OPTIONS FOR POLLUTING FIRMS: BANKABLE PERMITS OR ABATEMENT

by

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Abstract

This paper presents a theoretical framework for analyzing markets for bankable emissions permits. The innovation of this work is to incorporate the effects of uncertainty in downstream market prices on the price of permits and the price of alternative compliance measures. Air quality regulations allow firms to choose between making investments in abatement equipment and purchasing allowances to release specified quantities of pollution. Equilibrium conditions for the industry provide a link between the price of permits (allowances) and the price of alternative abatement measures. This paper shows that under ordinary circumstances, these prices will be such that the cost of compliance by abatement will be higher than the cost of compliance by permits. This result contradicts the conventional static analysis, but does a better job explaining empirical data. The research is motivated by evidence from the US Acid Rain program. The analytical model is developed with this industry in mind, and data from early implementation of the program illustrates an application of the model. The paper also introduces some policy implications, identifying how the results developed here could affect the determination of the optimal number of permits to issue.

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Introduction

Tradable pollution permits are emerging as a practical policy tool for cost-effective pollution control. The launch of the sulfur dioxide permit trading market as part of the US 1990 Clean Air Act Amendments (referred to as the US Acid Rain Program) has provided a wealth of empirical information regarding the performance of an emissions trading market and the behavior of the participants. The evidence so far has not always been consistent with expectations from theoretical models. This paper will present a new theoretical framework for examining markets for tradable permits that addresses the empirical evidence, and provides clearer intuition for the design and implementation of these markets.

A notable observation from the US Acid Rain Program that some researchers have found surprising is that firms were spending more to abate pollution than it would cost to purchase the right to emit the same pollution[1]. The cost of compliance using permits appears to be lower, in the long run, than the cost of compliance using scrubbers (which are pieces of equipment that remove sulfur dioxide from exhaust before it is released). The model presented here will show that this observation is actually the expected result in a competitive equilibrium

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[1] see, for example, Ellerman et al. (1997)

that correctly accounts for uncertainty and irreversible investments. This has direct implications for policy implementation.

The model is based on an options pricing framework that is useful for identifying critical aspects of optimal decisions under uncertainty, when investment is irreversible and information is revealed over time. This framework has already received some limited attention in the context of tradable permits, but in previous literature the focus has been on comparing the value of the option to pollute and the option to abate. In this analysis, the unconventional interpretation of permits and scrubbers as “options to produce electricity” (Hunter, 1998) provides direct insight into the equilibrium price relationship between different compliance choices.

The binomial options pricing model, introduced by Cox, Ross, & Rubinstein (1979), has been found to have a number of applications in economic analysis. Investment choices for firms can often be characterized as a portfolio of options[2]. In the area of sulfur dioxide emissions from coal-fired electricity generators, previous researchers have used this methodology to identify how utility managers can choose between alternative investments for abating pollution (Herbelot, 1992).

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[2] See Dixit and Pindyck (1994) for extensive treatment of this subject

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The literature on tradable permits as a means of regulating pollution is extensive. Early analytic treatment (such as Montgomery, 1972) established the value of this policy as a least-cost method of pollution control. Although application of this method has been slow to develop[3], the idea has established a secure position in environmental economic analysis[4].

Recent research addresses how the possibility of banking permits may affect the price path for permits (Kling & Rubin, 1997; and Bailey, 1998b), without considering any relationship with abatement costs. Some important work by Laffont & Tirole (1996a) begins to address this relationship between permit prices and other compliance options. They analyze the effect of overinvestment in alternative compliance methods (abatement) due to a price difference that comes from pricing permits by the Ramsey rule (which accounts for recycling permit revenue to reduce other distortionary taxes). There is also work that addresses firms' incentives to invest in the development of improved abatement techniques (Laffont & Tirole, 1996b; Jung, Krutilla & Boyd, 1997). None of the research to date seeks to determine the competitive equilibrium relationship between the price of bankable permits and the cost of abatement investments.

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[3] Hahn (1989) provides a comprehensive survey of policies in practice

[4] For an accessible informal discussion see Tomkins & Twomey (1994), and for a standard textbook treatment see Tietenberg (1992)).

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The U.S. Acid Rain Program is the first large-scale use of tradable permits in environmental policy. The 1990 Clean Air Act Amendments specify that pollutants causing acid rain (sulfur dioxide and nitrogen oxide) be reduced to 50% of 1980 levels. To implement the sulfur dioxide reduction cost-effectively, a permit market has been developed that allows firms (and other interested parties) to trade the right to emit sulfur dioxide. Under this program, permits are distributed among firms (based on previous pollution levels), which are then allowed to trade permits (the Environmental Protection Agency also auctions a small number of permits, primarily to help provide price information to the market). Phase I of the program, covering the nation's most polluting plants, became effective in 1995, after almost two years of permit trading. Each firm must cover the emissions generated each year by sufficient permits, and firms are allowed to bank permits for future use.

