Investment Effect of Emission Permits Banking under Technological Uncertainty*

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Abstract

The purpose of this paper is to analyze investment effect of tradable permit program (TPP) when emission permits are bankable and there is technological uncertainty regarding abatement cost. In the absence of abatement cost uncertainty, a bankable TPP decreases a firm's incentive to environmental investment because the firm can use banked permits for future abatement compliance instead of abatement investment. However, when cost uncertainty is prevalent, there arises a real option value associated with the investment and it may change a firm's investment strategy. The condition is derived under which a bankable TPP provides higher investment incentive than a non-bankable TPP.

Keywords: tradable emission permits, real option, investment, uncertainty

1 Introduction

Among environmental economists, there has been a consensus that a tradable permit program (TPP) is an efficient environmental management system to achieve environmental targets. One important criterion for evaluating the performance of TPPs is their effect on environmental investment.

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Although primary objective of environmental regulation is to correct externalities, its effect on investment in costly new pollution abatement equipment is a critical element to be considered since investment-inducing regulation improves social welfare as well as facilitates technology adoption and diffusion processes (Jaffe, Newell and Stavins, 2002). Many papers are motivated by this to examine investment effect of TPPs and their partial list includes Millman and Prince (1989), Jung, Krutilla and Boyd (1996) and Montero (1999).

Since many TPPs such as the U.S. Acid Rain Program and the Kyoto Protocol currently allow banking, it is essential to understand how banking affects a firm's incentive for the adoption of pollution abatement technology. Note that the previously cited papers do not analyze permit banking. On the other hand, while a series of papers including Cronshaw and Kruse (1996), Rubin (1996), Kling and Rubin (1997) and Yates and Cronshaw (2001) analyze banking system, they do not consider investment in pollution abatement technology. Their main purpose is rather to analyze how emission permit banking system changes the emission flow over time.

In response to inquiry on investment effect of banking system, recently, Phaneuf and Requate (2002) provide a two-stage optimization model. Their finding is that banking system unambiguously reduces abatement investment. If there were no banking system allowed, the only feasible strategy to reduce future abatement cost is an investment in cost-reducing abatement technology. However, under a bankable TPP, the firm can use banked permits for future abatement compliance strategy instead of relying on environmental investment. Extending their model from a deterministic setting, they argue that even the introduction of cost uncertainty does not change such substitution effect of banking for investment.

Although their finding is intuitive, some important aspects that may potentially change their result are disregarded in their model. As well known by Dixit and Pindyck (1994) among others, when uncertainty and irreversibility of investment are prevalent, a real option value arises for the investment and it increases investment hysteresis. Under such circumstance, a firm may exhibit different investment schedule depending on the presence of banking system.

As for the real option literature analyzing investment effect of TPPs, the first study is Herberlot (1994) which develops a model from the perspective of individual power plant firm. He considers two investment strategies, fuel switching and installation of FGD (flue gas desulfurization), during earlier periods of the 1990 Clean Air Act Amendment. His binomial real option model incorporates cost uncertainty as well as permit price uncertainty.

However, the model does not account for a bankable permits system.

Zhao (2003) presents a real option model in a general equilibrium framework. He investigates how investment incentive to the adoption of abatement technology is affected under TPPs and emission charge system. According to Zhao (2003), investment incentive is decreasing in cost uncertainty as consistent with real option argument but such adverse effect of uncertainty is less aggravated under TPPs than under emission charge system. Therefore, he concludes that TPPs in fact help maintain firms' investment incentives in the presence of uncertainty, compared to emission charge system. However, a bankable TPP is neither modeled in Zhao (2003).

In the paper, we provide a real option model to analyze the implications of bankable TPPs on dynamic capital adjustment. Stochastic feature is introduced via abatement cost uncertainty. An investment model is developed from the perspective of an individual firm and it compares the resulting investment rule under abatement cost uncertainty with deterministic investment rule. In a deterministic framework, we obtain unambiguous result as consistent with Phaneuf and Requate (2002): banking system weakens a firm's incentive to expand abatement capital. The reason is that investment reduces the value of permit stock because the banked permits become less valuable assets for future abatement compliance strategy once a firm's abatement capital increases.

If the abatement cost uncertainty is taken into account, the incentive to investment is reduced by hysteresis effect (Dixit and Pindyck, 1994). However, the degree of incentive reduction may come from different form depending on whether banking is allowed or not. In the case where banking is not allowed, the opportunity cost of exercising the investment option is substantial since the residual permits acquired through an investment should be immediately sold, otherwise they retain no value afterwards. Under such circumstance, a bankable TPP can facilitate more investment than a non-bankable TPP does when the residual permits can be used in later periods and the permits are valuable in the future. It implies that banking and investment are not exclusive strategies for firms to achieve cost minimization over time. In the paper, we derive a condition under which a bankable TPP provides higher investment incentive than a non-bankable TPP does.

The rest of paper is organized as follows: Section 2 presents an investment option model, encompassing banking system as well as non-banking system. Section 3 performs numerical simulations to explore empirical implications of the model using the data on the U.S. Acid Rain Program. Lastly, Section 4 provides conclusion.

2 Model

2.1 General model

Consider a firm regulated by a TPP whose baseline emission rate is $e(t)$. At each instant in time it receives emission permits $\bar{e}(t) < e(t)$ from a regulatory agency. A firm has two options for compliance. It can either abate emissions at rate $a(t) \leq e(t)$ or puchase additional permits at rate $q(t)$. If a firm reduces its emissions below $\bar{e}(t)$ the excess permits can either be sold, $q(t) < 0$, or banked for future use. The market for emission permits is assumed to be competitive so that firms take the permit price, $p(t)$, as given. The firm's stock of emission permits banked up to time t is denoted by $B(t)$. Its initial value, $B(0) = B_0 \geq 0$, is exogenously determined by the environmental regulatory agency. Let $b(t)$ denote permits that are instantaneously banked, $b(t) > 0$, or withdrawn, $b(t) < 0$. The stock of banked permits evolves according to the transition equation $\dot{B}(t) = b(t)$. Emissions, abatement, permit transactions and banking satify the accounting identity:

$$q(t) = e(t) - \bar{e}(t) - a(t) + b(t). \quad (1)$$

Note that if $b(t) > 0$, the opportunity cost of the instantaneous bank is $p(t)\, b(t)$, the amount the firm could earn if those permits were sold. On the other hand, when $b(t) < 0$, a firm receives $p(t)\, b(t)$, the cost saving it achieves by not having to purchase an equivalent quantity of permits from the market. In what follows, time t is suppressed for notational convenience unless it is needed for clarity.

Emission abatement costs depend on installed abatement capital, $k(t)$, the instantaneous rate of abatement, $a(t)$, and a parameter, θ, that represents industry-wide cost uncertainty common to all firms. The abatement cost function is given by:

$$C(a, \theta, k) = \theta c(k) a^{\gamma}. \quad (2)$$

The term $c(k)$ captures the effect of installed capital on abatement costs. It is assumed that $c'(k) < 0$. The implication is that a firm can reduce its future abatement costs by investing in more efficient abatement capital. At each instant the firm must decide whether to undertake investment and expand captial from k to $k + dk$, or maintain its current level of k without any adjustment. The unit cost of capital is w. Investment is considered irreversible so that $dk > 0$, and for simplicity, there is no depreciation.

