all scrubber capital is included in the firm's ratebase. Firm i's rate-of-return constraint can now be written $\pi_i \leq (s-r)(k_{1i} + \varphi k_{2i})$. Each firm receives the same ratebase treatment: φ is constant for the entire industry. Together with the choice of s (which is assumed to be fixed and strictly greater than r), in the CAC regime the selection of φ thus constitutes the ratemaking decision of the PSC.

The ith firm's decision problem may be written as

$$\max_{q_i, k_{1i}} \pi_i = p(q_i)q_i - C_i(w, q_i, k_{1i}) - r(k_{1i} + g_i(q_i; E_i)) \tag{1}$$

subject to

$$\pi_i \leq (s-r)(k_{1i} + \varphi g_i(q_i; E_i))$$

$$h_i(q_i, k_{2i}) \leq E_i.$$

As a measure of welfare in the industry we use the sum across markets of profits and simple market-wide consumer surplus (defined as the area beneath the demand curve and above the price line). Because it is assumed that firms face horizontal input supply curves, there is no need to consider the welfare effects in supplier markets.[14] Consumer surplus in market i, a function of output, is

$$CS_i(q_i) = \int_0^{q_i} p_i(z)\,dz - q_i p_i(q_i),$$

and economic welfare is given by

$$SW(E_1, E_2, \varphi) = \sum_{i=1}^{2} (\pi_i + CS_i).$$

[14]Consumer surplus has well-known deficiencies in this context as a measure of the well-being of society. Nevertheless, it is still used. See, for example, Spulber (1985), whose use of CS is similar to ours, and also Willig (1976).

It is this quantity that is used in the numerical exercises to compare the various candidate regulatory treatments.[15]

Allowance Trading Regime. Under the allowance trading regime, firms are each given a finite initial endowment $L_i > 0$ of allowances, or licenses. These they may trade with one another at price p_ℓ, where ℓ_i denotes the number of allowances held, after trading has occurred, by firm i. Trade can take place so long as each firm emits no more pollutant than it holds allowances: $h_i(q_i, k_{2i}) \leq \ell_i$. As with the capital variables, care must be taken to value allowances properly in the (single-period) profit function and in the ratebase. We assume that an allowance has an infinite life, generating in each period a coupon that may be redeemed (in that period or in any subsequent period) in exchange for the right to emit one ton of SO_2. The price of the one-period coupon is p_ℓ (which appears in the profit function), while the asset is valued at p_ℓ/r (which appears in the ratebase). Firms may be thought of as leasing "allowances" in this period, but it is assumed that the right to an allowance even for one period gives a firm the corresponding right to place the capitalized value of the allowance in its ratebase.[16] Each firm takes the allowance price p_ℓ as given. In addition to its choice of s and φ, the PSC must now also choose $\theta \in [0,1]$, the share of a firm's allowances that will count in its ratebase.

The firm's optimization problem now takes the form

$$(2) \qquad \max_{q_i, k_{1i}, k_{2i}} \pi_i = p(q_i)q_i - C_i(w, q_i, k_{1i}) - r(k_{1i} + k_{2i}) - p_\ell(h_i(q_i, k_{2i}) - L_i)$$

subject to

$$\pi_i \leq (s - r)(k_{1i} + \varphi k_{2i} + \theta(p_\ell/r)\ell_i)$$

$$h_i(q_i, k_{2i}) \leq \ell_i,$$

where p_ℓ/r is the capitalized value at which allowances trade.

[15] Because the pollution levels for each firm are here held fixed—and because the overall emission standard will be constant in the upcoming allowance trading case—there is no need to account for environmental damage in the welfare measure. Environmental damage is not unimportant, it simply doesn't change. See Kolstad (1986).

[16] There are several possibilities for modeling the ownership of allowances. One could distinguish for ratemaking purposes between allowance purchases and allowance leases, for example. In that case, the purchase of allowances might carry a premium over the lease of allowances, because the latter would not affect the purchaser's ratebase. We abstract away from such considerations by assuming the underlying asset moves in and out of its ratebase as a firm purchases the one-year right to a coupon. We thank Ted Graham-Tomasi for noting the importance of this distinction.

Given φ and θ, let the solution to problem (2) be given by the three implicit functions

$$q_i^* = q_i^*(r, s, p_\ell; L_i, \varphi, \theta)$$

$$k_{1i}^* = k_{1i}^*(r, s, p_\ell; L_i, \varphi, \theta)$$

$$k_{2i}^* = k_{2i}^*(r, s, p_\ell; L_i, \varphi, \theta),$$

where the "*" superscript denotes optimal behavior in the allowance trading regime. These three variable completely determine the system, including the optimal level of emissions, which may be written $\ell_i^* = h(q_i^*, k_{2i}^*)$. This function is firm i's demand for allowances. Using it, we may define an industry-wide equilibrium as follows.

DEFINITION. *Given a two-firm utility industry facing an emission allowance environmental constraint, an* **allowance trading equilibrium** *is an i-tuple of vectors* $(q_i^*, k_{1i}^*, k_{2i}^*)$ *satisfying:*

1) *For each firm,* $(q_i^*, k_{1i}^*, k_{2i}^*)$ *solves problem (2) (optimization); and*
2) $\sum_{i=1}^{2} \ell_i^* = \sum_{i=1}^{2} L_i$ *(markets clear).*

As in the CAC case, industry-wide welfare is defined as

$$SW(E_1, E_2, \varphi, \theta) = \sum_{i=1}^{2} (\pi_i + CS_i).$$

It is assumed that firms do not behave strategically when making their compliance decisions. What's more, political activity on the part of firms, consumers, and the regulator plays no role. We do not formulate an explicit optimization problem for the PSC.

3. The Numerical Model and Experiments

Transforming the theoretical model of the previous section consists primarily of selecting functional forms for the production, emission, and demand functions. It is assumed throughout that firms' production technologies are identical, and that they face identical (but distinct) demand functions and regulatory treatment. Heterogeneity enters only through the emissions functions, $h_i(q_i, k_{2i})$, and the initial endowments of allowances, the L_i.