Under the U.S. Acid Rain Program, firms have an incentive to abate pollution in order to save on permit costs. One primary method of abatement is to retrofit plants for flue gas desulfurization (Halkos, 1993). This requires an irreversible investment by the firm, at a time when future prices cannot be known with certainty. It is this situation, combined with the new market for bankable permits, which motivates this research.

The next section outlines a simple example that helps introduce ideas and motivate the development of the model. Next comes the formal model, from which the results can be derived quite easily, followed by an examination of empirical evidence from the US Acid Rain Program. We also include an introduction to the policy implications of the options pricing model, particularly with regard to analyzing the correct number of permits to issue. This model can address a number of other important questions, and these are discussed in the conclusion.

A simple example

A call option is a right, but not an obligation, to purchase a specific asset at a specified price (called the strike price). These options have value to their owners whenever there is some possibility that the asset price will rise above the strike price before the option expires. When this happens, the option owner could use the option ("exercise" the option) to make a profit: purchase the asset at a price (the strike price) lower than the market price, and resell the asset at market value.

How do these concepts apply to the electricity production industry and the U.S. Acid Rain program? A firm that owns a permit has the right (but not the obligation) to produce electricity in a manner that causes a certain amount of pollution. That action has a cost (the production cost), but it also provides the firm with something of value: some amount of electricity that can be sold in the downstream market. The permit is an option, the asset is the electricity, and the strike price is the cost of production (Hunter, 1998).

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A similar interpretation can be made for scrubbers. Suppose that scrubbers eliminate pollution entirely, so that firms with scrubbers can produce electricity without regard to pollution regulation. The cost of producing electricity with scrubbers is higher than without scrubbers, because of the operating and maintenance cost (O&M cost) of the scrubber. A scrubber is an option just like a permit, the asset is a certain amount of electricity, and the strike price is the cost of generating electricity plus the O&M cost. To keep the model simple, assume that permits and scrubbers are measured in units with equal scale: one scrubber can remove the amount of sulfur dioxide that would be covered by one permit. Then scrubbers and permits are both options for the same underlying asset (one unit of electricity). The only difference is the strike price (the marginal cost of producing electricity), which is higher for scrubbers due to the O&M cost.

Two time periods will be sufficient to capture the essential details of the model: period 0 is “now” and period 1 is “later”. A firm owning a permit (or a scrubber) can decide to exercise its option now by producing electricity now, or hold the option for use later. Take the following assumptions for electricity production and sale on the margin. Suppose the downstream price of electricity now is $22 (for one unit that can be produced with one permit or one scrubber). The only uncertainty in the model is in the price of electricity later: there is an equal probability that the price will go up to $25 or drop to $20. Let the cost of generating electricity be certain at \$20, and the additional O&M cost for a scrubber be \$1. Finally, let the interest rate be 10%.

Consider the equilibrium price for permits. The value of exercising a permit now is simply the short run marginal profit of producing another unit of electricity, \$22 - \$20 = \$2. Alternatively, a firm could choose to hold a permit for use in the next period (later), in which case the value would be the discounted expected profit:

$$0.5\frac{\$25-\$20}{1+0.10}+0.5\frac{\$20-\$20}{1+0.10}=\$2.27 \qquad (1)$$

In this example, a permit is more valuable when it is used later (\$2.27>2.00), so the firm holds onto permits (on the margin). If the price for permits was anything other than \$2.27, then there is an opportunity for arbitrage. For example, if the price is higher than \$2.27, then the firm could sell off permits that it already holds to similar firms. If the price is lower than \$2.27, then the firm could buy them and hold them for future use.

Now consider the equilibrium price for scrubbers. The value of a scrubber exercised now is again equal to the short run marginal profit, which is the market price of electricity now minus the cost of generation and the O&M cost of the scrubber: \$22 - (\$20 + \$1) = \$1.00. In the next period, if the price of electricity drops to \$20, then the cost of generating electricity plus the scrubber O&M cost would be higher than the market price (\$21>\$20). Exercising the scrubber option, i.e. producing electricity, in this state gives a negative profit. This means scrubbers that are held until period 1 will not be used to produce electricity if the down state occurs (on the margin). If, however, the price of electricity goes up to \$25, then it would be profitable to “exercise” a scrubber option and produce electricity. Thus, the discounted expected profit for scrubbers is:

$$0.5\frac{\$25-\$21}{1+0.10}+0.5\frac{\$0}{1+0.10}=\$1.82 \tag{2}$$

Once again, the option is more valuable (on the margin) when held for future use than when exercised now. This establishes the equilibrium scrubber price. If the price for scrubbers were anything other than \$1.82, then there would be an opportunity for arbitrage.