Current abatement cost is known but there is uncertainty over future abatement costs. Uncertainty is represented by assuming the cost parameter, θ, follows the geometric Brownian motion stochastic process:

$$d\theta = -\alpha\theta dt + \sigma\theta dz,$$

where dz is the increment of a standard Wiener process, uncorrelated over time, with $E(dz) = 0$, $Var(dz) = dt$ and $\theta(0) = \theta_0 \geq 0$. The drift parameter, $-\alpha$, measures the expected growth rate of the stochastic process. The fact that it is negative implies that firms face uncertainty over cost reducing technical change. The parameter σ represents the volatility rate of the stochastic process and $\sigma > 0$ implies that the variance of future costs increases with the time horizon over which forecasts are being made. The parameter γ is the elasticity of cost with respect to abatement. To simplify the presentation and obtain an explicit analytical solution we assume a quadratic specification where $\gamma = 2$.[1]

Total compliance cost is given by abatement cost plus permit purchase cost (or less permit sales revenue). Using (1) and (2) this can be expressed as:

$$C(a, \theta, k) + pq = \theta c(k)a^2 + p(e - \bar{e} - a + b). \tag{3}$$

The decision problem for the firm can be summarized as follows. Given the state, $(\theta(t), k(t), B(t))$, the firm chooses a policy for abatement, permit transactions, permit banking and investment in abatement capital to minimize the expected discounted stream of costs over time. Formally, the cost minimizing value of an optimal investment and abatement policy can be represented as:

$$V(\theta, k, B) = \max_{a,b,dk} - E\int_0^\infty e^{-rt}\left[(\theta c(k)a^2 + p(e - \bar{e} - a + b))dt - wdk\right], \tag{4}$$

where r is the discount rate.

First, consider the firm's optimal policy for abatement. Minimizing (3) with respect to a yields the optimal abatement schedule

$$a(t) = \frac{p(t)}{2\theta(t)c(k(t))}. \tag{5}$$

[1] Zhao (2003) takes a similar approach.

Optimal abatement is increasing in the permit price and decreasing in the abatement cost parameter, θ. Investment in capital reduces the marginal cost of instantaneous abatement which increases optimal abatement.

Next, consider a firm's investment decision. When the marginal value of investment, $V_k(\theta, k, B)$, is less than the cost of capital, w, the optimal policy is to maintain the current capital stock k. Conversely, if $V_k(\theta, k, B) \geq w$, investment occurs and the stock of capital is increased. This problem is a *barrier control* problem where the main task is to determine the optimal threshold at which investment occurs.[2]

Suppose that the initial value of the cost parameter, θ_0, is sufficiently high so that immediate investment is not optimal. Then the value function can be expressed as:

$$rV(\theta, k, B) = \max_{a,b} \left[-\theta c(k)a^2 - p(e - \bar{e} - a + b) + \frac{1}{dt} E_t dV(\theta, k, B) \right].$$

Using Ito's Lemma this leads to the Hamilton-Jacobi-Bellman (HJB) equation:

$$\begin{aligned} rV(\theta, k, B) &= \max_{a,b} -\theta c(k)a^2 - p(e - \bar{e} - a + b) \\ &\quad + bV_B(\theta, k, B) - \alpha\theta V_\theta(\theta, k, B) + \frac{1}{2}\sigma^2\theta^2 V_{\theta\theta}(\theta, k, B). \quad (6) \end{aligned}$$

The second partial subscript denotes partial derivative. The optimization problem can be solved in stages by first substituting the optimal abatement schedule (5) to obtain the *reduced form* HJB equation:

$$\begin{aligned} rV(\theta, k, B) &= \max_{b} \pi(k)\theta^{-1} - p(e - \bar{e} + b) + bV_B(\theta, k, B) \\ &\quad - \alpha\theta V_\theta(\theta, k, B) + \frac{1}{2}\sigma^2\theta^2 V_{\theta\theta}(\theta, k, B), \quad (7) \end{aligned}$$

where $\pi(k) = p^2/4c(k)$.

The main objective of the paper is to analyze the optimal investment policy of a firm under both a non-bankable and a bankable TPP. To this end define $V^N(\theta, k)$ and $V^B(\theta, k, B)$ to be the cost minimizing value functions under a non-bankable and bankable TPP, respectively. We first consider investment under a non-bankable TPP.

[2] See Harrison and Taskar (1983), Harrison (1985, ch. 6) or Dumas (1991) for a formal discussion of barrier control. Dixit (1993) and Dixit and Pindyk (1994) provide a less rigorous, but more intuitive exposition.

2.2 Investment option value under a non-bankable TPP

Let θ^* denote the optimal investment threshold under a non-bankable TPP. Under a non-bankable TPP, $B = b = 0$, and the HJB equation (7) is:

$$rV^N(\theta, k) = \pi(k)\,\theta^{-1} - p(e - \bar{e}) - \alpha\theta V_\theta^N(\theta, k) + \frac{1}{2}\sigma^2\theta^2 V_{\theta\theta}^N(\theta, k). \quad (8)$$

It is natural to require that a solution to this equation should satisfy the boundary condition:

$$\lim_{\theta\to\infty} V^N(\theta, k) = -p(e - \bar{e})/r \quad (9)$$

so that no abatement occurs when the abatement cost is infinite and the expected present value of compliance is comprised only of permit purchase cost.

Using the method of undetermined coefficients, a particular solution for the non-homogeneous component of (8) is given by

$$V^{Np}(\theta, k) = \frac{\pi(k)}{\theta(r - \alpha - \sigma^2)} - \frac{p(e - \bar{e})}{r}. \quad (10)$$

Superscript p denotes particular solution. The second term on the right hand side is the present value of net permit purchase cost after taking into account the cost savings through the abatement. The first term represents the present value of abatement at currently installed k. The following assumption insures the existence of a strictly positive threshold from which it is optimal to invest:

A.1. $r - \alpha - \sigma^2 > 0$.

The option value of investment is obtained by solving the homogeneous part of (8), $rV^N = -\alpha\theta V_\theta^N + (1/2)\,\sigma^2\theta^2 V_{\theta\theta}^N$. The general solution denoted with superscript g is given by

$$V^{Ng}(\theta, k) = A_{N1}(k)\theta^{\phi_{N1}} + A_{N2}(k)\theta^{\phi_{N2}} \quad (11)$$

where $A_{N1}(k)$ and $A_{N2}(k)$ are constants to be determined using additional boundary conditions. ϕ_{N1} and ϕ_{N2} are the positive and negative roots, respectively, of the characteristic equation $\Omega_N = 0.5\sigma^2\phi_N(\phi_N - 1) - \alpha\phi_N - r$:

$$\phi_{N1} = \frac{1}{2} + \frac{\alpha}{\sigma^2} + \sqrt{\left(\frac{1}{2} + \frac{\alpha}{\sigma^2}\right)^2 + \frac{2r}{\sigma^2}} > 1, \quad (12)$$

$$\phi_{N2} = \frac{1}{2} + \frac{\alpha}{\sigma^2} - \sqrt{\left(\frac{1}{2} + \frac{\alpha}{\sigma^2}\right)^2 + \frac{2r}{\sigma^2}} < -1 \quad (13)$$

where the inequality of (13) follows from $A.1$.[3] If $A_{N1}(k) \neq 0$, then $\phi_{N1} > 1$ implies $\lim_{\theta \to \infty} V^{Ng}(\theta, k) = \infty$. Since this violates the boundary condition (9) the first option term in (11) is eliminated by setting $A_{N1}(k) = 0$. The intuition is that infinite abatement costs are sufficient to deter any investment in abatement capital. Given that $A_{N1}(k) = 0$ we can simplify notation and express the subscript $N2$ as N throughout the remaining analysis.

