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Rate of Return Regulation and Emission Permits Trading under Uncertainty

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Abstract

This paper analyzes the dynamic effects of rate-of-return regulation on firms' emissions compliance behavior when the price of emissions permits is uncertain. The paper shows that uncertainty regarding the price of permits would motivate a regulated firm to adopt a more self-sufficient strategy and would reduce the cost-effectiveness of emission allowance trading. When allowance transactions are treated as capital investments, uncertainty could reverse the classic Averch-Johnson effect, so that a regulated firm would purchase fewer permits in the ex ante period than its unregulated counterpart. These results are driven by the asymmetric impact of a price change on the expected marginal value of allowances under rate-of-return regulation. A wider variation in the permit price and a decline in the regulated rate of return would amplify the asymmetry. These results have implications for the efficiency of the proposed global carbon trading system.

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Rate of Return Regulation and Emission Permits Trading under Uncertainty

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1 Introduction

Cap-and-trade systems of pollution rights have gained popularity since the early 1990s as a market-based policy instrument to minimize the costs of environmental regulation. They have been used at the regional, national and municipal levels to control a range of pollutants, such as carbon dioxide (CO_2), as under the European Union Emissions Trading Program, sulfur dioxide (SO_2), as under the U.S. Acid Rain Program, and nitrogen oxides (NO_x), as under the U.S. NO_x Budget Program.

Economic theory predicts that, in a first-best world, the marginal abatement costs of all firms participating in an emissions trading program are equalized with the permit (allowance) price in each trading period and that the overall cost of achieving a given reduction in aggregate emissions is minimized (Cropper and Oates 1992; Kling and Rubin 1997; Montgomery 1972; Rubin 1996; Tietenberg 1985).[3]

In practice, the cost-effectiveness of a cap-and-trade system could be affected by various factors, including market power (Hahn 1984; Liski and Montero 2006; Misiolek and Elder 1989), transaction costs (Cason and Gangadharan 2003; Montero 1998; Stavins 1995), allowance allocations (Goulder, Hafstead, and Dworsky 2010; Hahn and Stavins 2010; Parry and Williams 2010), interaction pollutants (Zylicz 1993), and overlap of the cap-and-trade system with local environmental (Coggins and Swinton 1996; Goulder 2013) and economic regulations.

On the overlay between emissions trading and local economic regulations, many studies have analyzed the impact of the rate-of-return regulation of state public utilities commissions (PUCs) as a source of distortion. Existing literature points out that, by setting some maximum "fair" rate of return to capital inputs, the regulatory agency creates an incentive for electric utilities to

3. Throughout the paper we use "permit" and "allowance" interchangeably.

choose a capital-intensive abatement option relative to the optimum. This is the well-known Averch-Johnson effect (Averch and Johnson 1962).

For example, Bohi and Burtraw (1992) investigate the performance of the allowance market in the presence of rate-of-return regulation. They show that the behavior of utilities regarding emissions abatement depends on the rate-based rules of regulators. When the net return on new investments is positive, a utility will inflate its rate base by choosing the more expensive abatement option for compliance.

Coggins and Smith (1993) simulate market outcomes under two regulatory policies in which the expense of scrubbers and allowances is either included or excluded from the rate base. They argue that including the cost of allowances in the rate base may improve welfare by encouraging firms to participate in the allowance market and by discouraging firms from overinvesting in productive capital since abatement costs are counted as part of the rate base. Kolstad and Wolak (2003) show that regulated electric utilities benefited from higher allowances prices when they were allowed to incorporate the permit price in the rate base.

Fullerton, McDermott, and Caulkins (1997) model firms' choice of either permits or three abatement technologies when facing constraints on both emissions and profits. Based on economic and engineering information, they numerically solve the compliance plans under alternative regulatory scenarios. They show that PUC regulatory rules could more than double the costs of compliance.

Cronshaw and Kruse (1996) consider the dynamic nature of allowance trading when firms are allowed to bank permits. Among other things, they argue that firms would likely bank permits if the costs of permits were initially treated as an operating expense, but then capitalized in the rate base at some future date, because capitalization appreciates the value of permits.

Most of the recent work on emissions permits trading is conducted in a riskless framework. A few studies also look at the impact of price uncertainty on a firm's compliance strategy.

Schennach (2000) analyzes the implications of output market uncertainty on individual firms' emissions trading and finds that the higher the expected price of electricity, the lower the emissions in earlier periods. Schennach (2000) also emphasizes the role of the non-negativity constraint, a special feature associated with the U.S. Acid Rain Program, arguing that the expectation of a potential stock-out of the banked permits may induce a reduction in emissions in earlier periods. Feng and Zhao (2006) explore efficiency of the permit system when there is information asymmetry regarding uncertainty between the regulatory agency and the regulated firm and find that the higher is the degree of asymmetry, the greater are the potential benefits from a regime of bankable permits. Ben-David et al. (2000) present experimental results suggesting that the abatement efforts of risk-averse sellers (buyers) of permits are lower (higher) under permit price uncertainty than under permit price certainty. Baldursson and von der Fehr (2004) obtain a similar result, showing that risk aversion limits the volume of trading.

In this paper, we investigate the impact of uncertainty in the price of allowances on a rate-of-return regulated firm's emissions abatement behavior. We find that in a stochastic setting, a risk-neutral firm may react to rate-of-return regulation in an anti–Averch-Johnson fashion. That is, when allowances are treated like capital, a regulated monopolist is likely to underpurchase allowances and to overreduce emissions if permit prices are uncertain. The more volatile is the permit price and the more stringent is the rate-of-return regulation, the larger is the distortion. The analysis demonstrates that the impact of PUC regulation on the trading of emissions permits could be more subtle and complicated in the presence of stochastic permit prices.

In the wake of electricity restructuring in the United States, two dozen states and the District of Columbia took steps to replace rate-of-return regulation with competitive pricing. In states where restructuring was not initiated, utilities are still allowed to operate as regulated monopolies. We show that having a nationwide emissions trading system that overlays nonuniform PUC regulation at the state level compromises the efficiency of the environmental market. Even when abatement capital and allowances are treated symmetrically in the rate base, the existence of uncertainty regarding allowance prices distorts their relative costs and market equilibrium.