This marginal analysis gives all the information necessary to determine the relationship between the prices of the two options: permits vs. scrubbers. In a competitive market for permits (or scrubbers), firms would pay the same price for all of the permits (or scrubbers) that they purchase. Empirical observation would reveal a number of firms using some permits and some scrubbers in the current period, and also holding on to some permits and some scrubbers for use later. The permits used in the current period could be inframarginal units with the same or higher value (perhaps because marginal costs are increasing so the production cost for the inframarginal units is lower), but the market price for all permits (and for all scrubbers) would be established by the “no-arbitrage” prices calculated above.

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Electricity Price		
now	$22	
later	25	with probability 50%
	20	with probability 50%
Generation cost	20	
Scrubber O&M	1	
Interest rate	10%	

	Permit	Scrubber
Compliance instrument	$2.27	$1.82
Add’l costs	0.00	1.00 (O&M cost)
Total compliance cost	2.27	2.82

Table 1: Summary of compliance options simple example

The cost of compliance follows directly from these prices. Suppose we observe many firms producing electricity in the current period, some with permits and some with scrubbers, and some holding permits and scrubbers for use later (this is what is actually seen for the US Acid Rain Program). The marginal permits and the marginal scrubbers are priced according to the no-arbitrage conditions established above. For permits, the cost of compliance is the price of the permit: \$2.27. For scrubbers the cost of compliance is the price of the scrubber plus the O&M cost of the scrubber: \$1.82 + \$1.00 = \$2.82. This is higher than the cost of compliance using permits. Table 1 summarizes the details of this example.

This example serves to illustrate the pitfalls of ignoring uncertainty in the price of electricity when analyzing costs of compliance. More importantly, it lays out the direction by which the analysis can proceed more accurately. Full development of the model in the next section clarifies the relationship between prices and net revenues, but the intuition provided by this example extends to the general model. The most important idea is that when there is uncertainty about future prices and information is revealed over time, it may be optimal for firms to hold on to permits or scrubbers now for possible use later. If this is the case when the market is in equilibrium, then the relative prices for these compliance instruments will be determined by the value for future use.

The model

Assumptions. The development of this model is intended to closely parallel the electricity production industry, but the primary objective is to determine the expected equilibrium prices for compliance options in a competitive equilibrium that correctly accounts for uncertainty and irreversible investments. Thus, the model rests on the following assumptions:

1) The electricity market is competitive. This assumption does not accurately represent the current electricity market. In the United States, and indeed in most countries, utilities are highly regulated and firms often have considerable market power (although in many areas the spread of deregulation seems to be moving the electricity industry towards a competitive market). The point here is to isolate the effect of uncertainty and irreversible investments, so the model is framed in the simplest possible setting, a competitive equilibrium.

2) The price of electricity is the only source of uncertainty in the market. The demand for electricity in the future will be affected by fluctuations in climate, population, and consumer tastes. Also, the supply of substitute energy sources may be uncertain due to changes in resource availability and technology. In this model, electricity prices fluctuate over time, but all other sources of uncertainty are excluded from consideration. In particular, production costs are certain and do not change over time.

3) There are no opportunities for arbitrage at market prices. This statement asserts that market prices will not allow any agent to profit from moving commodities about the market, which establishes a price equilibrium condition. The effect of this condition is to fix the prices of any risk-free portfolio of assets, and to link option prices with the current and expected future prices of the underlying assets. Permit prices are then linked to the underlying asset, electricity, and so are scrubber prices. Therefore, the prices of the different compliance measures will have an exact relationship that will be exploited to determine how the costs of compliance are related.

It is fruitful at this point to consider in some detail what this no-arbitrage condition means for the electricity market over time. The price of electricity "now" must be linked to the price of electricity "later" in a particular fashion: the price of electricity follows a martingale process. This means that the current price of electricity is the discounted expected value of future prices and dividends (the explanation for dividends in this context is laid out more fully below). For this assumption to hold, there needs to be sufficient intertemporal trading of electricity to balance out current prices with future expectations.