Combining (10) and (11), the solution for the value function V^N is given by

$$V^N(\theta, k) = \frac{\pi(k)}{\theta(r - \alpha - \sigma^2)} - \frac{p(e - \bar{e})}{r} + A_N(k)\theta^{\phi_N}. \tag{14}$$

In what follows, it is important to comprehend a property of ϕ_N (i.e., ϕ_{N2}) with respect to the drift and volatility parameters. First, ϕ_N is increasing in α: $\partial\phi_N/\partial\alpha > 0$. This can be checked using the characteristic equation by letting $\Omega_N = 0$. From the total differentiation, $[\partial\Omega_N/\partial\phi_N][\partial\phi_N/\partial\alpha] + \partial\Omega_N/\partial\alpha = 0$. Since $\partial\Omega_N/\partial\alpha = -\phi_N > 0$ and $\partial\Omega_N/\partial\phi_N < 0$ with $\phi_N < 0$, the substitution of them to the total differentiation yields $\partial\phi_N/\partial\alpha > 0$. In a similar manner, it can be shown that ϕ_N is increasing in σ: $\partial\phi_N/\partial\sigma > 0$. In sum, the properties of ϕ_N (i.e., ϕ_{N2}) are summarized as follows:

Remark 1 *(i) $\phi_N < 0$, (ii) $\partial\phi_N/\partial\alpha > 0$, (iii) $\partial\phi_N/\partial\sigma > 0$, and (iv) $\partial\phi_N/\partial r < 0$*

To determine the optimal investment trigger θ^* and the constant term $A_N(k)$, the value-matching condition (15) and super-contact condition (16) are required (Dumas, 1991):

$$V_k^N(\theta^*, k) = w, \tag{15}$$

$$V_{k\theta}^N(\theta^*, k) = 0. \tag{16}$$

The value-matching condition states that the marginal value of investment is equal to the marginal capital adjustment cost at the optimal threshold of θ^*. The super-contact condition (16) allows a smooth transition from the no-investment regime to the investment regime. By solving two boundary conditions simultaneously, we have

[3] Suppose, by contradiction, $\phi_N + 1 \geq 0$. From (13), $3/2 + \alpha/\sigma^2 \geq \sqrt{(1/2 + \alpha/\sigma^2)^2 + 2r/\sigma^2}$. Take squares to both RHS and LHS. By rearranging terms, one obtains $r - \alpha - \sigma^2 \leq 0$ that is contradictory to the assumption A.

Lemma 1 *The optimal investment threshold that specifies an investment rule, (15) and (16), is*

$$\theta^* = \frac{\pi'(k)}{(r-\alpha-\sigma^2)}\left(\frac{1}{wH_N}\right) > 0 \tag{17}$$

where $H_N = \phi_N/(\phi_N+1)$.

Proof. The derivation of θ^* is straightforward from two boundary conditions, (15) and (16). Note that they can be explicitly rewritten as

$$A_N'(k)\theta^{*\phi_N} = \frac{-\pi'(k)}{\theta^*(r-\alpha-\sigma^2)} + w \tag{18}$$

$$\phi_N A_N'(k)\theta^{*\phi_N} = \frac{\pi'(k)}{\theta^*(r-\alpha-\sigma^2)} \tag{19}$$

where $\pi'(k) = -c'(k)\,p^2/4c(k)^2$. By substituting $A_N'(k)\theta^{*\phi_N}$ of (19) into (18), and then rearranging terms, θ^* is obtained as (17). Since $r-\alpha-\sigma^2 > 0$ and $H_N > 0$ from the assumption A, θ^* is an intuitively valid threshold that is positive. ■

Note that θ^* in (17) is represented with the marginal expected present value of abatement devided by the capital adjustment cost, w, and the option value multiple, H_N. We shall discuss more about H_N shortly. The LHS in (18) is the marginal option value for an investment and the RHS in (18) represents the marginal change of the expected present value of the compliance cost plus the capital adjustment cost. A waiting value at θ is measured by $-A_N'(k)\theta^{\phi_N} - \left[\frac{\pi'(k)}{\theta(r-\alpha-\sigma^2)} - w\right]$. Until θ reaches θ^*, a positive waiting value prevails but at $\theta \leq \theta^*$, no more waiting value exists. Therefore, the value-matching condition implies that the waiting value becomes zero at θ^* and it is optimal for the firm to adjust its capital immediately. Figure 1 depicts how the waiting value changes as θ evolves from the right to the left and how θ^* is determined.

The option value multiple H_N captures hysteresis effect in a non-bankable TPP, measuring degree of reluctance to undertake an investment. The larger value of H_N indicates greater reluctance to adjust capital since it lowers the investment threshold. From Remark 1, following properties of H_N are immediate:

Lemma 2 *(i)* $\partial H_N/\partial\alpha > 0$, *(ii)* $\partial H_N/\partial\sigma > 0$, *and (iii)* $\partial H_N/\partial r < 0$.

Figure 1: Determination of Investment Threshold

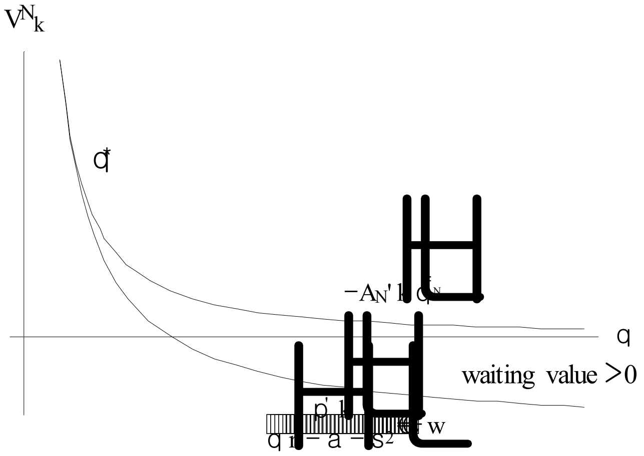


Figure 2:

As consistent with conventional real option result, larger uncertainty creates larger hysteresis: $\partial H_N/\partial\sigma > 0$. When technological progress rate is high due to larger value of α, the attraction for the immediate investment may decrease. By this we mean that α is associated with the opportunity cost of exercising the option (Dixit and Pindyck, 1994; Trigeorgis, 1996). Therefore, we observe from Lemma 2 that the higher is α, the higher is the opportunity cost for undertaking an investment rather than holding the option. As we shall see later, this property plays a critical role by distinguishing the investment threshold under a bankable TPP from the one under a non-bankable TPP, by changing the opportunity cost of exercising the option.

Now, combined with Lemma 2, Lemma 1 develops following comparative statics on θ^*:

Lemma 3 *(i) $\partial\theta^*/\partial w < 0$, (ii) $\partial\theta^*/\partial p > 0$, but (iii) the signs of $\partial\theta^*/\partial\sigma$, $\partial\theta^*/\partial\alpha$, and $\partial\theta^*/\partial r$ are indeterminate.*

An increase in irreversible investment cost lowers the threshold and consequently creates further delay for the capital adjustment. On the other hand, an increase in permit price raises the investment incentive. However, the effects of α, σ and r are not determinate because these parameters have opposite effects on the option value multiple and the marginal expected present value of abatement. For example, suppose σ increases. Then greater uncertainty implies larger H_N as explained in Lemma 2. This will reduce the level of θ^*. However, greater uncertainty results in a lager marginal expected present value of abatement and it will increase the level of θ^*. Consequently, the total effect of uncertainty on θ^* is determined depending on underlying parameter values.