Let the firms' production, emission, and demand functions be given by, respectively,

(3a) $$f_i(x_i, k_{1i}) = Ax_i^\alpha k_{1i}^{1-\alpha}$$

(3b) $$h_i(q_i, k_{2i}) = \frac{B_i q_i}{k_{2i}^\gamma}$$

(3c) $$p_i(q_i) = c - dq_i,$$

where it is assumed that $\alpha \in (0,1)$, that $\gamma \in (0,1)$, and that c, d, A, and B_i are strictly positive. Parameters that appear without an i subscript are identical across firms. Equation (3b) yields the function $g_i(q_i; E_i) = (B_i q_i / E_i)^{1/\gamma}$, which determines, for any q_i, the optimal level of k_{2i} in problem (1). Given prices and q_i, firm i's variable cost function can be extracted from (3a) as

$$C_i(w; q_i, k_{1i}) = \left(\frac{q_i}{A}\right)^{1/\alpha} \cdot k_{1i}^{(\alpha-1)/\alpha} \cdot w.$$

Using the fact that the emissions constraint is met with equality, the lagrangian function corresponding to problem (1)—the command and control regime—is given by

$$\text{(4)} \qquad \mathcal{L}^{(1)}(q_i, k_{1i}; \lambda) = p(q_i)q_i - C_i(w, q_i, k_{1i}) - r(k_{1i} + g_i(q_i; E_i)) + \\ \lambda\Big((s - r)(k_{1i} + \varphi g_i(q_i; E_i)) - p_i(q_i)q_i + C_i(w, q_i, k_{1i}) + r(k_{1i} + g_i(q_i; E_i))\Big),$$

where $\lambda \geq 0$ is the Lagrange multiplier on the profit constraint. The three first order conditions for this general program are derived in the Appendix, along with a demonstration that $\lambda < 1$. Using the functional forms specified in equations 3, the first order conditions are given by

$$\text{(5a)} \quad 0 = (1-\lambda)\left(c - 2dq_i - \left(\frac{w}{\alpha A^{1/\alpha}}\right)\left(\frac{q_i}{k_{1i}}\right)^{\frac{1-\alpha}{\alpha}}\right) - \left(\frac{B_i q_i^{(1-\gamma)}}{E_i}\right)^{\frac{1}{\gamma}} \frac{(r(1-\lambda) - \lambda(s-r)\varphi)}{\gamma}$$

$$\text{(5b)} \quad 0 = (\lambda - 1)\frac{\alpha - 1}{\alpha}\left(\frac{q_i}{A}\right)^{1/\alpha} k_{1i}^{-1/\alpha} w - r + \lambda s$$

$$\text{(5c)} \quad 0 = (c - dq_i)q_i - \left(\frac{q_i}{A}\right)^{1/\alpha} k_{1i}^{(\alpha-1)/\alpha} w - sk_{1i} - \left(\frac{B_i}{E_i}\right)^{1/\gamma} q_i^{1/\gamma}(r + \varphi(s - r))).$$

The functional forms that are used guarantee that the choice variables take optimal values on the interior of the relevant choice sets. A simultaneous solution to these three equations represents a solution to program (1).

The parameter values chosen for the numerical exercises appear in Table I. Firm 1 is the clean firm, with $B_1 = 1$, and firm 2 is the dirty firm, with $B_2 = 3$. Firm 1 emits less of the pollutant at any output level, and it is also given a lower initial endowment of allowances ($L_1 = 12$ and $L_2 = 16$).

The numerical exercise for problem (1) consists in fixing φ, deriving a solution for each firm, recording the solutions, and then increasing φ by 0.01 as it ranges over the closed interval from zero to one. The resulting calculations yield equilibrium relationships between φ on the one hand and firm productive and compliance behavior, consumer surplus, and welfare on the other.

With the same set of functional forms, and once again assuming the emissions constraint $h_i(q_i, k_{2i}) \leq \ell_i$ is satisfied with equality, the lagrangian function corresponding to problem (2) is given by

$$\text{(6)} \qquad \mathcal{L}^{(2)}(q_i, k_{1i}; \lambda) = p(q_i)q_i - C_i(w, q_i, k_{1i}) - r(k_{1i} + k_{2i}) - p_\ell(h_i(q_i, k_{2i}) - L_i) +$$
$$\lambda\Big((s-r)(k_{1i} + \varphi k_{2i} + \theta(p_\ell/r)h_i) - p_i(q_i)q_i + C_i(w, q_i, k_{1i}) + r(k_{1i} + k_{2i}) + p_\ell(h_i(q_i, k_{2i}) - L_i)\Big),$$

where, as before, it may be shown that $\lambda < 1$. The set of first order necessary conditions corresponding to an optimal solution to this problem are developed in the appendix. The variables appearing in the system are q_i, k_{1i}, k_{2i}, and λ. A solution to this system will be denoted $z_i^* = (q_i^*, k_{1i}^*, k_{2i}^*, \lambda^*)$.

Whereas in the CAC case only φ is varied in the numerical experiments, now one may explore the consequences of changes in φ and in θ. We conduct five experiments in the allowance trading framework. The first three involve fixing φ at zero, one-half, and one, respectively, and allowing θ to range from zero to one in increments of 0.01. The remaining two involve fixing θ at zero and at one, respectively, and allowing φ to range from zero to one in increments of 0.01. For each (φ, θ)-pair, the allowance price p_ℓ^* at which the allowance market clears is calculated numerically. The calculation of p_ℓ^* is the critical step in our allowance trading experiments, for it embodies optimal behavior by firms and the market-clearing condition in the allowance market. The excess supply and excess demand curves, given by $12 - \ell_1^*$ and $\ell_2^* - 16$, respectively, are used to locate the equilibrium price.[17] At each equilibrium price, in addition to the values calculated for the CAC regime, we also record the volume of allowance trading.

Figure 1 presents four sets of excess supply and demand curves, for (φ, θ) equal to $(0,0)$, $(0,1)$, $(1,0)$, and $(1,1)$, respectively. The corresponding equilibrium allowance price is calculated numerically in our experiment for each (φ, θ)-pair, by performing a successively finer grid search over the p_ℓ parameter, until excess demand becomes sufficiently close to zero.

4. The CAC Experiment

We begin with the command and control experiment primarily because it provides a handy benchmark against which to compare the welfare effects of allowance trading. It is also more

[17]As one would expect, in all cases firm 1, the clean firm, is a net supplier of allowances while firm 2 is a net demander of allowances.

straightforward computationally than the allowance-trading version. A rate-of-return regulated firm has an incentive to employ an inefficient input mix, using more than the cost-minimizing level of capital and thereby inflating its ratebase and ultimately its profits as well. Here, we assume all productive capital k_{1i} is in the ratebase, and introduce the CAC environmental constraint. Recall that emissions are fixed in this model and that there are two methods the firm may use to acheive a given emission level E_i. It may either reduce its output or else it may increase its use of k_{2i}. The former will harm consumers as the output price moves upward along the monopolist's demand curve. The effect of changing k_{2i} is less clear, however, and is further complicated by the PSC's choice of φ. If $\varphi = 1$, then for purposes of increasing its ratebase (though *not* for purposes of producing electricity) k_{1i} and k_{2i} are perfect substitutes. Now the possibility arises for abatement capital to supplant productive capital as the ratebase-inflating instrument, possibly reducing the productive inefficiency engendered by ROR regulation.