How does intertemporal trading occur for a commodity that cannot be stored over time? Consider a situation where the current demand for electricity is unusually high, so that the price of electricity is higher than expected. A firm that produces electricity now can sell it at a relatively high price. The difference between price and variable cost of production will be short run "profit", but part of that profit must be devoted to repayment of fixed (capital) costs. These quasi-rents represent a dividend that accrues only to firms that purchase the asset (produce the electricity) in the current period. In a competitive market with no long run profit, the entire short run profit is quasi-rent. When a demand shock creates an unusually high market price, this dividend is high. Firms that have received this high dividend from current period production have covered more of their fixed costs. In future periods, these firms can produce profitably when prices are lower than normal (instead of exiting the market). Thus, future prices are tied to current prices minus current dividends. These “dividends” serve to tie together prices between periods, even though electricity itself cannot be traded over time.

4) For each unit of electricity produced, firms are required to use either one permit or one scrubber. The production of electricity from coal-fired power plants produces the harmful byproduct sulfur dioxide, which causes acid rain when released in large amounts. Under the US Acid Rain Program, a firm operating a coal-fired electrical generator must obtain sufficient permits to cover the amount of sulfur dioxide that is emitted. Firms can reduce the number of permits required by spending money on abatement, so that less sulfur dioxide is produced with each unit of output. There are two primary means of abating sulfur emissions: flue gas desulfurization (scrubbing), and fuel switching (to low-sulfur coal or natural gas). This model addresses the relationship between compliance using permits and compliance using abatement, not between different abatement choices, so only the first abatement method (scrubbing) is considered here.

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In the actual market, one permit allows the production of a very small amount of electricity compared to a large scrubber installed in a high capacity plant. This model ignores the scale difference. This can be interpreted in two ways: 1) that a "permit" is actually a large bundle of small permits sufficient to match one scrubber, or 2) that scrubbers are easily divisible (and that the fixed cost of a scrubber is linear in its capacity). A further simplification is achieved by assuming that a scrubber eliminates pollution completely, so a firm that installs a scrubber in a plant need not purchase any permits for that plant.

5) There are two periods: prices are known for period 0 ("now"), but in period 1 ("later") the price of electricity will either be "up" or "down". This assumption provides the simplest framework for using the binomial options pricing model. Everything developed within this framework can be extended to further periods, without substantially changing the results[5].

6) Firms are homogeneous, with increasing marginal cost for producing electricity. In this model, all firms have the same quadratic cost function. The use of permits as a pollution control policy is taken as given in this analysis[6]. An

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[5] For a description of how to extend the binomial options pricing model to more periods, see Cox, Ross, and Rubenstein (1979).

[6] Simply for clarity of exposition, we choose to ignore the fact that the reason to have permits in the first place is to reduce compliance costs by allowing different types of (heterogeneous) firms to choose different methods of complying with pollution regulations.

important task for future research will be to address the complications in this model that arise from firm heterogeneity.

7) The cost of operating and maintaining scrubbers is constant on the margin. Without this assumption, the quantity of electricity produced will differ depending on which compliance option is chosen. This creates some interesting complications, but it obscures the means by which uncertainty alone causes different compliance cost. With the assumption that O&M cost is constant on the margin, the results of the analysis will hold regardless of the equilibrium quantity of electricity produced in the market or the quantity produced by individual firms within the market.

Value functions and demand. Based on these assumptions, it is possible to determine a typical firm’s demand for each of the two compliance options. The first step is to identify the value functions: the maximum that a firm would be willing to pay for a permit (or scrubber) given a certain marginal cost of generating electricity. These value functions can be interpreted as representing the first-order conditions of a profit-maximization problem for the firm. In each case, the relationship described in the value function equates the marginal cost of production with marginal revenue. A firm’s choices for outputs and other production inputs are thus submerged within the value function, so that attention can be directed exclusively to compliance choices.

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In the aggregate, the value functions define an aggregate market demand curve. We will first develop a value function for permits alone (essentially assuming that scrubbers do not exist), then for scrubbers alone, then show how the substitutability of scrubbers and permits affects the aggregate demand curves. Throughout the model, a zero subscript denotes period 0, or "now", whereas a *u* subscript denotes the *up* state of period 1, or "later", and a *d* subscript denotes the *down* state of period 1.

If a firm chooses to exercise a permit option in the current period, then the firm pays the marginal cost of production for one unit of electricity, K, and receives revenue equal to the current price of one unit of electricity, y_0. This defines the maximum that the firm is willing to pay for that permit, if it must be used in the current period. This defines the "value function for time 0":

$$V_0^P(K) = y_o - K \tag{1}$$

For a permit that will be used in the following period, the value depends on the expected net revenue, because the price of electricity is uncertain. Also cash flows in the future must be discounted to obtain current values. Define p_i as the probability of state i occurring, and f_i as this probability divided by one plus the risk-free interest rate, r, so that $f_i = p_i/(1+r)$. It is consistent with the assumption of homogeneous firms to assume that all firms share the same subjective probability[7].