The investment trigger θ^* can be compared to a deterministic optimal threshold derived under the NPV approach. Denote θ^*_{NPV} as the NPV investment threshold. In the absence of uncertainty, a firm's present value becomes $\left[\theta c(k)a^2 + p(e - \bar{e} - a)\right]/r$. After substituting the optimal abatement schedule into the present value, we differentiate it with respect to k. Then, equating the unit investment cost w to the marginal option value of investment produces

$$\theta^*_{NPV} = \frac{\pi'(k)}{r}\left(\frac{1}{w}\right). \tag{20}$$

θ^*_{NPV} is often called a *Marshallian* NPV trigger in a sense that it equates the marginal benefit from investment to the marginal investment cost. Notice that θ^*_{NPV} includes no option value multiple, H_N, as in θ^*. Finally, the ordering of investment thresholds between θ^* and θ^*_{NPV} are

Proposition 1 *Deterministic investment threshold is always higher than investment threshold under uncertainty, i.e.,* $\theta^* < \theta^*_{NPV}$.

Proof. We prove by contradiction. Suppose $\theta^* \geq \theta^*_{NPV}$. Then $1/(r - \alpha - \sigma^2)H_N \geq 1/r$. After transposing terms, this is reduced to $\frac{r}{\alpha+\sigma^2} \leq -\phi_N$ that can be explicitly rewritten using (13):

$$\frac{1}{2} + \frac{\alpha}{\sigma^2} + \frac{r}{\alpha + \sigma^2} \leq \sqrt{\left(\frac{1}{2} + \frac{\alpha}{\sigma^2}\right)^2 + \frac{2r}{\sigma^2}}.$$

By taking squares to both terms and rearranging, we have $\frac{r-\alpha-\sigma^2}{(\alpha+\sigma^2)^2} \leq 0$. But this is contradictory to the assumption A. ■

Proposition 1 implies that, by failing to account for managerial flexibility, a deterministic decision rule induces earlier investment relative to the uncertainty case.

So far, we have only solved for θ^*. Remaining task is to derive $A_N'(k)$ by solving (15) and (16) with θ^*:

$$A_N'(k) = \frac{1}{\theta^{*\phi_N+1}} \left(\frac{p}{2c(k)}\right)^2 \frac{-c'(k)}{\phi_N(r-\alpha-\sigma^2)}.$$

The fact that $A_N'(k)$ is negative is intuitive because the investment option value is decreasing in abatement capital. Therefore, the marginal option value in dollar terms is denoted as $-A_N'(k)\theta^{\phi_N}$. By integrating $-A_N'(k)$, the constant term of integration is calculated:

$$A_N(k) = \int_0^k \left[-A_N'(s)\right] ds = \frac{p^2}{4\phi_N(r-\alpha-\sigma^2)} \int_0^k \frac{c'(s)}{c(s)^2\,\theta^{*\phi_N+1}} ds.$$

Now we have all necessary information to evaluate the investment option under a non-bankable TPP. In the next section, the investment option value under a bankable TPP is analyzed.

2.3 Investment option value under a bankable TPP

Denote θ^{**} as an investment threshold when emission permits are bankable. According to the transition equation governing the evolution of the permit stock, $\dot{B}(t) = b(t)$, a firm considers its permits intuitively as a natural resource and allocates them over time through the saving and withdrawing. Under banking system, a firm retains two compliance strategies, permit banking or investment in pollution abatement technology. We focus only on permit banking and do not consider permit borrowing in the paper since there are few borrowable TPPs in place.

Under banking system, a particular concern has been raised on the emission clustering that may be caused by excessive concentration of permits as a result of trading. Hence, similar to Kling and Rubin (1997), we assume that a constraint under a bankable TPP is imposed on the maximum number of permits that can be instantly bought and sold.[4] Denote $\bar{q}$ and $\underline{q}$ as the maximal constrained rates at which a firm is allowed to buy and sell permits, respectively. Then along with $\bar{q}$ and $\underline{q}$ given $e, \bar{e}$, and a, the accounting equation (1) produces the maximal saving rate, $\bar{b}$, and the maximal withdrawing rate, $\underline{b}$, respectively. As before, the constrained HJB is obtained

[4] However, when Kling and Rubin (1997) actually solve the problem, they disregard the bounding condition to simplify model exposition.

by inserting the optimal abatement schedule to (6):

$$\begin{aligned} rV^B(\theta,k,B) &= \max_b \pi(k)\theta^{-1} - p(e-\bar{e}+b) + bV_B^B(\theta,k,B) \\ &\quad -\alpha\theta V_\theta^B(\theta,k,B) + \frac{1}{2}\sigma^2\theta^2 V_{\theta\theta}^B(\theta,k,B). \end{aligned} \tag{21}$$

The HJB (21) should be solved with boundary conditions:

$$\lim_{\theta\to\infty, B\to 0} V^B(\theta,k,B) = -p(e-\bar{e})/r, \tag{22}$$

$$\lim_{B\to 0} V^B(\theta,k,B) = V^N(\theta,k). \tag{23}$$

The boundary condition (22) implies that when cost grows infinitely and there is no available banked permit stock, a firm's compliance cost entirely consists only of the permit purchase cost. The boundary condition (23) states that the value function is reduced to the value function of a non-bankable permit program when the permit stock is exhausted.

Linearity of (21) with respect to the control variable b ensures the existence of an optimal bang-bang solution because b is bounded by $\bar{b}$ and $\underline{b}$. The solution is then characterized by

$$\begin{aligned} b &= \bar{b} \text{ if } p < V_B^B(\theta,k,B), \\ b &= \underline{b} \text{ if } p > V_B^B(\theta,k,B). \end{aligned} \tag{24}$$

The optimality condition (24) reflects an intertemporal trading condition which relates the permit price to the marginal value of permit stock.[5] The first inequality corresponds to the *saving regime* where a firm saves permits at the maximal saving rate, $\bar{b}$, because the current permit price is less than the marginal value of permit stock. On the other hand, the second inequality in (24) corresponds to the *withdrawing regime* where a firm

[5] Another special case of interest is when $p = V_B^B$. In the context of the current model, it can be achieved for two cases. First is when $B = 0$ and this case shall be discussed below. The other case is when there are no trading constraints. Under the circumstance, firms can infinitely bank or withdraw permits and $V^B(\theta,B,k)$ degenerates to $V^N(\theta,k)$. But, as discussed above, environmental regulations more likely implement a maximal capacity of intertemporally tradable permits so as to avoid excessive emissions onto some period. Also, infinite speculation or trades of permits is not possible in equilibrium as argued by Phaneuf and Requate (2002, p.373).

withdraws permits at the maximal rate, $\underline{b}$, to sell permit surplus when the current permit price is greater than the marginal value of permit stock.

The maximal saving and withdrawing rates are endogenously dependent of k when, through the optimal abatement schedule (5), a is increasing in k. Then, from the accounting equation (1), for given level of $\bar{q}$, an increase of a at $p < V_B^B$ results in an increase of $\bar{b}$. Similarly, for given level of $\underline{q}$, an increase of a at $p > V_B^B$ also results in an increase of $\underline{b}$. Therefore, we can represent the maximal rate as a function of k when there is abatement activity.