The rest of the paper proceeds in the following way. Section 2 introduces a minimum framework necessary for assessing the joint effects of rate-of-return regulation and permit price uncertainty on emissions abatement in the context of the SO_2 Allowance Trading Program in the United States. For this, we develop a simple partial-equilibrium model in which a firm uses low- and high-sulfur coal to produce electricity subject to a profit constraint; the firm decides on the amount of permits to be used and emissions to be reduced before a permit price is observed. Sections 3 and 4 derive and compare the profit-maximizing conditions under rate-of-return regulation in deterministic and stochastic cases. We show that the central result derived under a riskless scenario cannot be generalized once a random term is introduced to a permit price. Price uncertainty could affect the factor substitution of a regulated net buyer of permits in the opposite direction of the Averch-Johnson effect. Numerical simulations further demonstrate that the wider is the price variation and the more stringent is the rate-of-return regulation, the higher is the distortion. Section 5 interprets the analytical results, and section 6 concludes the paper.

2 Basic Firm Model

The U.S. SO_2 Allowance Trading Program, also known as the Acid Rain Program, was established under Title IV of the Clean Air Act Amendments of 1990. Under Title IV, the Environmental Regulatory Agency sets an annual cap that limits the total SO_2 emissions from the electricity industry to less than half of their 1980 level (from 18.9 million tons in 1980 to 8.9 million tons in 2001). The agency then divides the quantity up to a given number of allowances and allocates them to individual units based on their historical heat inputs. Each allowance authorizes a unit to emit one ton of SO_2 emissions. Utilities are allowed to trade allowances among each other and also to save unused allowances for future years. On an annual basis, each unit must deduct enough allowances from its account to cover its emissions at the "true-up" date. Title IV was implemented in two phases, with the first round of emissions regulation taking effect in 1995 and a more stringent regulation starting in 2000.

Most of the units affected by Title IV are coal-based power plants. Consider a risk-neutral firm that uses adjustable levels of low- and high-sulfur coal (l and h) to generate electricity. The output is given by $g(l,h)$, which is assumed to be quasi-concave and increasing in both arguments. Some previous studies assume that low- and high-sulfur coals are perfect substitutes that differ only in the sulfur contents. For example, Arimura (2002) uses a linear function to describe the production technology with low- and high-sulfur coals as the factor inputs. In reality, low- and high-sulfur coal cannot so easily be substituted for each other. Typically, power plants are designed for a particular type of coal. Deviations of coal properties from the initial design may result in reduced efficiencies, impaired plant performance, or even serious operating problems, and the damage increases as the deviations multiply. [4]

As a by-product of coal combustion, SO_2 is produced and emitted to the air. Denote the emission function as $e(l,h) = \mu_l l + \mu_h h$, where μ_l and μ_h ($\mu_l < \mu_h$) are the sulfur content of low- and high-sulfur coal, respectively.

Since the majority of coal purchases are locked into long-term contracts, we assume that the price of low- and high-sulfur coal (P_l and P_h) is constant, while the price of a permit (P_a) evolves stochastically. Price uncertainty manifests both in fluctuations in the trend and in the standard deviation from the trend. In this paper, we focus on the impact of price volatility around an expected value by assuming that the permit price evolves following a mean-preserving process. Specifically, let P_a be defined by $P_a = \bar{P}_a + \varepsilon$, where $\bar{P}_a$ is a constant and ε is a random

4 For more details on the impact of blending high-sulfur coal with low-sulfur coal on production performance, refer to International Energy Agency Fuel Research (1993).

variable. Without loss of generality, assume that ε has a zero mean, that is $\int_{\varepsilon^{min}}^{\varepsilon^{max}} \varepsilon f(\varepsilon) d\varepsilon = 0$, where $f(\cdot)$ is the probability density function of ε and is known to the firm's manager at the time of choosing the factor inputs. ε^{max} and ε^{min} represent the upper and lower bounds of the random term.

To simplify the notation, it is convenient to assume that the level of productive capital (k) is fixed, although relaxing this assumption does not affect our main conclusions. Utilities had mainly preferred two compliance strategies under the Acid Rain Program: substituting low-sulfur coal for high-sulfur coal, and/or purchasing allowances in addition to their initial allocation.[5] The firm chooses low- and high-sulfur coal inputs before observing the allowance price. The transaction of allowances is then decided *ex post*. If total emissions during the production period exceed the initial allocation of allowances (A), the firm purchases extra allowances [$e(l,h) - A$] to meet the emissions constraint; if total emissions are less than the endowed allowances [$e(l,h) < A$], the firm sells the surplus of allowances to make a profit.

Under rate-of-return regulation, the firm maximizes expected profits subject to a profit constraint: after subtracting its expected operating expenses from gross revenues, the remaining revenue should be just enough to compensate the firm for its capital investment at an allowed rate of return (s). If the profit constraint is violated, the regulatory agency may intervene by changing the output price. Finally, define the market interest rate as r. Following the previous literature, we assume that the regulatory agency would allow the firm to earn some profit, implying that $s > r$.

This model presents a simple framework for analyzing the dynamic effect of rate-of-return regulation on the trading of emissions permits when their price is uncertain. This model is in nature

5. According to the Energy Information Administration (1997), 52 percent of the Phase I units chose to switch or blend fuels, 32 percent chose to purchase allowances, while less than 6 percent installed scrubbers.

the same as a multiperiod framework in which firms choose the share of low- and high-sulfur coal in inputs and the amount of permits to bank before future permit prices are resolved.

3 Expense Policy

For rate-making purposes, state PUCs have generally applied two types of cost recovery rules to allowance transactions: the value of used allowances is treated either as an operating expense or as a capital investment (Lile and Burtraw 1998). In the following, we refer to these two types of rate-making rules as expense policy and capital policy, respectively.[6] We first consider expense policy and develop profit-maximizing solutions under both deterministic and stochastic scenarios. Following similar procedures, we then analyze a firm's optimal choice of inputs and decisions regarding lower emissions under a capital policy in section 4.

When $P_a = \bar{P}_a$, the question reduces to a deterministic case. The profit maximization problem is described as follows:

$$\max_{l,h} \pi = R(l,h) - P_l l - P_h h - rk - \bar{P}_a[e(l,h) - A] \qquad (1)$$
$$s.t. \qquad \pi \leq (s - r)k$$

Here $R(l,h) = P_e g(l,h)$ denotes the revenue function. P_e represents the price of electricity, which may or may not be a function of output.