The maximum that the firm is willing to pay for a permit that will be used in period 1 defines the "value function for period 1":

$$\bar{V}_1^P(K) = f_u Max\{y_u - K, 0\} + f_d Max\{y_d - K, 0\} \qquad (2)$$

Note that, by assumption, the price in the down state, y_d, is lower than the price in the up state, y_u. This means that some high enough marginal cost of production, K, the second term becomes zero while the first term is still positive. At that point, the value function becomes flatter; the function will be continuous and piecewise linear, but kinked. The first section (which will be labeled V_1^P) represents the value when the strike price is low enough to guarantee that the option is exercised in either state. The second section (which will be labeled V_u^P) represents the value when the strike price is high enough so that the option is only exercised in the *up* state. Substituting $y_1 = f_u y_u + f_d y_d$ for the discounted expected value of future prices, and using the fact that $f_u + f_d = 1/(1+r)$, the two sections of the value function for period 1 are:

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[7] This is the likely result in a long run equilibrium, but it is not even a necessary condition for the existence of a unique value for f_i (for a formal explanation of this point, see Cox, Ross, Rubinstein (1979)).

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$$\begin{aligned} V_1^P(K) &= f_u(y_u - K) + f_d(y_d - K) = y_1 - \frac{K}{1+r} \\ V_u^P(K) &= f_u(y_u - K) \end{aligned} \qquad (2')$$

Next we consider which value is higher, the value for permits used now or the value for permits used later. Ultimately, the upper envelope of these two functions determines the overall value for permits. To compare the value functions now and later, first define d using the difference between the current price and the discounted expected value of future prices, and the risk-free interest rate *r*:

$$d \equiv (1+r)(y_0 - y_1) \qquad (3)$$

This gives the following relationship between prices across periods (this is the martingale process discussed with assumption 4):

$$y_0 = f_u(y_u + d) + f_d(y_d + d) \qquad (4)$$

If the asset were a stock, then d could be interpreted as a dividend. The “asset” in this model is a commodity produced in a competitive market, so d is the quasi-rent that is applied to fixed costs of production (Hunter, 1998). Make the substitution $D \equiv d(f_u + f_d) = d/(1+r)$ for the discounted “dividend”. Then equation (4) can be succinctly expressed as: $y_0 = y_1 + D$. This says that current prices are equal to expected prices plus the discounted dividend.

The overall value function for the firm is the upper envelope of the value function for permits used now and the value function for permits used later (see figure 1). The difference in value between permits exercised in period 0 and permits exercised in period 1 is:

$$V_0^P(K) - V_1^P(K) = (y_0 - K) - \left(y_1 - \frac{1}{1+r}K\right) = D - \frac{r}{1+r}K \qquad (5)$$

At low marginal production costs, this equation is positive, so permits are more valuable for use in the current period. With a positive interest rate, there exists some sufficiently high marginal cost to make equation (5) negative. At this point, the firm will prefer to hold an option for use in period 1 rather than exercising it immediately.

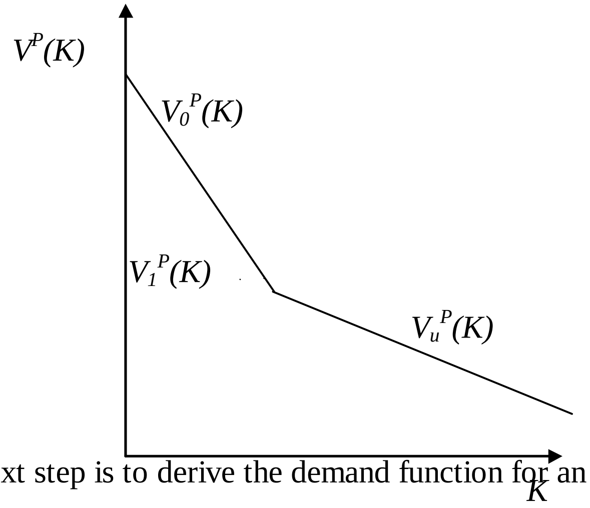

Figure 1: Value function for permits

The next step is to derive the demand function for an individual firm. The value function represents the maximum that a firm with a certain marginal cost of production will pay for a permit[8]. The inverse demand function, or the maximum willingness to pay for each additional permit, will then depend on the firm's

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[8] This is willingness to pay *on the margin* for permits, assuming that scrubbers do not exist.

marginal cost function. If the marginal cost of production were constant, a firm would want no permits at any price above that cost, and as many permits as possible at any price below that cost. In this case, the inverse demand function for an individual firm would be a horizontal line.