In the command and control regulatory regime the markets served by the two firms, and indeed the firms themselves, are completely independent. (This is not the case in the emission allowance regime and, as is illustrated below, net welfare gains may result from permitting trade in emission allowances.) Thus the effects of changes in φ in the two markets represent two seperate examples for the command and control case. Tables II(a) and II(b) show the effects of increasing φ on the optimal values for output q_i, productive capital k_{1i}, abatement capital k_{2i}, average production costs (APC$_i$), average abatement costs (AAC$_i$), firm profits, and economic economic welfare in each market.

The table shows that as the fraction of abatement capital included in the ratebase increases, in each case the optimal output levels increase monotonically and, with the movement down the demand curve, prices fall. Thus consumer welfare increases. Profits also rise monotonicaly. This is not the expected outcome. In the usual case, a ROR-regulated monopolist overproduces; that is, the firm is forced by the profit constraint to produce more than it would at the profit-maximizing level. Relaxing the profit constraint, by increasing the allowed rate of return, in the usual case results in lower output levels, higher prices, and lower consumer surplus. The case under study here is not the usual case, however; our result is just the opposite.

It appears from the table that two related effects are behind the paradox. The first has to do with technical efficiency and the firm's productive input choices. The second is related to pollution abatement and the firm's choice of compliance strategy. Let us consider each of these in turn.

Increasing φ relaxes the profit constraint, which leads to a reduction in λ, the shadow contribution of marginal capital to profits. (This variable is absent from the table, but it declines slightly for each firm, never straying far from 0.65, as φ steps from zero to one.) The relaxation of the constraint reduces the incentive for capital bias in the production process, thereby increasing the productive input ratio, x_i/k_{1i}. As the table shows, average production costs fall as φ increases, increasing profits at any given output level and, for this example, increasing output. This illustrates the beneficial efficiency-ehnancing effects of including abatement capital in a utility's ratebase.

The positive relationship between φ and output q_i is also due to the firm's emission abatement decision. Recall that emissions increase with q_i and decrease with k_{2i}. With emissions fixed at E_i, anything that causes an increase in k_{2i} will cause an increase in q_i as well. Increasing φ has precisely this effect on k_{2i}. To see this, note that the opportunity to count k_{2i} as part of its ratebase confers additional profit opportunities on the firm. If $\varphi = 1$, each additional unit of k_{2i} permits the firm to earn (almost) 0.06 extra units of profit. The "almost" is because each additional unit of k_{2i} will be slightly less effective—due to the shape of $h_i(q_i, k_{2i})$—than the previous units, and this reduction in marginal effectiveness mitigates the increase in k_{2i}. In our example, the urge to increase k_{2i} far outweighs this countervailing effect. The result is that for any given level of emissions, as φ increases there is an incentive to substitute abatement capital for productive capital in the ratebase. Table II shows that both firms find this to be optimal, and it also shows that in each market the production of electricity increases with φ.

Finally, average production costs fall because of reductions in productive input mix distortions while average abatement costs increase because the use of abatement capital increases more rapidly than does output. However, for both firms average total costs fall. Once again, in these examples, allowing firms to include more abatement capital in their ratebases sufficiently reduces distortions in productive input mixes and average total costs of production to allow firms to increase both output and profits. Table III records the industry-wide effects of changes in regulatory treatment of abatement capital. In that table, PC_i and AC_i denote the production costs $(rk_{1i} + wx_i)$ and the abatement costs (rk_{2i}) respectively incurred by firm i. Industry-wide production costs fall, abatement costs rise (to attain the required emissions target with greater output), but as φ increases both profits and consumer surplus go up in each market.[18]

5. The Allowance Trading Experiments

Allowance trading offers firms with differences in marginal abatement costs the opportunity for beneficial gains from trade. Firms with low abatement costs have incentives to reduce emissions by more than is required, and to sell the resulting excess allowances to their high-cost counterparts, who find the allowances a cheaper alternative than installing scrubbers. The argument (see, eg, Montgomery 1972) is that no alternative regulatory strategy can attain any given aggregate emissions target more cheaply than can an allowance trading regime.

However, in a regulated-utility setting the precise welfare effects of allowance trading and the distribution of those effects also depends upon PSC decisions regarding the ratemaking treatment of abatement capital and of emission allowances. The simulations presented in this section explore the implications of these alternative treatments. The results are in certain respects artifacts of the specific assumptions about production technology, abatement technology, market demand and target rates of return embodied in our model. However, they do indicate that the effects of PSC policies can be quite complex and that existing policies may not be optimal from an economic welfare viewpoint.

The first step of the simulations is to derive the market-clearing allowance price p_ℓ for each of a series of (φ, θ) pairs. Given this equilibrium allowance price, the firms' input, output, and abatement decisions can be easily calculated. The parameters φ and θ may take values anywhere in the closed unit square; an infinite number of simulations is possible. The two firms could also be subject to different PSC policies. To keep the analysis manageable we assume that both firms face the same regulatory treatment, and we choose a subset of the parameter space by sequentially fixing first φ at three levels while stepping θ from zero to one in 0.01 increments, and then reversing the parameters, fixing θ and stepping φ from zero to one in 0.01 increments.

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[18]It can be that the monopolist will reduce output in response to more generous ratebase treatment. In the following section there are examples in which profits can be increased only by reducing output towards its monopoly profit-maximizing level. In a fixed coefficients technology, for example, when a free-disposal assumption is satsified, firms will choose inputs so as to minimize production costs. In this case, relaxing the rate of return constraint (by any means) will result in lower output levels because lowering output is the firm's only strategy for increasing profits.

Figure 2a illustrates our first finding: irrespective of the fraction of abatement capital permitted in the ratebase, the welfare-maximizing value for θ is one. For our model, if the PSC's goal is to maximize the sum of producer and consumer welfare it should include the entire value of all emission allowances in the ratebase. The figure shows that economic welfare monotonically increases as the value of θ moves from zero to one for three values of φ ($\varphi = 0$, $\varphi = 0.5$ and $\varphi = 1$). With allowances included in the ratebase, firms are encouraged to make use of the allowance market, which in this model enhances social welfare. Firms are less inclined to inflate their ratebases through the use of k_{1i} or k_{2i} when their allowances may be counted as part of the ratebase.

As shown in Figure 2b for the case with $\varphi = 1$, the social welfare-maximizing treatment of allowances is not good for consumers: consumer surplus is at its lowest point when $\theta = 1$. Firms, as seen in Figure 2c, find their profits maximized when $\theta = 1$. Profits, in fact, are sufficiently enhanced by this treatment that firms could compensate consumers for their losses while leaving themselves better off. In order to avoid upsetting the optimality of this treatment, however, the compensation would have to be achieved by some means other than electricity price-setting. From Figure 2d, which depicts the movement of the equilibrium allowance price in response to changes in θ, one can gain some insight into the welfare-enhancing effects of ratemaking treatment of allowances. As θ increases, holding allowances becomes more attractive, which drives p_ℓ up. This in turn relieves the pressure felt by firms to over-use capital—either productive or abatement capital—to enlarge their ratebases. Absent this pressure, input decisions move toward the efficient levels, enhancing aggregate social welfare.