6. States may also differ in how the gains and the transaction costs of allowances are shared between ratepayers and shareholders. In some states, any gains and expenses from allowance transactions are automatically passed on to consumers, while in other states, incentive-based sharing of costs and savings allows utilities to retain a portion of gains or to recover a portion of expenses on a case-by-case basis. See Lile and Burtraw (1998) for a detailed discussion of state-level policies toward the regulatory treatment of allowance transactions. For the purpose of this paper, we assume that expenses are fully recovered and that utilities are allowed to retain gains from the sale of allowances. We also assume that gains from the sale of allowances and spending on emissions abatement and the purchase of allowances are treated symmetrically.

Let L and u represent the Lagrangian and Lagrangian multiplier of the constrained optimization. The Kuhn-Tucker necessary conditions for a maximum (l^R, h^R) are

$$\frac{\partial L}{\partial l} = (1-u)(R_l - P_l - P_a\mu_l) = 0 \tag{2}$$

$$\frac{\partial L}{\partial h} = (1-u)(R_h - P_h - P_a\mu_h) = 0 \tag{3}$$

$$u[(s-r)k - \pi] \geq 0 \tag{4}$$

where R_l and R_h are the marginal revenue product of low- and high-sulfur coal, respectively. Assume that $u > 0$—that is, the profit constraint is active at $P_a = \bar{P}_a$. Rearranging and cross-dividing equations (2) and (3), the optimal choice of inputs is characterized by the following:

$$\frac{g_{l^R}}{g_{h^R}} = \frac{P_l + P_a\mu_l}{P_h + P_a\mu_h} \tag{5}$$

Equation (5) is the familiar cost minimization rule, which equates the ratio of the marginal product of inputs to their marginal cost. Marginal cost consists of the given price of coal and the opportunity cost of producing emissions. Therefore, in the case of certainty, when expenditures on emissions allowances are treated as operating costs, a regulated firm would make the same compliance choice as its unregulated counterpart. The firm would operate efficiently in the sense that the cost is minimized at the given output level.

Next add a stochastic element in permit price ($P_a = \bar{P}_a + \varepsilon$). The firm selects inputs to maximize the expected profit. Suppose the firm is a net buyer of allowances—that is, $e(l^R, h^R) > A$. Assume that a value ε^* exists, such that $\varepsilon^* \in (\varepsilon^{min}, \varepsilon^{max})$; when $\varepsilon \geq \varepsilon^*$, the unconditionally maximized profits do not exceed the permissible profits $[(s-r)k]$, and when $\varepsilon < \varepsilon^*$, the regulation is effective and the regulated firm earns exactly the highest allowed profits. The profit of a net buyer of allowances is then given by the following:

$$\pi = R(l^R, h^R) - P_l l^R - P_h h^R - rk - (\bar{P}_a + \varepsilon)[e(l^R, h^R) - A] \qquad \text{for } \varepsilon \geq \varepsilon^*$$

$\pi = (s - r)k$ for $\varepsilon < \varepsilon^*$

Under this condition, the expected profit equals:

$$E(\pi) = (s-r)k \int_{\varepsilon^{min}}^{\varepsilon^*} f(\varepsilon)d\varepsilon + \int_{\varepsilon^*}^{\varepsilon^{max}} [P_e g - P_l l - P_h h - rk - (\bar{P}_a + \varepsilon)(e(l,h) - A)] f(\varepsilon)d\varepsilon \quad (6)$$

The first-order conditions for a maximum (l^R, h^R) for equation (6) are as follows:[7]

$$\begin{aligned} \frac{\partial E(\pi)}{\partial l} &= \int_{\varepsilon^*}^{\varepsilon_{max}} [R_l - P_l - (\bar{P}_a + \varepsilon)\mu_l] f(\varepsilon)d\varepsilon \\ &= (R_l - P_l - \bar{P}_a\mu_l) \int_{\varepsilon^*}^{\varepsilon^{max}} f(\varepsilon)d\varepsilon - \mu_l \int_{\varepsilon^*}^{\varepsilon_{max}} \varepsilon f(\varepsilon)d(\varepsilon) = 0 \qquad (7) \end{aligned}$$

$$\begin{aligned} \frac{\partial E(\pi)}{\partial h} &= \int_{\varepsilon^*}^{\varepsilon_{max}} [R_h - P_h - (\bar{P}_a + \varepsilon)\mu_h] f(\varepsilon)d\varepsilon \\ &= (R_h - P_h - \bar{P}_a\mu_h) \int_{\varepsilon^*}^{\varepsilon^{max}} f(\varepsilon)d\varepsilon - \mu_h \int_{\varepsilon^*}^{\varepsilon^{max}} \varepsilon f(\varepsilon)d(\varepsilon) = 0 \qquad (8) \end{aligned}$$

Cross-dividing equations (7) and (8) gives:

$$\frac{g_{l^R}}{g_{h^R}} = \frac{P_l + \bar{P}_a\mu_l + \mu_l C^B}{P_h + \bar{P}_a\mu_h + \mu_h C^B} \qquad (9)$$

where

$$C^B = \frac{\int_{\varepsilon^*}^{\varepsilon^{max}} \varepsilon f(\varepsilon)d(\varepsilon)}{\int_{\varepsilon^*}^{\varepsilon^{max}} f(\varepsilon)d\varepsilon} \qquad (10)$$

Because $\int_{\varepsilon^{min}}^{\varepsilon^{max}} \varepsilon f(\varepsilon)d\varepsilon = 0$, the numerator of C^B is positive ($\int_{\varepsilon^*}^{\varepsilon^{max}} \varepsilon f(\varepsilon)d\varepsilon > 0$). The denominator of C^B is the probability that the profit constraint is not binding: $\int_{\varepsilon^*}^{\varepsilon^{max}} f(\varepsilon)d\varepsilon = 1 - F(\varepsilon^*) > 0$, where $F(\cdot)$ is the cumulative density function of ε. Hence, C^B is positive, yielding the following inequality:

7 Note that ε^* is also a function of l and h, but the derivatives of ε^* with respect to l and h are canceled out: $(s-r)kf(\varepsilon^*)\frac{\partial \varepsilon^*}{\partial l} - [R(l^R(\varepsilon^*), h^R(\varepsilon^*)) - P_l l^R(\varepsilon^*) - P_h h^R(\varepsilon^*) - rk - (\bar{P}_a + \varepsilon^*)e(l^R(\varepsilon^*), h^R(\varepsilon^*))] f(\varepsilon^*)\frac{\partial \varepsilon^*}{\partial l} = 0$

$$\frac{g_{l^R}}{g_{h^R}} < \frac{P_l + \bar{P}_a \mu_l}{P_h + \bar{P}_a \mu_h} \tag{11}$$

Comparing equation (9) with equation (5) obtained under the deterministic case, the equilibrium condition is now different. The right side of equation (11) describes the optimal configuration of inputs of an unregulated firm. From the standard assumption of quasi-concave production function, equation (11) implies that the optimal share of low- and high-sulfur coal of a regulated firm is greater than that of a firm adopting a cost-minimizing strategy. In a situation of price uncertainty, a regulated firm would rely more on self-sufficient compliance strategy—that is, it would increase the share of low-sulfur coal in inputs more than it would if it were not regulated.

If the regulated firm is a net seller of allowances, the expected profit function becomes the following:[8]

$$E(\pi) = (s-r)k \int_{\varepsilon^*}^{\varepsilon^{max}} f(\varepsilon)d\varepsilon + \int_{\varepsilon^{min}}^{\varepsilon^*} [R(l,h) - P_l l - P_h h - rk - (\bar{P}_a + \varepsilon)(e(l,h) - A)] f(\varepsilon)d\varepsilon \tag{12}$$

For $\varepsilon < \varepsilon^*$, the firm acts as if there is no profit regulation and hence faces a simple profit maximization problem in deciding on its fuel inputs; for the complement of that set of ε, the regulation is effective and the regulated monopolist earns the upper bound of the allowed profit $[(s - r)k]$.

An examination of the corresponding first-order conditions yields the following:

$$\frac{g_l}{g_h} = \frac{P_l + \bar{P}_a \mu_l + \mu_l C^S}{P_h + \bar{P}_a \mu_h + \mu_h C^S} \tag{13}$$

where

8. For a net seller of permits, ε^* is defined as $\pi^* > (s - r)k$ for $\varepsilon > \varepsilon^*$; $\pi^* \leq (s - r)k$ for $\varepsilon \leq \varepsilon^*$, where $\pi^* = R(l^R,h^R) - P_l l^R - P_h h^R - (\bar{P}_a + \varepsilon)[e(l^R,h^R) - A]$.

$$C^S = \frac{\int_{\varepsilon^{min}}^{\varepsilon^*} \varepsilon f(\varepsilon) d(\varepsilon)}{\int_{\varepsilon^{min}}^{\varepsilon^*} f(\varepsilon) d\varepsilon} \tag{14}$$

The denominator of equation (14) is again the probability of having a nonbinding profit constraint and is assumed to be positive. Because ε has a zero expectation, the numerator is negative: $\int_{\varepsilon^*}^{\varepsilon^{max}} \varepsilon f(\varepsilon) d\varepsilon <$ 0. Therefore, $C^s < 0$. The inequality in equation (11) is reversed:

$$\frac{g_{l^R}}{g_{h^R}} > \frac{P_l + \bar{P}_a \mu_l}{P_h + \bar{P}_a \mu_h} \tag{15}$$

Equation (15) reveals that a net seller of permits would have less desire to sell allowances than its unregulated counterpart and would rely more on a pollution-intensive production technology.

Next we show that an increase in price uncertainty and a decrease in the allowed maximum rate of return would magnify the distortion in the choice of factor inputs of a regulated firm. An increase in uncertainty can be described as an increase in the distribution of the stochastic additive shift variable ε. Consider a linear expansion in the distribution of the random term ε. Let $\tilde{F}(\cdot)$ be the new cumulative density function, and $\varepsilon^{\widehat{max}}$ and $\varepsilon^{\widehat{min}}$ be the new upper and lower limits of ε. Let $\tilde{F}(a\varepsilon) = F(\varepsilon)$, $a > 1$. There are $\varepsilon^{\widehat{max}} = a\varepsilon^{max}$, and $\varepsilon^{\widehat{min}} = a\varepsilon^{min}$. Once again, assuming that the regulatory constraint is active when $P_a = \bar{P}_a$, for a net buyer of permits, the critical value ε^* will be less than zero. Thus $\varepsilon^* > a\varepsilon^*$, and $\tilde{F}(\varepsilon^*) \geq \tilde{F}(a\varepsilon^*) = F(\varepsilon^*)$. Therefore, the denominator of C^B in equation (10) will be smaller when the distribution of ε is more spread out: $\int_{\varepsilon^*}^{\varepsilon^{max}} \tilde{f}(\varepsilon) d\varepsilon = 1 - \tilde{F}(\varepsilon^*) < 1 - \tilde{F}(\varepsilon^*)$. Assuming that $\varepsilon^{\widehat{max}} > \varepsilon^{max}$, the numerator of C^B will increase as well.

Additionally, when s decreases, the cutoff value of ε where the profit constraint is active will be lower for a net buyer of permits. This will decrease the nominator of C^B and increase the denominator.

Because the ratio of marginal revenue products of low- and high-sulfur coal monotonically increases in C^B, the increase in uncertainty or decrease in s will deviate the input ratio of the regulated monopoly further away from the cost-minimizing solution. Following the same procedure, it is easy to prove that the conclusion applies to a net seller of permits as well.

The above analysis shows that after incorporating uncertainty, even when allowance expenses are treated neutrally like fuel costs, the share of low- and high-sulfur coal chosen by a rate-of-return regulated firm is different from that of a firm in the absence of profit regulation. The expected profit without regulatory constraint is described as $E(\pi) = R(l,h) - P_l l - P_h h - E(P_a)[e(l,h) - A]$. The second-order moments of P_a does not affect the choice of inputs.