In this model the marginal costs for generating electricity are assumed to be increasing as the production of electricity increases. Assume that dollar values are scaled such that marginal costs are increasing at a constant rate (one unit of cost per one unit of production)[9]. This means that the demand function will appear to be similar to the value function, except now the horizontal axis is quantity of permits used (which corresponds to quantity of electricity produced) instead of marginal cost. At low quantities, the demand curve corresponds exactly to the value function. For a small number of permits that would all be exercised in the current period, each permit is worth the difference between the price and the marginal cost. At some quantity, marginal cost rises to the point (K^*) where a firm is holding options (moving to $\overline{V}_1^P$). At this point, production in the next period returns to the low marginal cost that production began with in this period[10].

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[9] This means production costs are quadratic, so that marginal cost is linear. Alternative cost functions would give similar results; demand would just be a horizontally distorted version of the value function.

[10] This is by assumption. The periods discussed here are somewhat arbitrary, but the notion of increasing marginal cost is generally applied in a static context: marginal costs are increasing when more is produced now, not when more is produced at any time. Thus, we assume that marginal cost for a given period is independent of the flow of production in the previous period.

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Developing the demand function requires that we solve for *K**. Set the value function for period 0 equal to the value function for period 1 with no cost[11]:

$$\begin{aligned} y_o - K^* &= y_1 - 0 \\ K^* &= y_u - y_1 \end{aligned} \tag{6}$$

This is the same as the distance along the vertical axis between V_0^P and V_1^P. The demand function will equate price with the quantity when marginal cost was zero (in period one). This amounts to a horizontal shift of the period one value function. Thus, the demand function has a kink that occurs at the same point vertically that the value function for period one intersects the vertical axis (see figure 2). Thus, the equations for the price of permits used in period one is the value function evaluated at $q^P - D$, where q^P is the quantity of electricity produced using permits.

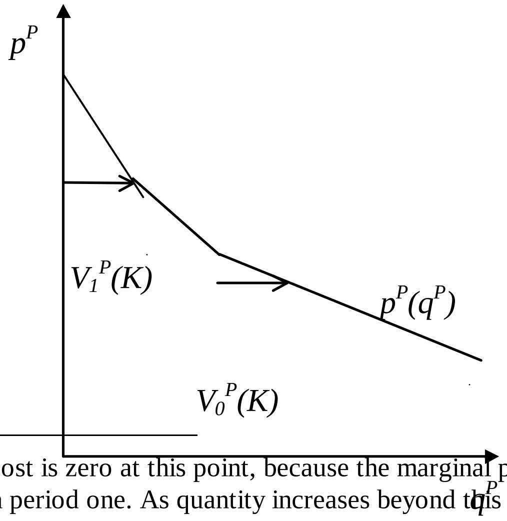

Figure 2: Demand function for permits

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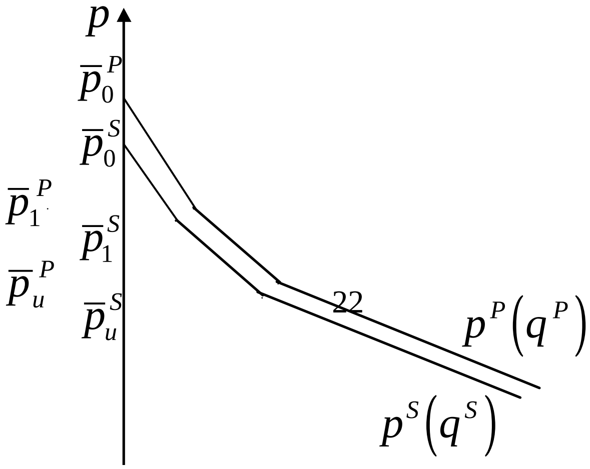
[11] The marginal cost is zero at this point, because the marginal permit will be held for production of the first unit in period one. As quantity increases beyond this point, marginal cost increases from zero in a linear fashion, just as it did in the initial period.

The derivation of the value function and demand function for scrubbers is very similar. The only difference from permits is the operating and maintenance (O&M) cost of scrubbers. This cost increases the strike price of the scrubber option relative to the permit option. At any given quantity, the strike price for the next unit is not only the marginal cost of producing the electricity but also the O&M cost for that unit. Let g represent the O&M cost of scrubbing, which is assumed to be constant on the margin. The value functions for scrubbers are the same as the value functions for permits, but for scrubbers the strike price K includes the O&M cost. The demand function for scrubbers then follows in exactly the same manner as for permits; in fact, the scrubber demand function is simply the permit demand function with a horizontal shift exactly equal to the constant marginal O&M cost. Figure 3 provides a complete picture of the inverse demand curves for scrubbers and for permits based on the all of the above assumptions.