To solve the value function, we start with the non-homogeneous component, denoted by V^{Bp}. To keep notation simple, let $m(k)$ denote the maximal rate, either to represent $\bar{b}(k)$ or $\underline{b}(k)$. The non-homogeneous component for the HJB equation (21) is constrained one further step by replacing b with the maximal rate, $m(k)$:

$$\begin{aligned} rV^{Bp}(\theta,k,B) &= \pi(k)\,\theta^{-1} - p(e-\bar{e}+m(k)) + m(k)\,V_B^{Bp}(\theta,k,B) \\ &\quad -\alpha\theta V_\theta^{Bp}(\theta,k,B) + \frac{1}{2}\sigma^2\theta^2 V_{\theta\theta}^{Bp}(\theta,k,B). \end{aligned} \tag{25}$$

It can be verified that the particular solution is

$$V^{Bp}(\theta,k,B) = \frac{\pi(k)}{\theta(r-\alpha-\sigma^2)} - \frac{p(e-\bar{e})}{r} - \frac{pm(k)}{r} + \frac{m(k)}{r}pe^{rT(k)}$$

where $T(k) = B/m(k)$.

The next task is to solve for the general solution of the homogeneous equation, denoted by $V^{Bg}(\theta,k,B)$. Intuitively, the homogeneous component corresponds to the case where there is neither abatement nor permit trades. Then, the homogeneous equation for $V^{Bg}(\theta,k,B)$ is

$$rV^{Bg}(\theta,k,B) = mV_B^{Bg}(\theta,k,B) - \alpha\theta V_\theta^{Bg}(\theta,k,B) + (1/2)\,\sigma^2\theta^2 V_{\theta\theta}^{Bg}(\theta,k,B).$$

Notice that m is independent of k in the homogeneous component because there is no abatement and hence the abatement capital has no relevance with the maximal rate. The general solution is

$$V^{Bg}(\theta,k,B) = A_B(k)\left(e^{\xi B}\theta\right)^{\phi_B} \tag{26}$$

where $A_B(k)$ is a constant term and ξ is a scaling parameter that will be determined later. ϕ_B is the negative root of the characteristic equation,

$\Omega_B = (1/2)\,\sigma^2\phi_B(\phi_B - 1) - \hat{\alpha}\phi_B - r$:

$$\phi_B = \frac{1}{2} + \frac{\hat{\alpha}}{\sigma^2} - \sqrt{\left(\frac{1}{2} + \frac{\hat{\alpha}}{\sigma^2}\right)^2 + \frac{2r}{\sigma^2}} < 0 \tag{27}$$

where $\hat{\alpha} = \alpha - \xi m$. Notice that ϕ_B is similar to ϕ_N except for changing from α to $\hat{\alpha}$. As was the case for α in ϕ_N, $\hat{\alpha}$ is also related to the opportunity cost of exercising the investment. However, $\hat{\alpha}$ is now adjusted by ξm and it results in substantial ordering change of investment thresholds, compared to a non-bankable TPP.

Combining the particular and the general solution, the value function is

$$\begin{aligned} V^B(\theta, k, B) \quad = \quad & \frac{\pi\,(k)}{\theta\,(r - \alpha - \sigma^2)} - \frac{p(e - \bar{e})}{r} \\ & -\frac{pm\,(k)}{r} + \frac{m\,(k)}{r} p e^{rT(k)} + A_B\,(k) \left(e^{\xi B}\theta\right)^{\phi_B} \end{aligned} \tag{28}$$

that depends on the current states of θ, B, and k. Using additional boundary conditions, θ^{**}, $A_B\,(k)$, and ξ will be solved below. The interpretation of the first and the second terms in (28) is the same as in (10): the present value of abatement and the present value of net permit purchase cost, respectively. The last term shows the option value of investment for abatement technology.

The third term on the RHS of (28) represents the present value of banking cost incurred to a firm when it saves permits by not using them now. However, the saved permits retain some value because they can be used in the future. This value is reflected in the fourth term. Note that the value of instantaneously banked permits grows exponentially with the continuous compounding factor $e^{rT(k)}$. Finally, if we let $\Psi\,(k) = -pm\,(k)\,/r + m\,(k)\,pe^{rT(k)}/r$, the sum of the third and fourth terms, this is nothing but the *net* present value of instantaneously banked permits. Therefore, its derivative with respect to k denoted by $\psi\,(k)$ is the marginal net present value of instantaneously banked permits with respect to k:

$$\psi\,(k) = \frac{pm'\,(k)}{r}\left(e^{rT(k)}\,(1 - rT\,(k)) - 1\right).$$

Observe that the total capital adjustment cost under a bankable TPP is represented by $w - \psi\,(k)$, the capital adjustment cost less the marginal net present value of banked permits with respect to k. Then, we have

Lemma 4 *The capital adjustment cost under a non-bankable TPP, w, is always less than or equal to the capital adjustment cost under a bankable*

TPP, $w-\psi(k)$*, because the latter includes the opportunity cost of the capital adjustment on instantaneously banked permits.*

Proof. It is sufficient to show that $\psi(k) \leq 0$ holds always. Let $F(T(k)) = e^{rT(k)}(1 - rT(k)) - 1$. Then its first derivative yields the maximal point, $T(k) = 0$. At $T(k) = 0$, $F(T(k)) = 0$. Also, we see $\lim_{T(k)\to\infty} F(T(k)) = -\infty$ and $\lim_{T(k)\to-\infty} F(T(k)) = -1 < 0$ from the limiting property. Thus, combined with $m'(k) > 0$, we know that $\psi(k)$ is always non-positive. ■

The reason for the marginal net present value of instantaneously banked permits to be non-positive is that the banked permits become less valuable assets when a firm's abatement capital increases. Now, we are in a position to derive the investment thresholds. To solve for θ^{**}, $A_B(k)$ and ξ, we use the following boundary conditions:

$$V_k^B(\theta^{**}, k, B) = w, \tag{29}$$

$$V_{k\theta}^B(\theta^{**}, k, B) = 0, \tag{30}$$

$$V_{kB}^B(\theta^{**}, k, B) = 0. \tag{31}$$

The first condition (29) is the conventional value-matching condition and (30) and (31) are the super-contact conditions that ensure the continuity of the marginal value function at the optimal threshold with respect to θ and B, respectively. By solving them simultaneously, we obtain

Lemma 5 *The optimal investment threshold under a bankable TPP is*

$$\theta^{**} = \frac{\pi'(k)}{(r-\alpha-\sigma^2)}\left(\frac{1}{(w-\psi(k))\,H_B}\right) > 0 \tag{32}$$

where $H_B = \phi_B/(\phi_B+1)$*, and*

$$\xi = \frac{rpm'(k)\,T(k)\,e^{rT(k)}}{(w-\psi(k))\,m(k)\,H_B}. \tag{33}$$

Proof. Solving (29) and rearranging terms yields

$$A_B'(k)\left(e^{\xi B}\theta^{**}\right)^{\phi_B} = \frac{-\pi'(k)}{\theta^{**}(r-\alpha-\sigma^2)} - \psi(k) + w. \tag{34}$$

The scaling parameter ξ can be calculated by solving (30) and (31) (Pindyck, 2002). The super-contact condition with respect to B is:

$$\phi_B A_B'(k)\left(e^{\xi B}\theta^{**}\right)^{\phi_B}\xi = \frac{rpm'(k)\,T(k)\,e^{rT(k)}}{m(k)}. \tag{35}$$

The super-contact condition for θ^{**} is obtained by differentiating (34) with respect to θ^{**}. This gives

$$\phi_B A_B'(k)\left(e^{\xi B}\theta^{**}\right)^{\phi_B} = \frac{\pi'(k)}{\theta^{**}\left(r-\alpha-\sigma^2\right)}. \tag{36}$$

By solving (35) and (36) in terms of ξ, we obtain (33). Then, substitute (36) into (34) to cancel out the term $A_B'(k)\left(e^{\xi B}\theta^{**}\right)^{\phi_B}$. This results in (32). Similar to a non-bankable permit program, $H_B > 0$ always holds assuring a positive level of θ^{**}. ■

The interpretation of (32) under a bankable permit is analogous to θ^{**} under a non-bankable permit and the option value multiple ,H_B, represents hysteresis effect. The calculation of ξ involves a complicated procedure to find the fixed point satisfying (33). Fortunately, however, we only need to verify the sign of ξ to construct the ordering of investment thresholds.