With rate-of-return regulation, the firm maximizes a Lagrangian function: $L = R(l,h) - P_l l - P_h h - E(P_a)[e(l,h) - A] - E(u)(s - r)k$, where $E(u)$ measures the expected change in the Lagrangian for a small change in profit subject to the constraint: $E(\pi) \leq (s - r)k$. Generally, $E(u)$ is not linear in the change in P_a. In the case of a net buyer of permits, $E(u) > 0$ if $\varepsilon \leq \varepsilon^*$ and $E(u) = 0$ if $\varepsilon > \varepsilon^*$. The variation in P_a affects the probability that the regulatory constraint is indeed effective. Therefore, the choice of factor input would be different from the choice that the firm would make based on the expected value of the price. Furthermore, increasing uncertainty or tightening regulatory constraints would increase the optimum ratio of low- to high-sulfur coal of a net buyer of permits compared with that of an unregulated firm.

Because the emissions rate monotonically decreases as the share of low-sulfur coal increases, a regulated net buyer of allowances will emit less than its unregulated counterpart. For the same reasons described above, a net seller of permits would emit more than its unregulated counterpart. Overall, price uncertainty combined with rate-of-return regulation would discourage firms from participating in allowance trading.

4 Capital Policy

Assume the same regulatory setting as in the previous section, but now include the actual purchase of allowances in the rate base. In a riskless scenario, that is, $P_a = \bar{P}_a$, the profit maximization under a capital policy is stated as follows:[9]

$$\max_{l,h} \pi = R(l,h) - P_l l - P_h h - rk - \bar{P}_a(e(l,h) - A) \tag{16}$$

$$\pi \leq (s - r)[\bar{P}_a e(l,h) + k] \tag{17}$$

The Kuhn-Tucker necessary conditions for a maximum (l^R,h^R) are derived, which yields the following ratio of marginal products of factor inputs:

$$\frac{g_{l^R}}{g_{h^R}} = \frac{P_l + \bar{P}_a\mu_l - \frac{u}{1-u}(s-r)\bar{P}_a\mu_l}{P_h + \bar{P}_a\mu_h - \frac{u}{1-u}(s-r)\bar{P}_a\mu_h} \tag{18}$$

where u is the Lagrangian multiplier. Once again assuming that the regulatory constraint is active when $P_a = \bar{P}_a$, $0 < u < 1$. The ratio of marginal products of low and high-sulfur coal in equation (18) is greater than that of an unregulated firm ($\frac{g_{l^R}}{g_{h^R}} > \frac{P_l+\bar{P}_a\mu_l}{P_h+\bar{P}_a\mu_h}$), leading to underuse of low-sulfur coal. Intuitively, because the value of a permit transaction included in the rate base is allowed to earn a positive capital gain, investment in allowances will increase profits and be favored in compliance plans. This is the widely studied Averch-Johnson effect. Note that the Averch-Johnson terms (the terms involving u) in equation (18) directly result in a bias in favor of pollution-intensive technology. Because u varies inversely with s, the closer is s to r, the larger is the Averch-Johnson bias.

Now consider that the firm faces a random permit price. Rearrange the profit constraint (equation 17) by moving P_a to the left side of the inequality:

$$R(l,h) - P_l l - P_h h - rk - [(1 + s - r)e(l,h) - A]P_a \leq (s - r)k \tag{19}$$

9. All notations are the same as in the previous section.

For $e(l,h) > A$, the left side of equation (19) is nonincreasing in P_a. By analogy with the definition of ε^* in the previous section, let us assume that there exists an $\hat{\varepsilon} \in (\varepsilon^{min}, \varepsilon^{max})$ such that when $\varepsilon > \hat{\varepsilon}$, the strict inequality in equation (19) holds at (l^R,h^R), and when $\varepsilon = \hat{\varepsilon}$ the equality in equation (19) holds for a net buyer of permits. The expected profit can then be written as follows:

$$E(\pi) = \int_{\varepsilon^{min}}^{\hat{\varepsilon}} (s-r)[(\bar{P}_a+\varepsilon)e(l,h)+k]f(\varepsilon)d\varepsilon + \int_{\hat{\varepsilon}}^{\varepsilon^{max}} [R(l,h)-P_l l-P_h h-rk-(\bar{P}_a+\varepsilon)(e(l,h)-A)]f(\varepsilon)d\varepsilon$$

The first-order conditions for a maximum (l^R,h^R) are as follows:[10]

$$\frac{\partial E(\pi)}{\partial l} = \int_{\varepsilon^{min}}^{\hat{\varepsilon}} (s-r)(\bar{P}_a+\varepsilon)\mu_l f(\varepsilon)d\varepsilon + \int_{\hat{\varepsilon}}^{\varepsilon^{max}} [R_{l^R} - P_l - (\bar{P}_a+\varepsilon)\mu_l]f(\varepsilon)d\varepsilon = 0 \quad (20)$$

$$\frac{\partial E(\pi)}{\partial h} = \int_{\varepsilon^{min}}^{\hat{\varepsilon}} (s-r)(\bar{P}_a+\varepsilon)\mu_h f(\varepsilon)d\varepsilon + \int_{\hat{\varepsilon}}^{\varepsilon^{max}} [R_{h^R} - P_h - (\bar{P}_a+\varepsilon)\mu_h]f(\varepsilon)d\varepsilon = 0 \quad (21)$$

From equations (20) and (21), the ratio of marginal products at (l^R,h^R) is as follows:

$$\frac{g_{l^R}}{g_{h^R}} = \frac{P_l + \bar{P}_a\mu_l + \mu_l\hat{C}^B}{P_h + \bar{P}_a\mu_h + \mu_h\hat{C}^B} \quad (22)$$

where

$$\begin{aligned} \hat{C}^B &= \frac{\int_{\hat{\varepsilon}}^{\varepsilon^{max}} \varepsilon f(\varepsilon)d\varepsilon - (s-r)\int_{\varepsilon^{min}}^{\hat{\varepsilon}}(\bar{P}_a+\varepsilon)f(\varepsilon)d\varepsilon}{\int_{\hat{\varepsilon}}^{\varepsilon^{max}} f(\varepsilon)d\varepsilon} \\ &= \frac{\int_{\varepsilon^{min}}^{\varepsilon^{max}} \varepsilon f(\varepsilon)d\varepsilon - \int_{\varepsilon^{min}}^{\hat{\varepsilon}} \varepsilon f(\varepsilon)d\varepsilon - (s-r)\int_{\varepsilon^{min}}^{\hat{\varepsilon}}(\bar{P}_a+\varepsilon)f(\varepsilon)d\varepsilon}{\int_{\hat{\varepsilon}}^{\varepsilon^{max}} f(\varepsilon)d\varepsilon} \\ &= \frac{(1+s-r)\int_{\hat{\varepsilon}}^{\varepsilon^{max}} \varepsilon f(\varepsilon)d\varepsilon - (s-r)\bar{P}_a F(\hat{\varepsilon})}{1-F(\hat{\varepsilon})} \end{aligned} \quad (23)$$