Given that allowances should be included in the ratebase, let us now fix θ at one, and proceed to examine the welfare effects of changes in φ, the proportion of abatement capital that is allowed in the ratebase. Figure 3a shows that economic welfare is not monotonically increasing in φ. Instead, with $\theta = 1$, welfare is maximized when $\varphi \approx 0.19$; welfare is lower if φ moves away from this point in either direction. In this case, it is seen that the optimal regulatory strategy (from a welfare perspective) is to include the value of all emission allowances in the ratebase but only about twenty percent of the value of abatement capital. This appears to have important policy consequences. Currently, as has been noted, 49 of the 50 states, and also the Federal Energy Regulatory Commission, treat abatement capital as a ratebase asset. Under the command-and-control regimes that are now in place, our results show this to be the optimal ratemaking treatment. In the presence of allowance trading akin to that called for in the 1990 Clean Air Act Amendments, it may no longer be so. Rather, PSCs will need to harmonize their treatment of an entirely new object—the emission allowance—with well-known and widely-accepted treatment of scrubbers. This promises to be a challenging task for state regulators.

Most often consumers are harmed by regulatory treatment that increases the size of a firm's ratebase. For this reason, consumer advocates usually seek to remove assets from the ratebase of utilities. Here, given that $\theta = 1$, consumers would prefer to see $\varphi = 1$; to have abatement capital *included* in the ratebase. Related to this is the result, depicted in Figure 3b, that consumers do not benefit from the welfare-maximizing treatment of abatement capital.

Most often a firm is helped by regulatory treatment that includes additional assets in their ratebase. This is not true here. Figure 3b also shows that firms actually prefer to have abatement capital k_{2i} *excluded* from the ratebase. They enjoy the greatest profits if $\varphi = 0$, contrary to the usual outcome. This result is explained at least in part by the outcome illustrated in Figure 3c. Firms benefit from regulatory treatment that causes the allowance price to increase—here, this happens when φ is small.

The claim has sometimes been made that the allowance market will only work well if trading volume is high. As shown in Figure 3d, our results indicate that when compliance strategies are chosen to maximize welfare, allowance trading is negligible. This is not to say that low allowance trading volume is good—only that trading volume needn't be high for the allowance market to have improve welfare. It is true that we have assumed the firms treat the allowance price as parametric, an assumption that may be least plausible with low trading volume. However, paradoxically, the allowance market itself is needed the least in this case. Firms simply emit pollution at (very nearly) the level of their endowments L_i. Granted, the allowance market must function at least to the extent that a price is established for purposes of valuing allowances in the ratebase. Once this price is available, however, each firm can value all of its allowances (recall $\theta = 1$) at the high price p_ℓ. If $\theta = 1$ and φ is small, then, firms would prefer to hold allowances for purposes of increasing their ratebases than for purposes of reducing compliance costs. And, for our model, this behavior sufficiently relieves the pressure to employ an inefficient input mix that social welfare is enhanced.

The finding that the economic welfare-maximizing values of φ and θ are different also raises questions about the appropriateness of setting ratebase policy with the objective of minimizing compliance costs. Bohi and Burtraw (1992) have shown that, for any given level of emissions, the firm minimizes compliance costs (the sum of expenditures on abatement capital and on emission allowances) when φ and θ are identical. However, the results presented here indicate this is not necessarily the welfare-maximizing treatment. First, ensuring that compliance costs are minimized for any given output level does not necessarily ensure that the sum of compliance costs and production costs are minimized. Second, equal ratebase treatment of investment in emission allowances and abatement capital does not necessarily guarantee optimal industry output levels.

The point is illustrated by comparing output levels, production costs and compliance costs at the welfare-maximizing values for φ and θ with their values when φ and θ are both equal to one. These comparisons appear in Table IV. Output levels (and consumer welfare) are lower in both markets at the optimal values than when both φ and θ are equal to one. However, average production costs are also lower at the optimal output levels. At the optimal levels of φ and θ, compliance costs to the individual firms are high because allowance values are high. Firms own emission allowances in the first place, though, so trades in allowances simply represent income transfers across firms. Social compliance costs consist only of expenditures on abatement capital, and these costs per unit of output are also lower at the optimal values for φ and θ.

Two final questions remain, both of which concern the basic premises of market-based environmental control. These are: 1) are abatement expenditures reduced as a result of allowance trading? and 2) is social welfare enhanced as a result of the trading scheme? The answers, from our simulation experiments, are "yes" and "yes."

Figure 4a addresses question 1). There, we plot abatement costs and social welfare as a function of φ in the CAC case and in the emission allowance trading case. To make the two cases comparable, we look only at the experiment where $\theta = 0$, so that firms do not use allowances for ratebase-inflation purposes: they can not do so by definition in the CAC case. For any value of $\varphi > 0$, one can see that abatement costs are greater in the CAC case than in the allowance trading case. That is, under the allowance trading program a given level of abatement (to a total of 28 units of emissions) is achieved at lower cost as firms, responding to p_ℓ, redistribute abatement optimally among themselves. The size of this savings depends upon PSC regulatory treatment.

Figure 4b illustrates that overall social welfare is increased through the use of an allowance trading regime. Once again setting $\theta = 0$ to make the two cases comparable, we see that our social welfare is greater under the allowance trading regime regardless of the ratemaking treatment of abatement capital. Figure 3a suggests that when $\theta = 1$, welfare is even higher, though that case is not as legitimate for this comparison. Figure 4b, however, provides what may be the strongest evidence in favor of market-based environmental regulation to come out of our experiments.

6. Conclusions

Market-based schemes to achieve environmental goals have long been promoted by economists. The 1990 Clean Air Act Amendments will institute nation-wide trading in sulfur dioxide pollution rights—a scale never before attempted. The experiment will be carried out in the electrical utility industry, which is already heavily regulated. The combined effects of the dual regulatory framework—economic and environmental regulation—are not well understood. In this paper we have employed a simple two-firm simulation model to show that the welfare effects of alternative environmental regulation of the electric power industry depend upon the ratebase policies of utility regulators. Distortions that we take as given are the monopoly positions of sellers and the rate-of-return regulation they face. Factor markets and emission allowances markets are assumed to be perfectly competitive.

A major conclusion of the analysis is that, given uniform ratebase treatment of abatement capital across firms, a command and control environmental regulation is inferior to a tradeable emission allowance policy when emission allowances are excluded from the ratebase. There is always some tradeable allowance-ratebase regulation policy mix that is preferred to a command and control environmental policy.