The marginal option value is calculated by

$$A_B'(k)\left(e^{\xi B}\theta\right)^{\phi_B} = \left(\frac{\theta^{\phi_B}}{\theta^{**\phi_B+1}}\right)\left(\frac{p}{2c(k)}\right)^2\frac{-c'(k)}{\phi_B(r-\alpha-\sigma^2)} \tag{37}$$

that is negative because the value of investment must be decreasing in the stock of abatement capital. By integrating (37) with respect to k, the investment option value is obtained as before. The NPV threshold under a bankable TPP is derived as follows:

$$\theta_{NPV}^{**} = \frac{\pi'(k)}{r}\left(\frac{1}{w-\psi(k)}\right). \tag{38}$$

Consequently, we characterize the ordering of investment thresholds, θ^*, θ^{**}, θ_{NPV}^* and θ_{NPV}^{**} by pulling together all the results above.

2.4 Characterization of investment thresholds

The relationship between θ^{**} and θ_{NPV}^{**} is consistent with the conventional real option argument: $\theta^{**} < \theta_{NPV}^{**}$. This can be proved in a manner similar to Proposition 1. The ordering of the deterministic thresholds is unambiguous:

Proposition 2 *In the absence of uncertainty, $\theta_{NPV}^{**} < \theta_{NPV}^*$ for $B > 0$ and $\theta_{NPV}^* = \theta_{NPV}^{**}$ at $B = 0$.*

The proof is immediate with reference to (20) and (38) along with Lemma 4. The rationale behind this result is the negative value of the marginal net present value of instantaneously banked permits. Also, the result is consistent to Phaneuf and Requate (2002) arguing that a banking system discourages investment in pollution abatement technology.[6] However, as we shall show below, the presence of uncertainty affects the investment incentive by creating the option value. Next we compare the thresholds under uncertainty.

Proposition 3 *In the presence of uncertainty, $\theta^{**} > \theta^*$ if $(w - \psi(k)) H_B < wH_N$ in the saving regime whereas $\theta^{**} < \theta^*$ in the withdrawing regime.*

Proof. Firstly, consider where $p < V_B^B(\theta, k, B)$. Then following from $m(k) = \bar{b}(k)$ and $m'(k) > 0$, we know $\xi > 0$. Combined with $\xi m > 0$, $\hat{\alpha} < \alpha$ results in $H_B < H_N$ due to Lemma 2. Consequently, we obtain $\theta^{**} > (<)$ θ^* if $(w - \psi(k)) H_B < (>) \; wH_N$. Next, consider where $p > V_B^B(\theta, k, B)$. Then, $m(k) = \underline{b}(k)$, $m'(k) > 0$ and $\xi > 0$ yield $\xi m < 0$. This results in $H_B > H_N$ due to $\hat{\alpha} > \alpha$. Finally, $\theta^{**} < \theta^*$ in the withdrawing regime. ■

In the saving regime where $p < V_B^B(\theta, k, B)$, investment hysteresis is reduced because the opportunity cost of exercising the investment option under a bankable TPP is less than the one under a non-bankable TPP. It is because when banking is profitable, investment can be a better compliance strategy as the residual permits to be saved increases through the investment. However, the final ordering of θ^* and θ^{**} is going to be determined by comparing the relative effect of the hysteresis and the capital adjustment costs under both regimes of TPPs. If the effect of the reduced hysteresis under a bankable TPP is sufficient to offset the relatively higher capital adjustment cost, we have $\theta^{**} > \theta^*$. On the other hand, in the withdrawing regime where $p > V_B^B(\theta, k, B)$, the opportunity cost of exercising the investment option increases and it yields $\theta^{**} < \theta^*$ always. In sum, the above proposition argues that, unlike the certainty case, when a firm facing future cost uncertainty can increase its permit stock through an investment, there exists a condition under which a bankable TPP increases investment incentive more than a non-bankable TPP does.

[6] Phaneuf and Requate (2002) show that the investment *size* under a bankable TPP is less than under a non-bankable TPP. On the other hand, we focus on investment *timing* under a non-bankable and a bankable TPP.

2.4.1 Effect of an intertemporal offset provision

According to Krupnick, Oates and Verg (1983), the offset provision allows new sources of a pollutant in a particular area to be offset by compensating abatement in other sources of that pollutant in that area. Traditionally this concept has been applied in a static framework to offset permits within emission sources or certain geographical locations, as long as the aggregate emissions after the offset do not exceed a prespecified environmental standard.

We translate this concept to an *intertemporal* setting under which an environmental agency allows an incremental change in the maximal lower rate to the extent that emissions are additionally abated by adjustment of k as long as the ex-post emission level does not exceed the predetermined environmental capacity. Therefore, the level of maximal lower rate, $\underline{q}$, is set to be increasing proportional to k: $\underline{q}(k) < 0$ and $\underline{q}'(k) < 0$. Consequently, $\underline{b}'(k) < 0$ holds if $\int_k^{k+\Delta k} a(s)\,ds < -\int_k^{k+\Delta k} \underline{q}(s)\,ds$. Then we obtain

Corollary to Proposition 3. *Consider an intertemporal offset provision under which* $\underline{q}$ *is increasing in* k *in terms of absoulte value. Then* $\theta^{**} > \theta^{*}$ *holds if* $\overline{H}_B(w-\psi) < H_N w$ *in the withdrawing regime.*

2.4.2 Effect of initial free permit allocation

Another interesting issue is to analyze the effect of the initial allocation of free permits. Careful examination of (33) with $B(0) = 0$ or equivalently $T(k) = 0$ reveals $\theta^{*} = \theta^{**}$ because of $\psi(k) = 0$. It implies that when there is no available permit stock in the initial period, the investment incentive is the same under a non-bankable and a bankable TPP.