The direction of factor substitution relative to a deterministic scenario is determined by the sign of $\hat{C}^B$. A positive $\hat{C}^B$ makes the ratio of the marginal revenue products of low- and high-sulfur coal lower than would be chosen at the cost-minimizing point of an unregulated firm. This implies that a regulated firm would employ a higher share of low-sulfur coal and emit less than if it were not subject to profit regulation. Such a result is opposite to the classic Averch-Johnson effect.

10. $\hat{\varepsilon}$ is also a function of l and h, but the derivatives of $\hat{\varepsilon}$ with respect to l and h cancel out.

To examine the sign of $\hat{C}^B$, notice that the denominator of equation (23) is the probability that the regulatory constraint is inactive and is assumed to be positive. The nominator of equation (23) is composed of two terms. The integral in the first term ($\int_{\hat{\varepsilon}}^{\varepsilon^{max}} \varepsilon f(\varepsilon) d\varepsilon$) measures the expected value of ε that corresponds to having an ineffective profit constraint. $F(\hat{\varepsilon})$ in the second term measures the probability of having a binding profit constraint. An anti–Averch-Johnson effect occurs if the first term outweighs the second term. Therefore, the first term can be interpreted as an anti–Averch-Johnson component, while the second term contributes to the Averch-Johnson effect. The direction of factor substitution is determined by the relative importance of the two terms.

Because by assumption both terms in the nominator of equation (23) are positive, the sign of $\hat{C}^B$ is generally undetermined. The exceptions correspond to some extreme scenarios—for example, if s is chosen close enough to r, such that $\hat{\varepsilon} \to 0$ and $F(\hat{\varepsilon}) \to \frac{1}{2}$. Meanwhile, when the uncertainty as measured by the distribution of the stochastic variable ε is large enough such that the expected value of ε over $(0, \varepsilon^{max})$ is greater than $\frac{1}{2}\frac{1}{1/(s-r)+1}\bar{P}_a$, an anti–Averch-Johnson effect will dominate.

To demonstrate the existence of an anti–Averch-Johnson effect further, we numerically solve the profit maximization problem given in equations (16) and (17) based on specific assumptions about the revenue function and the probability distribution of P_a. We discuss the role of s and the variance of allowance prices (ε) in determining the compliance strategy of a net buyer of permits.

Assume that the revenue function takes the form: $R(l,h) = (Gl^{\alpha}h^{1-\alpha})^{\delta}$, where G is a productivity parameter and $0 < \alpha < 1$ is the share of low-sulfur coal. $0 < \delta < 1$ can be interpreted as the demand elasticity or the return to scale of the production function. The optimal coal inputs are determined by the following equations:

$$l^R = \frac{\alpha\delta R}{P_l + \bar{P}_a\mu_l + \mu_l\hat{C}^B}$$

$$h^R = \frac{(1-\alpha)\delta R}{P_h + \bar{P}_a \mu_h + \mu_h \hat{C}^B}$$

Consider ε following a normal distribution $f(\varepsilon) \sim N(0, a^2)$, where a is the standard deviation and $a^2 = \varepsilon^{max}$.[11] Then $\hat{C}^B$ is given by the following:

$$\hat{C}^B = \frac{(1+s-r)\frac{a}{\sqrt{2\pi}} exp(-\frac{(\hat{\varepsilon})^2}{2a^2}) - (s-r)\bar{P}_a \Phi(\hat{\varepsilon}/a)}{1 - \Phi(\hat{\varepsilon}/a)}$$

where Φ is the frequency function of a standard normal distribution. We assume that $A = 0$ and therefore only consider the emissions decisions of a net buyer of permits. The parameter values of G, α, δ, μ_l, μ_h, P_l, P_h, P_e, $\bar{P}_a$, and r are given in table 1.[12]

<<Table 1 about here>>

Figure 1 illustrates the joint impact of rate-of-return regulation and permit price uncertainty in generating the anti–Averch-Johnson effect. In this figure, the dashed line corresponds to the amount of pollutants emitted when there is no profit regulation. It is horizontal, indicating that without rate-of-return regulation, the variation of ε has no impact on decisions regarding emissions. All the other lines indicate total emissions of a regulated firm as a function of the variance of permit price (ε^{max}) and the profit constraint (s). When uncertainty is low (ε^{max} is small), the Averch-Johnson effect dominates at each level of s. Regulated firms use more allowances and produce more emissions than the unregulated benchmark. As the variance of the permit price goes up, the volume of emissions declines. When ε^{max} > is greater than US$27 per ton, the anti–Averch-Johnson effect dominates such that for all values of s, the total amount of emissions of a rate-of-return regulated firm is less than that of an unregulated firm. The impact of s on emissions depends

11. Assuming another probability distribution of ε, such as a uniform distribution, does not change the conclusion.

12. The values of μ_l, μ_h, P_l, P_h, and $\bar{P}_a$ are comparable to actual observations of the SO_2 allowance market.

on the volatility of permit price. In the range of price uncertainty where the anti–Averch-Johnson effect dominates, the larger is *s*, the lower are emissions.[13]

Figure 2 shows the simulation results while allowing *s* to change continuously. Similar to the pattern of emissions shown in figure 1, at a given level of *s*, emissions decrease as the variance of permit price increases. Moreover, as *s* increases (the profit constraint becomes more relaxed), the anti–Averch-Johnson effect becomes smaller, and emissions under rate-of-return regulation gradually converge to the unregulated benchmark.