A second result is that policies that increase the ratebase ameliorate costly Averch-Jonson effects on productive input choices because they reduce incentives for capital bias. Thus, for example, policies that increase the proportion of emission allowances that can be included in the ratebase reduce average production costs and, often, the sum of average production costs and abatement costs.

We have also shown that the welfare-maximizing PSC ratebase policy may require differential ratebase treatment for the two compliance instruments available to utilities: emission allowances and abatement capital. In our example, the optimal policy is to include all emission allowances in the ratebase but only about twenty percent of abatement capital. Currently, utility regulators permit utilities to include all abatement capital in their ratebases. Bohi and Burtraw have demonstrated that individual utilities minimize compliance costs (the sum of expenditures on abatement capital and allowances) when emission allowances and abatement capital are treated identically in the ratebase. However, at least in our example, firms do not necessarily minimize abatement costs, average production costs or average total costs when this policy is adopted. Economic welfare is not maximized. Thus, such a policy guarantees neither productive efficiency nor economic efficiency.

Finally, the simulation model shows that (in the absence of income transfers) the ratebase policy that maximizes economic welfare is not necessarily identical to the policy that maximizes consumer welfare. Relaxing the rate-of-return constraint through generous ratebase treatment of environmental investments in abatement capital and emission incentives reduces the marginal effect on profits of additional units of capital. Thus firms have incentives to reorganize input use to reduce average production costs (a social gain) but at the same time may also reduce output and raise prices, adversely affecting consumer welfare (a social cost). The socially optimal ratebase policy equates reductions in production costs with reductions in consumer welfare resulting from a marginal increase in the rate base.

The simulation results are subject to an important caveat. They are all based on specific assumptions about production technologies, abatement technologies and other market conditions. However, our purpose here has been to illustrate that ratebase policy with respect to environmental investments may have complex and often subtle economic welfare implications. Our findings raise questions concerning some commonly-held beliefs about optimal ratebase treatment of environmental investments. The interaction between input and output decisions on the one hand, and compliance decisions on the other, can lead to outcomes in which society benefits from regulatory treatment that would seem to be harmful.

APPENDIX

In this appendix the first order necessary conditions for a solution to programs (1) and (2) are derived. To reduce notational clutter, the i subscript is dropped in what follows. In all instances, we use the interiority assumption mentioned in the text. This assumption is not restrictive given the Cobb-Douglas production technology and the exponential form of the emission technology.

The lagrangian for the command and control problem (1) is

$$\mathcal{L}^{(1)}(q,k_1;\lambda) = p(q)q - C(w,q,k_1) - r(k_1 + g(q;E)) +$$
$$\lambda\Big((s-r)(k_1+\varphi g(q;E)) - p(q)q + C(w,q,k_1) + r(k_1+g(q;E))\Big).$$

Our production, emission, and demand functions are

$$f_i(x_i,k_{1i}) = Ax_i^{\alpha}k_{1i}^{1-\alpha} \qquad h_i(q_i,k_{2i}) = \frac{B_i q_i}{k_{2i}^{\gamma}} \qquad \text{and} \qquad p_i(q_i) = c - dq_i.$$

The cost and g functions are, respectively,

$$C(w;q,k_1) = \left(\frac{q}{A}\right)^{1/\alpha} \cdot k_1^{\frac{(\alpha-1)}{\alpha}} \cdot w \qquad \text{and} \qquad g(q;E) = \left(\frac{Bq}{E}\right)^{1/\gamma}.$$

The derivatives of $\mathcal{L}^{(1)}$ with respect to q, k_1, and λ, the first order conditions we seek, are given by

$$\text{(A-1a)} \qquad \frac{\partial\mathcal{L}^{(1)}}{\partial q} = (p + qp'(q) - \partial C/\partial q - rg'(q))(1-\lambda) + \lambda(s-r)\varphi g'(q) = 0$$

$$\text{(A-1b)} \qquad \frac{\partial\mathcal{L}^{(1)}}{\partial k_1} = \partial C/\partial k_1 + r - \lambda((s-r) + \partial C/\partial k_1 + r) = 0$$

$$\text{(A-1c)} \qquad \frac{\partial\mathcal{L}^{(1)}}{\partial \lambda} = p(q)q - C(w,q,k_1) - r(k_1+g(q)) - (s-r)(k_1+\varphi g(q)) = 0.$$

The second of these quations yields $\lambda = (\partial C/\partial k_1 + r)/(\partial C/\partial k_1 + s) < 1$, which is needed for some of the manipulations to follow.

Inserting the derivative expressions

$$\frac{\partial C}{\partial q} = \left(\frac{w}{\alpha A^{\delta}}\right) \cdot q^{\epsilon} \cdot k_1^{-\epsilon} \cdot w \qquad \text{and} \qquad \frac{\partial C}{\partial k_1} = \left(\frac{q}{A}\right)^{\delta} \cdot (-\epsilon) \cdot k_1^{-\delta} \cdot w$$

directly into (A-1a), we find

$$0 = (1-\lambda)\left(c - 2dq - \left(\frac{w}{\alpha A^{\delta}}\right)q^{\epsilon} \cdot k_1^{-\epsilon}\right) - \left(\frac{B}{E}\right)^{\delta}\frac{(r(1-\lambda) - \lambda(s-r)\varphi)}{\gamma}q^{(1-\gamma)/\gamma},$$

where $\delta = 1/\alpha$ and $\epsilon = (1-\alpha)/\alpha$. This expression agrees with equation (5a). Similarly for (A-1b) and (A-1c), we find

$$0 = (1-\lambda)\epsilon\left(\frac{q}{A}\right)^{\delta} k_1^{-\delta} w - r + \lambda s \qquad \text{and}$$

$$0 = (c - dq)q - \left(\frac{q}{A}\right)^{\delta} k_1^{-\delta} w - sk_1 - \left(\frac{B}{E}\right)^{\frac{1}{\gamma}} q^{\frac{1}{\gamma}} (r + \varphi(s-r))),$$

which agree respectively with (5b) and (5c).