When there is a positive advance allocation, $B(0) > 0$, the relative ordering of θ^{*} and θ^{**} changes. Note that

$$\frac{\partial\theta^{**}}{\partial B} = \left(\frac{p}{2c(k)}\right)^2 \frac{-c'(k)}{(r-\alpha-\sigma^2)(w-\psi(k))^2 H_B^2} \times \left[\underbrace{\frac{-\partial(w-\psi(k))}{\partial B}}_{(-)} H_B - (w-\psi(k)) \underbrace{\frac{\partial H_B}{\partial\xi}}_{(-)} \frac{\partial\xi}{\partial B}\right]$$

in which the signs of all terms are easily verified except for $\partial\xi/\partial B$ in the last term inside the bracket. Suppose $\partial\xi/\partial B \leq 0$, then $\partial\theta^{**}/\partial B < 0$,

Figure 3: Sensitivity of Parameter ξ

but otherwise the sign of $\partial\theta^{**}/\partial B$ becomes dependent of all underlying parameters. Given the specification of model, it is hard to show analytically the relationship of ξ with respect to B. Hence, a graphical visualization is helpful to examine how the sign of $\partial\xi/\partial B$ changes. With some hypothetical parameter values ($r = 0.06$, $b = 10$, $b' = 4$, $w = 230$, $p = 150$), Figure 2 illustrates that the sign of $\partial\xi/\partial B$ is positive over low values of B (in this case, up to $B = 40$) and after then it becomes negative and asymptotically approaches to 0 as the permit stock grows. The example illustrates the inverse relationship of the advanced allocation and investment incentives.

2.4.3 Effect of an emission credit bonus

The investment effect of an emission credit bonus can be easily examined in the context of the current model. For instance, the emission credit bonus provision was adopted in the U.S. Acid Rain Program to sustain demand for high sulfur coal in several states, mostly high sulfur coal producing states. According to the bonus provision, a total of 3.5 million tons emission permits were provided for utilities that installed scrubbers (flue gas desulfurization) rather than switching input lines to low sulfur coal.

This emission credit can be incorporated into the model by changing $\bar{e}$ to $\bar{e}(k)$ and $\bar{e}'(k) > 0$. To simplify discussion, we focus only on a non-bankable TPP. When the bonus permits are given in accordance with $\bar{e}(k)$, the investment threshold is derived as

$$\theta^{***} = \left(\frac{p}{2c(k)}\right)^2 \frac{-c'(k)}{(w - p\bar{e}'(k)/r)(r - \alpha - \sigma^2) H_N}$$

and it can be readily verified that θ^{***} is always larger than θ^{*}, implying that emission credit facilitates investment.

3 Numerical Illustration

This section provides a numerical illustration by calculating investment option values using the U.S. Acid Rain Program, Title IV of the 1990 Clean Air Act Amendments. This program is the first large scale environmental program relying on bankable tradable allowances. If an emission allowance is not used to cover SO_2 in its specified year, it can be banked for future use.

Before calibrating investment option values are estimated some model parameters specifying the abatement cost function. Rest of parameter values that are necessary to calculate option values are appropriately assumed or, if feasible, imported from other sources.

Since the amount of abatement is endogenously determined in the model, we use a reduced form of the abatement cost function: $C = f(\mathbf{x})$ where $\mathbf{x}$ is the vector of variables that determine SO_2 abatement. Explicitly, when there are observations on a panel of I plants through T periods, we estimate the following Cobb-Douglas cost function:

$$\begin{aligned} \ln \mathrm{COST}_{it} &= \mathrm{constant} + \beta_1 \mathrm{TIME} + \beta_2 \ln \mathrm{WAGE}_{it} + \beta_3 \ln \mathrm{REM}_{it} \\ &\quad + \beta_4 \mathrm{REG}_{it} + \beta_5 \ln \mathrm{KAP}_{it} + u_{it} \end{aligned} \tag{39}$$

where u_{it} is error component. The dependent variable, COST, represents FGD expenditure of plant i. The vector of explanatory variables, $\mathbf{x}$, consists of the time variable (TIME), the FGD stock (KAP), the wage rate for the employed labor to operate FGDs (WAGE), removal efficiency (REM), and regional-specific dummy variable (REG). The variable TIME is used to identify technological progress that is common to all plants. The dummy variable REG is introduced because, as once adequately predicted by Cropper and Oates (1992, p.691), several state governments or public utility commissions introduced some restrictions on the use of lower sulfur coal prior to or during Phase I. The high sulfur coal deposit states such as Illinois, Indiana, Iowa, Kentucky, Ohio, Oklahoma, Pennsylvania and West Virginia (Lie and Burtraw, 1998) imposed regulations to induce firms to commit to use of high sulfur coal. Hence, the dummy variable is set to be equal to 1 if the plants are located in these states, otherwise equal to 0. Appendix provides detail explanations for each variables and data sources.

Parameter	Value	Description of parameters
r	0.09	risk-adjusted discount rate
α	0.0745	expected growth rate of abatement cost
σ	(0∼0.12)	volatility rate of abatement cost
k	106.00	installed abatement capital ($/kwh)
η	-0.0089	scale parameter of investment

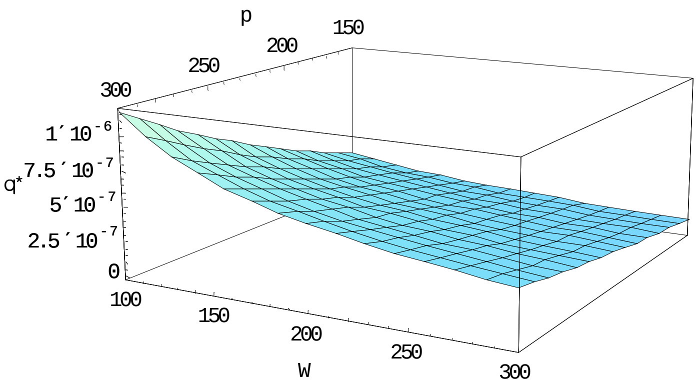
Table 1: Parameter Values for Numerical Analysis

The cost function specified in (39) is similar to a short-run variable abatement cost function with abatement capital stock as a quasi fixed input. Many papers use short-run cost functions to represent how firms adjust quasi fixed factors in response to changes in exogenous variables (Kulatilaka, 1987; Kolstad and Lee, 1993). The use of the short-run cost function is justified in the current context since a barrier control policy described in the previous section is consistent with a short-run specification. Recall that the barrier control policy explains occasional bursts of investment only when the underlying stochastic process crosses the investment threshold. Likewise, the quasi-fixed input is adjusted not by a continuous flow of investment. For the estimation, we use panel data on coal-fired electric power plants regulated by the U.S. Acid Rain Program. The data ranges from 1996 to 2000. Table A.1 reports the estimation results.

Drift parameter α is set to be 0.0745 using the estimate of β_1 for TIME. It captures exogenous technological progress over time. If we let $c(k) = k^{\eta}$, the value of η is imported from the estimate of β_4: -0.0089. We allow a range for the capital adjustment cost, w, from \$100 to \$400 per kwh. Based on the empirical observation, the permit price is set, as a benchmark, at $p = \$150$. But, if necessary, some range is provided for p. The value for k is imported from the EIA-767. The amount of SO_2 abatement is imputed using the EIA-767, showing average abatement is 2,790 thousand tons. We assume $r = 0.09$. For the volatility level, σ, a range between 0 to 0.12 is chosen to ensure $r - \alpha - \sigma^2 > 0$. The parameter values to be used in the following numerical analyses are summarized in Table 1. First, the optimal investment threshold under a non-bankable TPP, θ^*, is calibrated while varying allowance price from \$150 to \$300 and the capital adjustment cost from \$100 to \$300. Figure 3 illustrates the result of sensitivity analysis, showing that, consistent with Lemma 3, θ^* is increasing in p but decreasing in w.