To complete the analysis, we also simulate firms' emissions decisions under expense policy. Figure 3 depicts the results. The dashed line again indicates the total amount of emissions without profit regulation. All the other lines correspond to the emissions of a rate-of-return regulated net buyer of permits. It is apparent that the emissions of a regulated firm subject to expense policy are unambiguously lower than the unregulated benchmark. The more volatile is the permit price and the more stringent is the profit regulation, the larger is the distortion.

5 Interpretation of the Results

Intuitively, these results can be understood as driven primarily by an asymmetric/nonlinear impact of a change in permit price on the expected marginal value of permits. Under an effective rate-of-return regulation, the opportunity cost of permits for a regulated firm is less than the price of permits for an unregulated firm. The wedge between them is the extra profit that a regulated firm is allowed to earn either through a positive capital gain from treating emissions permits as an expense (capital policy) or through a relaxation of the profit constraint to cover other operating

13. The spot market price of SO_2 allowances ranged from a low of US$66 per ton in 1997 to a high of US$1,200 per ton in 2005 (before the virtual collapse of the SO2 market after 2006). The actual variance of allowance prices largely exceeded the threshold of US$27 per ton identified in the simulation.

costs (expense policy). Because the rate-of-return regulation imparts an implicit reduction in the cost of permits, there is an impetus to increase the use of permits, all else being equal. This is the rationale behind the conventional Averch-Johnson effect.

In the presence of stochastic permit prices, rate-of-return regulation could impose a nonlinear impact on the marginal value of permits: for a certain set of permit prices, the profit constraint would never be binding, and the marginal cost of permits would equal the market price; for the complement of that set, the profit constraint would be effective, and the marginal cost of permits for a regulated firm would be lower than the market price.

Suppose a firm initially operates in a region where regulation is effective, but expects that the permit price may change to such an extent that the profit constraint becomes ineffective—that is, the permissible profit will exceed the unconditionally maximized profit.[14] The firm's incentive will depend on its market position. A net buyer of permits would find it attractive to increase abatement (increase the share of low-sulfur coal) and save permits, as the potential gain—the expected marginal value of saving an extra unit of permits when the allowance price increases—is higher than the potential marginal loss of saving excessive permits when the price of a permit falls. When uncertainty is more pronounced, very high and very low permit prices are more likely, the asymmetric impact becomes more salient, and the anti–Averch-Johnson effects eventually will prevail.

Similarly, for a net seller of permits, the marginal value of a permit is asymmetrically affected by the price movement of permits: the lower limit of the marginal value of permits is not bounded, but the upper limit is constrained by rate-of-return regulation. The wider the variance in

14. An important condition for this to hold is that the allowed rate of return is independent of a change in permit price. This could be justified by the existence of regulatory lag.

permit price, the lower the expected marginal profit from selling permits. In this case, uncertainty exacerbates the Averch-Johnson bias.

A decline in the allowed rate of return (s) toward the cost of capital (r) will decrease/increase the optimal amount of emissions of a net buyer/seller of permits. Intuitively, this occurs because when the regulatory constraint is tightened, the range of permit prices where the profit constraint is effective becomes smaller for a net buyer and larger for a net seller. Given the same distribution of permit price, the expected marginal value of permits will be higher from the point of view of a permit buyer and lower from the point of view of a permit seller. Therefore, a net buyer would have less desire to buy allowances, while a net seller would have less desire to sell allowances in the *ex ante* period.

An extension of this analysis is to consider scenarios where uncertainty also arises from lack of regulatory guidance. Expectations regarding future regulatory policies affect the expected value of allowances and the corresponding compliance strategy. A regulated firm will increase abatement in anticipation of a change in regulatory policy that reduces the future value of allowances, and vice versa. Therefore, during a transitional period of electricity market restructuring, firms would tend to accumulate permits through overcompliance, since moving toward restructuring implies the eventual loss of cost recovery ($u \rightarrow 0$), thus increasing the expected marginal value of allowances. This is consistent with Burtraw (1996) and Arimura (2002) who find that uncertainty about restructuring policy and cost recovery rules on the sale and purchase of allowances may have inclined utilities to adopt a self-sufficient strategy and lessened the volume of emissions permits traded in the market.

6 Conclusion

This paper examines how the combination of rate-of-return regulation and the price uncertainty of emissions permits affects a risk-neutral firm's strategy for complying with environmental regulations. We show that because of the asymmetric impact of a change in permit price on the expected marginal value of permits, a regulated firm would adopt a compliance strategy that is different from what is predicted by a theory that ignores the presence of uncertainty.

When allowance transactions are treated as operating expenses, a net buyer of permits will abate too many emissions and a net seller of permits will abate too few compared to a cost-effective solution. When allowance transactions are treated as capital investments, the presence of price uncertainty would mitigate the conventional Averch-Johnson effect if a firm purchases allowances on a net basis. When price variation is large enough or the profit constraint is stringent enough, the overcapitalization influences of the Averch-Johnson effect would be completely reversed: a net buyer of permits would use fewer allowances and reduce more emissions in the *ex ante* period.

Overall, the combination of price uncertainty and rate-of-return regulation distorts the relative price of allowances and of low-sulfur fuel. It makes a self-sufficient abatement strategy more attractive and discourages use of the allowance market. A wider variation in permit price and a decline in the regulated rate of return toward the cost of capital will exacerbate the distortion.

The results highlight two issues. First, under rate-of-return regulation, the second-order moments of the price distribution can be as important as the mean price in determining firms' emissions behavior. Second, the overlap between a nationwide cap-and-trade system and statewide PUC regulation would compromise the efficiency of the environmental market. In a tradable quota system, firms equalize marginal abatement costs with their private opportunity cost of trading permits. The latter is affected by the perceived risk of permit price uncertainty and rate-making policies in the product market. These results have implications for the efficiency of the proposed global carbon trading. Electricity restructuring has occurred unevenly across states and countries, and for those whose electricity markets are still regulated, the rate-making policies vary significantly. With this wide variety of institutional structure in the electricity market, the optimality property of a tradable quota system—that is, the marginal abatement cost of pollution sources is equalized with the permit price—will not hold. Policies aimed at alleviating the uncertainty of carbon prices can help improve efficiency from this perspective.

In the paper, we do not consider that the fuel market is likely to respond to fluctuations in the price of emissions allowances so that the price premium for low-sulfur coal also becomes uncertain. To analyze the more complicated effects resulting from the correlation between uncertainties in input markets is an interesting topic for future research.