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Symbolically, the inverse demand curves are given below:

$$\begin{aligned} p_0^P\left(q^P\right) &= y_0 - q^P \\ p_1^P\left(q^P\right) &= y_1 - \frac{q^P - D}{1+r} \\ p_u^P\left(q^P\right) &= f_u\left(y_u - \left(q^P - D\right)\right) \end{aligned} \tag{7}$$

$$\begin{aligned} p_0^S\left(q^S\right) &= y_0 - \left(q^S + g\right) \\ p_1^S\left(q^S\right) &= y_1 - \frac{q^S + g - D}{1+r} \\ p_u^S\left(q^S\right) &= f_u\left(y_u - \left(q^S + g - D\right)\right) \end{aligned} \tag{8}$$

Also, it may be useful to know the coordinates for the kinked points along the individual demand curves. For example, the first kink in the demand curve for permits is $\left(\bar{q}_1^P, \bar{p}_1^P\right)$. Straightforward algebraic manipulation gives the following values:

$$
\begin{array}{ll}
\bar{p}_0^P = y_0 & \bar{p}_0^S = y_0 - g \\
\bar{p}_1^P = y_1 & \bar{p}_1^S = y_1 - g/(1+r) \\
\bar{p}_u^P = f_u y_u & \bar{p}_u^S = f_u (y_u - g) \\
\bar{q}_1^P = D & \bar{q}_1^S = D - g \\
\bar{q}_u^P = D + y_d & \bar{q}_u^S = D + y_d - g
\end{array}
\tag{9}
$$

Market equilibrium

Aggregate demand and equilibrium prices. Conceptually, the aggregate demand curve for permits is quite simple; it is the horizontal sum of all of the individual demand curves for firms that use permits. Likewise the aggregate demand curve for scrubbers is the horizontal sum of all of the individual demand curves for firms that use scrubbers. With the assumption that all firms are identical the aggregate demand curves are the same as the individual demand curves, except the scale of the horizontal axis is changed.

The market for permits and the market for scrubbers are linked by substitution between the compliance alternatives. The quantity of permits demanded in the aggregate reflects the number of electricity generating units that are covered by permits as a means of complying with air quality regulation, as opposed to the number of electricity generating units that have scrubbers installed. At equilibrium prices, all of the firms in the market must be indifferent between either alternative, just as they are indifferent to a marginal change in the quantity of either alternative.

The demand curves depicted in figure 3 do not account for substitution between permits and scrubbers, but nevertheless the figure can be reinterpreted in a useful fashion. Consider the horizontal axis to be the *total* number of compliance options (both permits and scrubbers) purchased by a firm. Then the demand curves in figure 3 represent the maximal willingness to pay for an additional unit of either permits (on the upper curve) or scrubbers (on the lower curve). The equilibrium condition then implies that *the market prices for permits and scrubbers must be related by the vertical distance between the two curves*. If this were not the case, the firm would have an incentive to change the amount of one of the compliance instruments owned, either permits or scrubbers, and the market would not be in equilibrium.

Since all firms are homogeneous, it suffices to consider just a single firm's demand curves, with free substitution between permits and scrubbers. With the exception of two small intervals at the kink points, $\left(\bar{q}_1^S, \bar{q}_1^P\right)$ and $\left(\bar{q}_{u1}^S, \bar{q}_u^P\right)$, the difference in prices for permits and scrubbers is directly related to the operating and maintenance (O&M) cost of scrubbing. Ignoring these exceptions, there are 3 cases: 1) all options are used in period 0, 2) all options on the margin are used in either state of period 1, 3) all options on the margin are used only in the up state of period 1. The price relationship between permits and scrubbers will depend on which case applies.

In the first case, the price of scrubbers plus the operating and maintenance (O&M) cost of scrubbing is exactly equal to the price of permits. This corresponds to the conventional static analysis where the cost of compliance does not depend on which alternative is chosen. In this case, the uncertainty about electricity prices later does not affect the current equilibrium because all the compliance options are used in the current period. Thus, the conventional static analysis appears here as a specific case of our more general dynamic analysis with uncertainty.

In the second case, the difference between the price of permits and the price of scrubbers is the O&M cost discounted by one period. In current dollar values, scrubbing which occurs in the next period has the same cost of compliance as permits. For scrubbing done in this period, however, the cost of compliance (the price of the scrubber plus the O&M cost) is slightly higher than the cost of compliance using permits. In other words, scrubbing done with inframarginal units used in the current period will have a lower cost of compliance, simply because of the discounting of the O&M costs for the marginal scrubbing unit.