Figure 4 provides a sensitivity analysis of θ^* with respect to σ and w,

Figure 4: Sensitivity of θ^* with respect to p and w

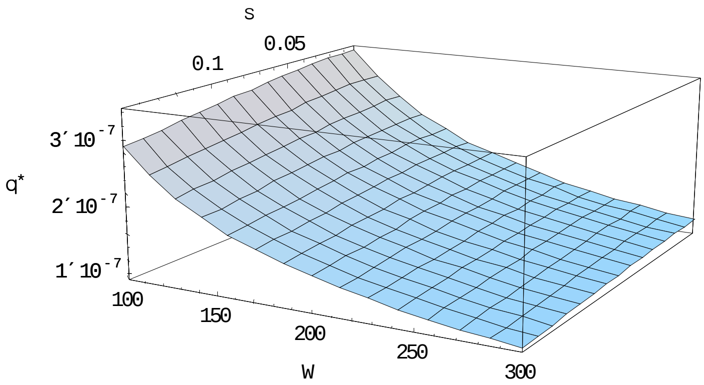


illustrating that the firm's investment decision is inversely related to σ and w. In this particular illustration, θ^* appears to be more sensitive to w than σ, implying that for determining the investment trigger level, capital adjustment cost plays a more critical role than the volatility of technological progress does.

It is hard to comprehend the economic implication by just comparing the thresholds, θ^* and θ^{**}. Therefore, given the model parameter values, we translate them using (2) so as to obtain the trigger abatement cost below which it is optimal to undertake investment. Table 2 shows the trigger costs under a non-bankable and a bankable TPP.[7] The trigger costs under the non-bankable TPP is lower than the one under the saving regime (third column in the table), but higher than the withdrawing regime (fourth column). However, the fifth column shows a case where an intertemporal offset provision is provided so that this hypothetical firm increase the number of instantaneously withdrawn permits in accordance with increase of abatement capital. In this case, as argued in the corollary to Proposition 3, the trigger cost may increase.

[7] Since ξ involves transcendental functions of the variables in an essentially non-algebraic way, the appropriate value of ξ can be obtained computationally by finding a fixed point which satisfies equation (33). Then, ξ is substituted into (27) to calculate ϕ_B. For the numerical analysis, we use Newton-Raphson method.

Figure 5: Sensitivity of θ^* with respect to σ and w



w	non-bankable	bankable $p < V_B^B$	bankable $p > V_B^B$	bankable $p > V_B^B$
200	1.80	5.37	0.50	5.59
220	1.63	4.59	0.48	4.29
240	1.50	3.98	0.47	3.48
260	1.38	3.50	0.46	2.92
280	1.28	3.11	0.45	2.52
300	1.20	2.79	0.44	2.21
320	1.12	2.52	0.43	1.97
340	1.06	2.29	0.42	1.78
		$B = 10$ $\bar{b} = 100$ $\bar{b}'(k) = 2$	$B = 10$ $\underline{b} = -5$ $\underline{b}'(k) = 2$	$B = 10$ $\underline{b} = -10$ $\underline{b}'(k) = -1$

Table 2: Trigger Costs (unit: cents per kWh)

4 Conclusion

In spite of a growing number of environmental policies that allow permit banking, the effects of banking on environmental investment has received less attention than the effects of a non-bankable TPP. The foregoing analysis develops a model for investment option valuation that encompasses non-bankable as well as bankable TPPs.

We show uncertainty may be a major source of investment delay under TPPs, but it does not always discourage investment. Depending on all the underlying parameter values, uncertainty may facilitate investment because under uncertainty a firm is willing to undertake investment to increase the size of permit stock as a future compliance measure. As opposed to Phaneuf and Requate (2002), we show that one cannot simply argue that a bankable system is inferior to a non-bankable system in terms of investment incentives.

An intertemporal variant of an emission offset provision is proposed to facilitate investment but this topic needs more comprehensive analysis to determine its effect on firms' optimal abatement behavior and the associated social welfare. In addition, we show that the advance allocation of permits would have a positive effect on investment only for a small range of advance allocation amounts. The allocation of free permits in advance reduces firms' investment incentive in long-run.

Since the design of TPPs accompanies more or less practical questions including all these policy alternatives, the results derived in this paper should serve to provide some limited policy implications. Particularly, it should be noted that, by focusing on a model of an individual firm's investment behavior, social aspects of the effect of TPPs on firms' emission behavior are disregarded.

Several possible extensions of the model should be discussed. One way is to consider the investment option in a general equilibrium framework as in Zhao (2003). Also, the present model implicitly relies on the efficiency of permit markets without considering issues of market power and transaction costs. A firm with market power can strategically manipulate the holding of permits in order to raise its rivals' costs or to build entry barriers and thereby gain market power on a product market, as well known in the literature of 'exclusionary manipulation'. The presence of dominant firms exercising market power may change strategic investment option behavior. In order to preempt others from acquiring permits each firm may invest earlier than in the case without a dominant firm. Lastly, the present model does not discuss normative issues such as social efficiency and equity. For a more complete understanding of the effects of TPPs, future research should include normative issues as well.

Appendix

Data for estimating the abatement cost function mainly comes from the Energy Information Administration's EIA-767 form. This form is used for various economic and regulatory analyses as in Carlson et al. (2000), Arimura (2002) and Popp (2001). For the analysis, we use the data for coal-fired electric power plants, ranging from 1996 to 2000.

FGD O&M expenditure is provided by the database RANNUAL in EIA-767. Although it would be more appropriate to deduct the sales revenue of commercially salable waste products from FGD O&M costs, it is not considered because of substantial number of non-responses.

As for wage rate, we distinguish maintenance labor and operating labor. In general, maintenance labor cost is more expensive than operating labor cost since maintenance requires more skilled personnel. In every year the Department of Labor reports in its *Monthly Labor Review* hourly wage rates associated with labor employed for maintenance of environmental protection facilities. We use this wage rate to represent maintenance wage rates. Maintenance wages for each plant are compiled by matching each county's wage rate to the county code of each plant. To compute an annual wage rate for each plant, we use the convention that, following the *EPA Air Pollution Control Cost Manual* of the EPA (2002, p.2-31), supervisory labor is a flat fifteen per cent of the operating labor requirement. Also, according to EPA (2002, p.2-31), many cost studies use a 10% premium over the operations labor wage rate for maintenance labor costs. Hence, the annual labor wage (WAGE) is decomposed such that WAGE $= OP \times (0.85 wage_o + 0.15 \times 1.1 \times wage_o)$ where $wage_o$ is hourly wage rate for operating labor and OP is annual in service hours reported in the EIA-767.

As for the capital stock related to scrubbing, we import the construction cost data from the EIA-767. The manual of the EIA-767 instructs firms to report all costs incurred to bring a planned system to commercial operation, including the cost of all major modifications. We assume 5 percent depreciation rate for the capital stock remaining in each year. Removal efficiency of the installed FGDs are provided by the EIA-767.

The number of observations is reduced from 195 to 120 after eliminating inconsistent or non-response observations. In estimation, we transform each variables by dividing them with electricity generation capacity (kWh) of each plants. Table A.1 provides the estimation result.

Table A.1 Estimation Results for the Abatement Cost Function

Variable	Coefficients	Stand. Error	T-ratio
constant	-12.0340	0.9618	-12.511
TIME	-0.0745	0.0207	-3.597
WAGE	0.5371	0.0450	11.928
REM	-0.2722	0.0731	-3.721
REG	0.8064	0.0727	11.902
KAP	-0.0089	0.0018	-5.075
R^2	0.9998		
Log likelihood	-498.3487		

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