The lagrangian function for program (2), the allowance trading regime, is given by

$$\mathcal{L}^{(2)}(q, k_1, k_2; \lambda) = p(q)q - C(w, q, k_1) - r(k_1 + k_2) - p_\ell(h(q, k_2) - L_0) +$$
$$\lambda\big((s-r)(k_1 + \varphi k_2 + \theta(p_\ell/r)\ell - p(q)q + C(w, q, k_1) + r(k_1 + k_2) + p_\ell(h(q, k_2) - L_0)\big).$$

Here we use the emissions function $h(q, k_2) = Bq/k_2^{\gamma}$. The derivatives of $\mathcal{L}^{(2)}$ with respect to q, k_1, k_2, and λ respectively are given by

$$\text{(A-2a)} \qquad \frac{\partial \mathcal{L}^{(2)}}{\partial q} = (p + qp'(q) - \partial C/\partial q - p_\ell h_q)(1-\lambda) + \lambda(s-r)(\theta p_\ell/r)h_q = 0$$

$$\text{(A-2b)} \qquad \frac{\partial \mathcal{L}^{(2)}}{\partial k_1} = \partial C/\partial k_1 + r - \lambda((s-r) + \partial C/\partial k_1 + r) = 0$$

$$\text{(A-2c)} \qquad \frac{\partial \mathcal{L}^{(2)}}{\partial k_2} = p_\ell h_{k_2} + r - \lambda((s-r) + (\theta p_\ell/r)h_{k_2}(s-r) + r - p_\ell h_{k_2}) = 0$$

$$\text{(A-2d)} \qquad \frac{\partial \mathcal{L}^{(2)}}{\partial \lambda} = p(q)q - C(w, q, k_1) - r(k_1 + k_2) - p_\ell(h(q, k_2) - L_0) -$$
$$(s-r)(k_1 + k_2 + \theta(p_\ell/r)\ell) = 0.$$

Now inserting the derivative expressions

$$\frac{\partial h}{\partial q} = \frac{B}{k_2^{\gamma}} \qquad \text{and} \qquad \frac{\partial h}{\partial k_2} = \frac{-\gamma Bq}{k_2^{\gamma+1}},$$

along with the derivatives of C into equations (A-2), we arrive at the following set of first order conditions for an interior maximum to problem (2).

$$0 = (1-\lambda)\left(c - 2dq - \left(\frac{w}{\alpha A^{\delta}}\right) q^{\epsilon} \cdot k_1^{-\epsilon} - \frac{p_\ell B}{k_2^{\gamma}}\right) + \frac{\lambda\theta p_\ell(s-r)B}{rk_2^{\gamma}}$$

$$0 = \epsilon(1-\lambda)\left(\frac{q}{A}\right)^{\delta} k_1^{-\delta} w - r + \lambda s$$

$$0 = p_\ell \frac{-\gamma Bq}{k_2^{\gamma+1}}\left(1 - \lambda - \frac{\lambda(s-r)\theta}{r}\right) + r - \lambda(s-r)\varphi + r$$

$$0 = (s-r)(k_1 + \varphi k_2 + \theta(p_\ell/r)\ell - p(q)q + C(w, q, k_1) + r(k_1 + k_2) + p_\ell(h(q, k_2) - L_0).$$

A solution to these equations constitutes a solution to the firm's problem in the presence of allowance trading.

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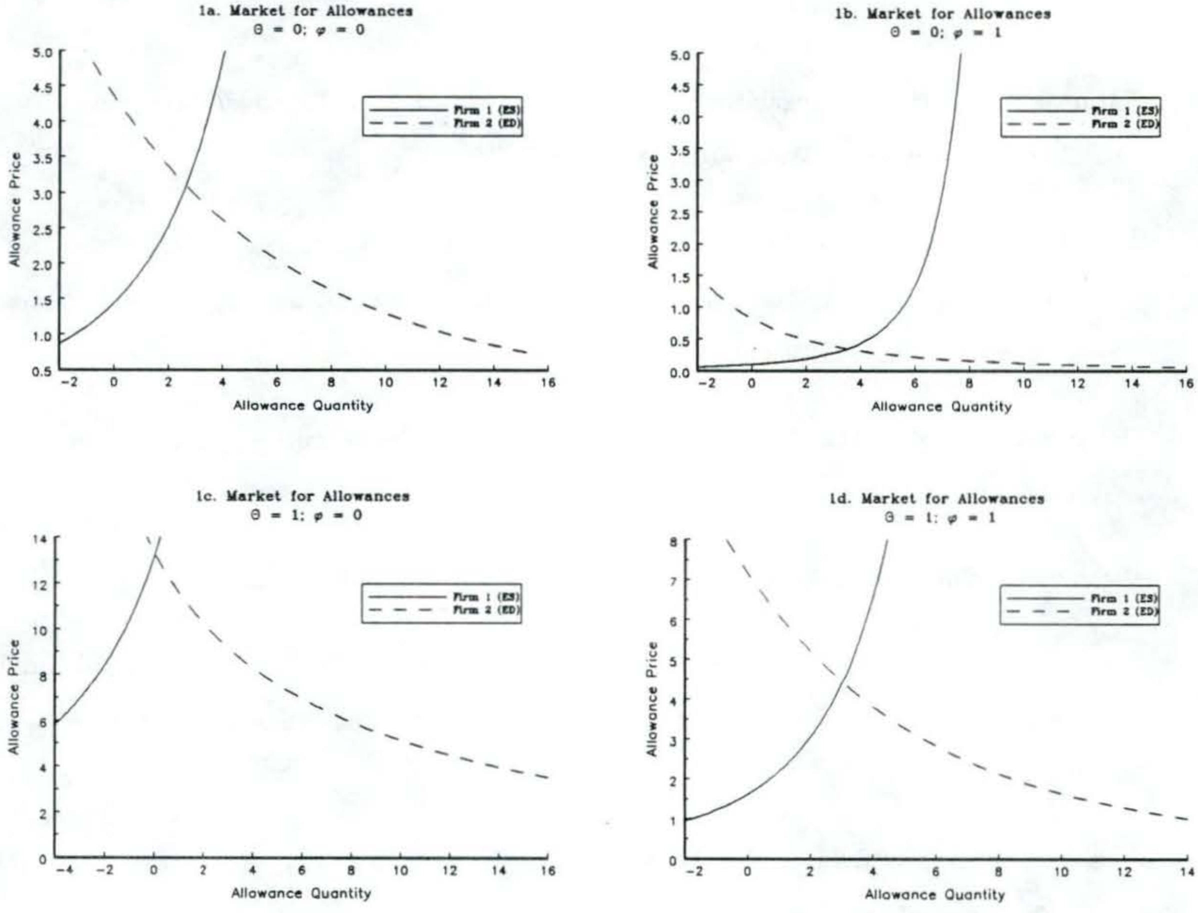

Figure 1. Equilibrium in the allowance market under alternative ratemaking treatment.