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Table 1 Parameter Values for Numerical Simulation

Parameters	Value	Parameters	Value
r	0.05	μ_l (lbs/MMBtu)	1.64
k	5000	μ_h (lbs/MMBtu)	4.41
δ	0.8	P_l (cents/MMBtu)	126.7
G	2000	P_h (cents/MMBtu)	120
α	0.6	P_e (cents/kWh)	4.21
A(tons)	0	$\bar{P}_a$ (dollars/ton)	100

Figure 1 Emissions as a Function of the Variance of Permit Prices and Regulated Rate of Return (*s*) under Capital Policy

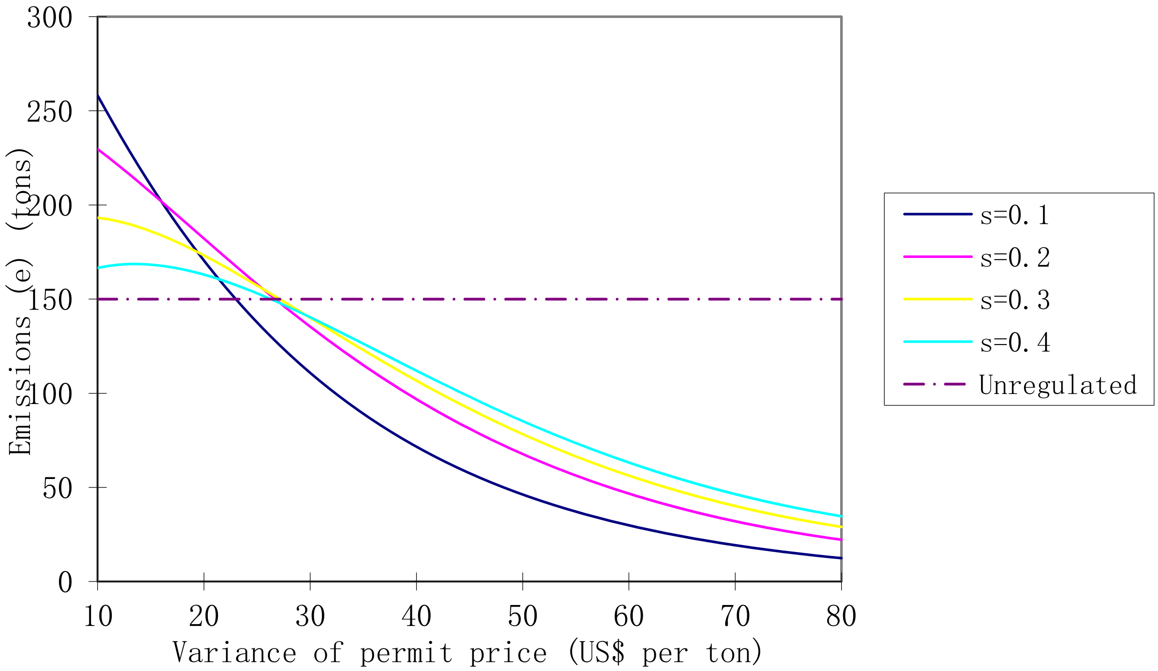
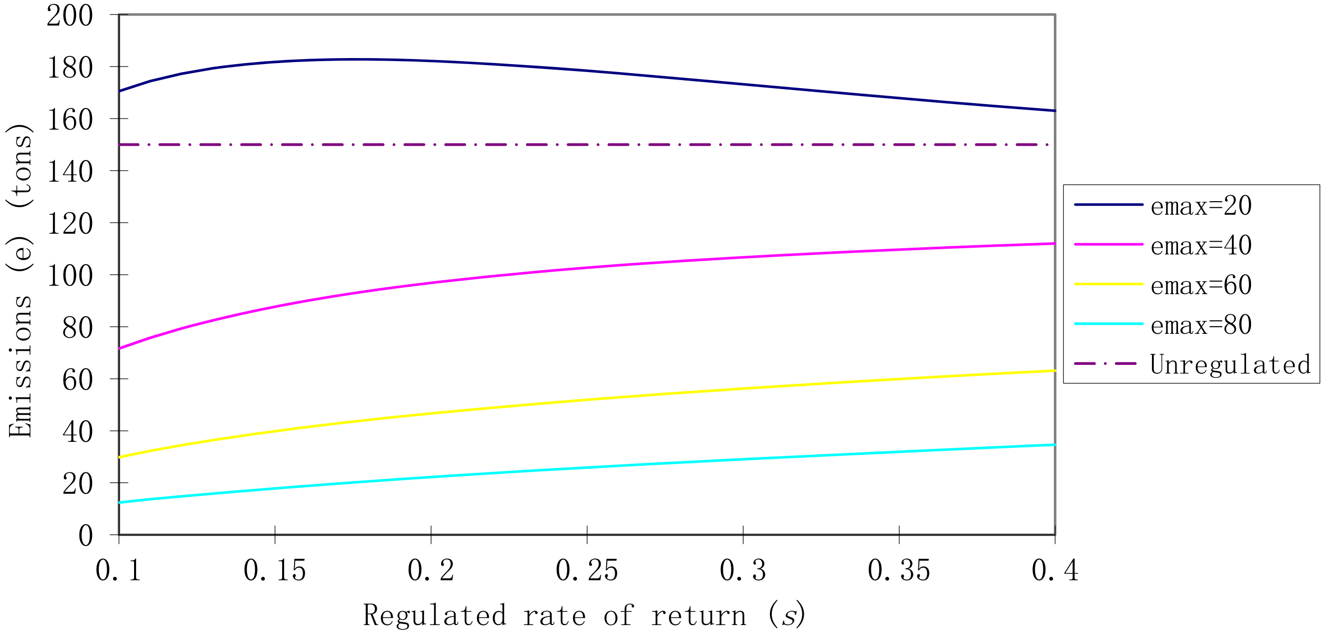


Figure 2 Emissions as a Function of Regulated Rate of Return (*s*) and the Variance of Permit Prices under Capital Policy



Note: emax = ε (US$ per ton).

Figure 3 Emissions as a Function of the Variance of Permit Prices and Regulated Rate of Return (*s*) under Expense Policy