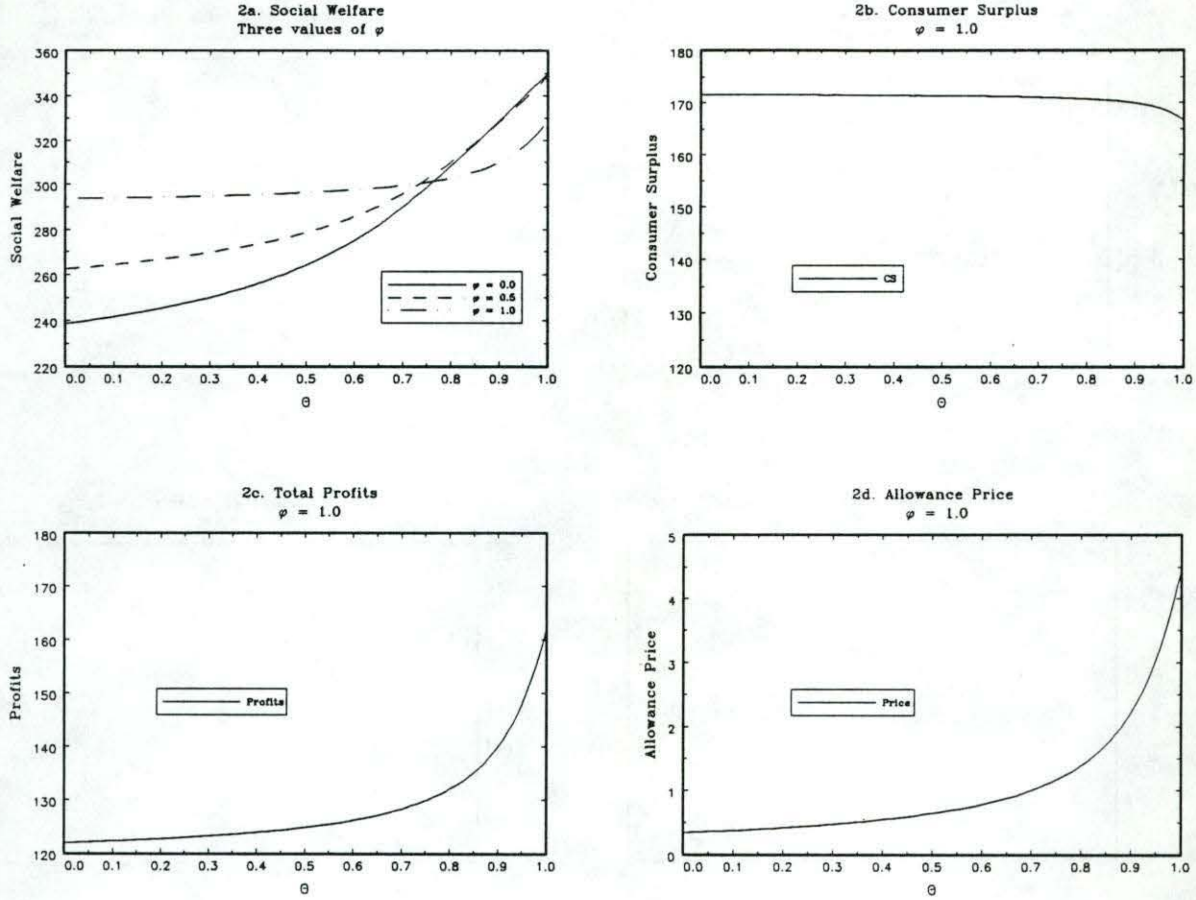

Figure 2. Effects of changes in emission allowance ratebase treatment (θ) on consumer surplus, profits, and allowance prices when $\varphi = 1$.

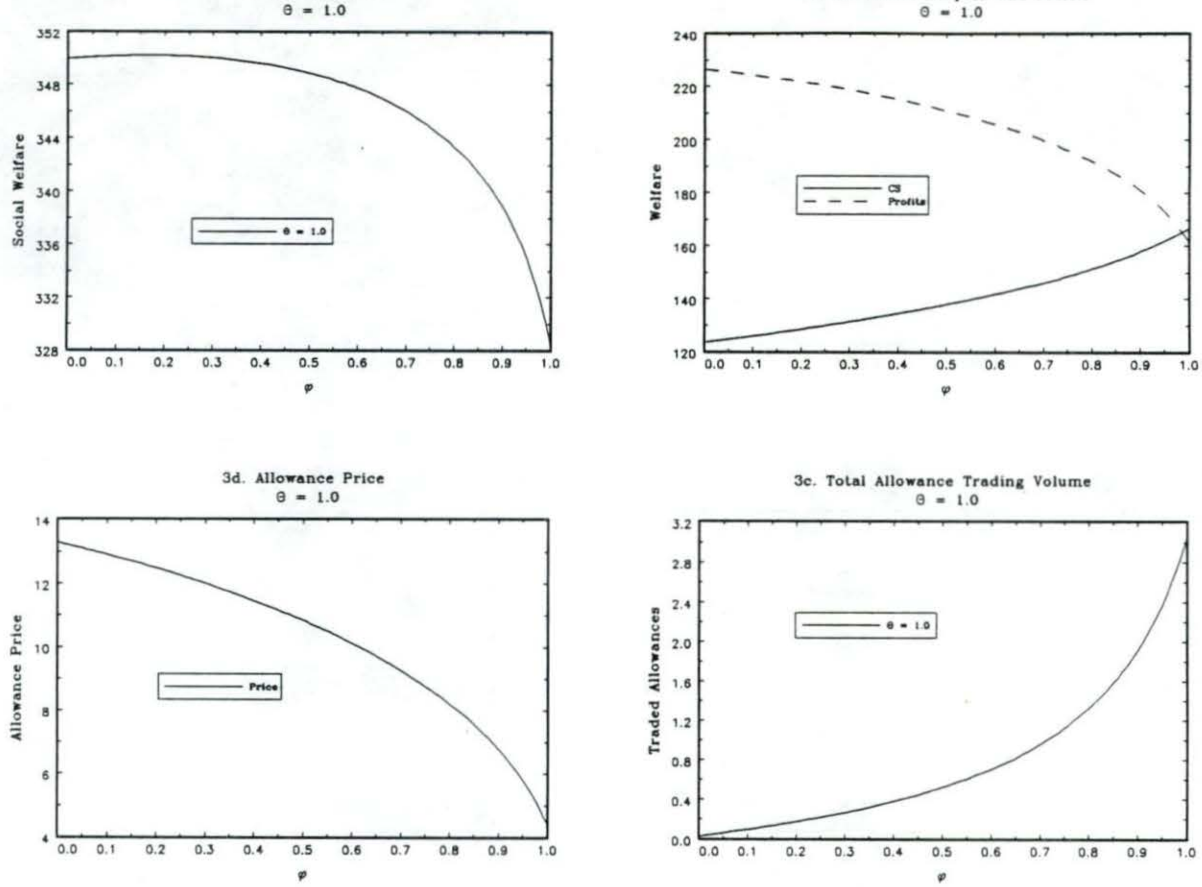

Figure 3. Effects of changes in φ on welfare, allowance price, and trading volume when $\theta = 1$.

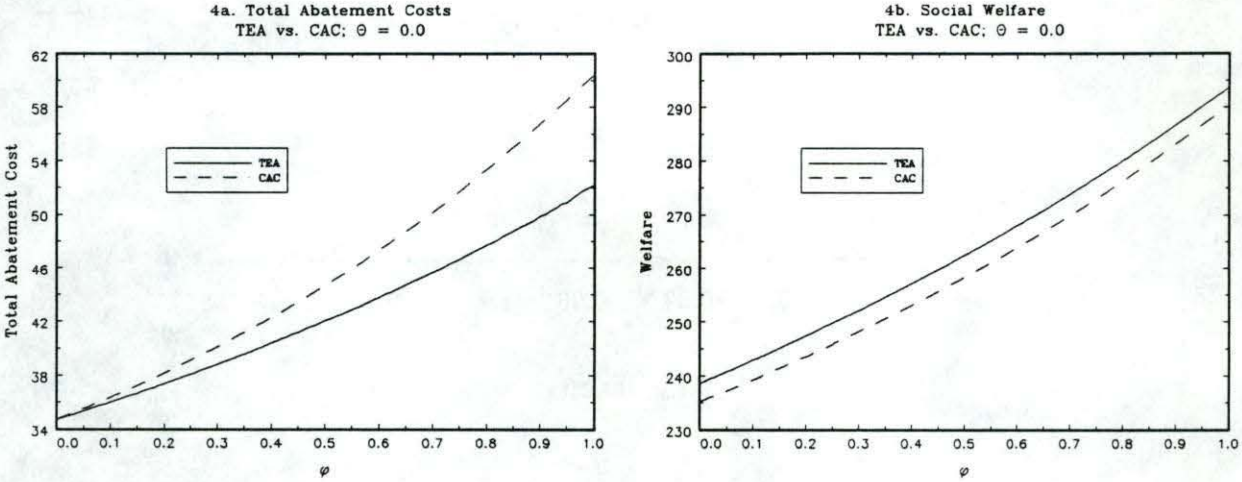

Figure 4. Comparison of abatement costs and economic welfare under command and control (CAC) and emission allowance environmental regulation when $\theta = 0$.

Table I. Parameter values.

PARAMETERS COMMON ACROSS FIRMS

α	γ	s	r	w	A	c	d
0.9	0.4	0.09	0.06	1.0	1.0	5.0	0.025

FIRM-SPECIFIC PARAMETERS

B_1	L_1	B_2	L_2
1.0	12.0	3.0	16.0

Table II. Response, by firm, of production, costs, profits, and welfare to changes in φ.

Command and Control.

(a)

φ	q_1	x_1/k_{11}	k_{21}	APC_1	AAC_1	ATC_1	π_1	CS_1	SW_1
0.0	80.1	0.0285	115.2	2.174	0.086	2.260	59.0	80.2	139.3
0.1	80.5	0.0287	116.5	2.165	0.087	2.252	59.3	81.0	140.2
0.2	80.9	0.0290	117.9	2.155	0.087	2.243	59.5	81.7	141.2
0.3	81.2	0.0292	119.3	2.146	0.088	2.234	59.7	82.5	142.2
0.4	81.6	0.0294	120.7	2.136	0.089	2.225	60.0	83.3	143.2
0.5	82.0	0.0297	122.1	2.126	0.089	2.216	60.2	84.1	144.3
0.6	82.4	0.0299	123.6	2.117	0.090	2.207	60.4	84.9	145.3
0.7	82.8	0.0302	125.1	2.107	0.091	2.197	60.7	85.7	146.4
0.8	83.2	0.0304	126.7	2.096	0.091	2.188	60.9	86.6	147.5
0.9	83.6	0.0307	128.2	2.086	0.092	2.178	61.2	87.4	148.6
1.0	84.0	0.0310	129.8	2.076	0.093	2.168	61.4	88.3	149.7

(b)

φ	q_2	x_2/k_{12}	k_{22}	APC_2	AAC_2	ATC_2	π_2	CS_2	SW_2
0.0	62.1	0.0273	463.2	2.232	0.447	2.679	47.7	48.3	95.9
0.1	63.5	0.0283	489.4	2.184	0.462	2.647	48.6	50.4	99.0
0.2	65.0	0.0295	518.1	2.134	0.478	2.612	49.6	52.8	102.4
0.3	66.5	0.0308	549.7	2.080	0.496	2.576	50.6	55.3	106.0
0.4	68.2	0.0324	584.4	2.022	0.514	2.536	51.8	58.1	109.9
0.5	69.9	0.0344	622.6	1.961	0.534	2.495	52.9	61.1	114.1
0.6	71.8	0.0366	664.8	1.895	0.556	2.450	54.2	64.4	118.6
0.7	73.8	0.0395	711.3	1.825	0.579	2.403	55.5	68.0	123.5
0.8	75.8	0.0429	762.3	1.750	0.603	2.353	57.0	71.9	128.8
0.9	78.0	0.0474	817.8	1.671	0.629	2.300	58.5	76.0	134.5
1.0	80.2	0.0530	877.2	1.589	0.656	2.245	60.1	80.4	140.6

Table III. Aggregate response of costs and welfare to changes in φ.

Command and Control.

φ	$\sum_i PC_i$	$\sum_i AC_i$	$\sum_i \pi_i$	$\sum_i CS_i$	$\sum_i SW_i$
0.0	312.9	34.7	106.7	128.5	235.2
0.1	313.0	36.4	107.9	131.4	239.3
0.2	312.9	38.2	109.1	134.5	243.5
0.3	312.7	40.1	110.4	137.8	248.2
0.4	312.2	42.3	111.7	141.4	253.1
0.5	311.5	44.7	113.1	145.2	258.3
0.6	310.4	47.3	114.6	149.3	263.9
0.7	309.0	50.2	116.2	153.7	269.9
0.8	307.1	53.3	117.9	158.4	276.3
0.9	304.8	56.8	119.7	163.4	283.1
1.0	301.9	60.4	121.6	168.7	290.3

Table IV. Comparison of Costs and Welfare at two regulatory regimes:

$(\varphi, \theta) = (0.19, 1)$ and $(\varphi, \theta) = (1, 1)$.

Market 1

φ	θ	q_1^*	PC_1	AC_1	k_{21}	π_1	CS_1	SW_1
0.19	1.0	79.75	126.48	155.02	117.86	108.26	79.50	187.76
1.0	1.0	83.49	161.88	55.50	264.31	78.83	87.13	165.96

Market 2

φ	θ	q_2^*	PC_2	AC_2	k_{22}	π_2	CS_2	SW_2
0.19	1.0	62.48	71.63	229.54	327.62	113.63	48.80	162.43
1.0	1.0	79.79	109.81	117.78	560.87	82.92	79.58	162.50

Industry Totals

φ	θ	$\sum_i q_i^*$	$\sum_i PC_i$	$\sum_i AC_1$	$\sum_i k_{2i}$	$\sum_i \pi_i$	$\sum_i CS_i$	$\sum_i SW_1$
0.19	1.0	142.23	198.11	384.56	445.48	221.89	128.30	350.20
1.0	1.0	163.28	271.69	173.29	825.18	161.75	166.71	328.46