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It is the third case where the difference in compliance cost is most extreme. Here, the cost of compliance with scrubbers is some fraction of the discounted O&M cost, representing the expected O&M cost conditional on not using the scrubber in the down state. Here, firms are holding onto permits and scrubbers in the expectation that they will be used only if the price of electricity is high in the next period. The actual price difference between permits and scrubbers depends on the discounted state probabilities for period 1 and the O&M cost, and is equal to $f_u\, g$. The cost of compliance for scrubbers is the price of the scrubber plus the O&M cost, $p_u^S(q) + g$, whereas the cost of compliance for permits is simply the permit price, $p_u^P(q)$. The difference in compliance cost is

$$p_u^S(q) + g - p_u^P(q) = g - \left(p_u^P(q) - p_u^S\right) = (1 - f_u)\,g.$$

This is the main result of this paper. *In a competitive equilibrium, the cost of compliance by abatement may be substantially higher than the cost of compliance by permits*. All that is required is that the supply of scrubbers and permits be such that the equilibrium falls at a point where firms are purchasing both compliance measures for conditional future use[12]. With the US Acid Rain Program, for example, both permits and scrubbers have been purchased, and some generating capacity for either compliance option remains unused in each period.

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[12] "Conditional future use" means that, on the margin, permits and scrubbers are being held for future use, and will be used if the up state occurs, but not if the down state occurs.

This equilibrium corresponds to this third case, where both compliance options are being held for use later and not always being used.

Evidence from the US Acid Rain Program

This section details some of the data available from the US Acid Rain Program, in order to illustrate the result explained above. All of the data is drawn from a comprehensive report prepared by the MIT Center for Energy and Environmental Policy Research (Ellerman et al., 1997). In contrast to the conventional static analysis, the binomial options pricing model does correctly predict the direction of the discrepancy in compliance costs observed in the data. Nevertheless, the discrepancy still appears to be wider than predicted by this model. As is noted above, the assumptions in this model do not always reflect important features of the US electricity generation industry, so this comparison can only serve as a rough guide for further investigation.

The model developed here requires comparing contemporaneous prices for alternative compliance options. Unfortunately, the data that is available does not allow for a direct match at a given point in time, because investments in scrubbers did not occur simultaneously with an established market for permits. By carefully considering the timeline of events affecting prices for these commodities, we have been able to identify prices where the comparison is fairly reasonable, if not exact.

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A limited amount of permit sales occurred in 1992 and 1993, but the permits were not traded in significant numbers until 1994. There was very little information with which to gauge accurately the price of permits in 1993, but by mid-1994 it appears that prices settled into a stable range near $150 (which was the clearing price for 1995 vintage permits in the March, 1994 EPA auction). In 1995, there was a sharp drop in permit prices, all the way to $65 by the end of the year, then recovering in 1996 to $100 (Ellerman, et al. p. 25-27). The dramatic drop in permit prices corresponded to rapid changes in transportation costs for low-sulfur coal due to rail deregulation[13].

The process of retrofitting a plant for flue gas desulfurization requires considerable lead-time and capital investment. Most of the scrubbers installed were contracted in 1992-1993. Data on O&M costs come from actual use of scrubbers after the regulations took effect in 1995. The binomial options pricing model presented here predicts the price relationship for alternative compliance options sold concurrently. As time passes, information is revealed that affects prices in different ways. For the Acid Rain Program, the most significant piece of information that became available over time was the decrease in transportation costs for low sulfur coal, which would have the effect of lowering prices for either compliance options. Since this information disseminated through the market in

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[13] This drop in low-sulfur coal prices represents a source of uncertainty not included in our

1994 and 1995, it would be incorrect to compare 1995 permit prices with 1993 scrubber prices.

The best comparison from the data available appears to be to get scrubber prices from capital prices in 1993 and O&M costs in 1995, and to get permit prices from the established market in 1994. In this analysis, we use 1994 dollars throughout. The capital costs of scrubbers were $203 per ton of sulfur dioxide removal (Ellerman, et al., 1997, p. 43), but this requires an adjustment. As an additional incentive to install scrubbers, the "extension" provisions of the Acid Rain Program provided extra permits to firms that chose to retrofit, ostensibly to cover emissions while waiting for the retrofit process to be completed. The total investment in retrofitting was $3.5 billion, and the "extension" provisions provided for 3.5 million additional permits. These permits are distributed mostly over 1995 and 1996 vintages, but the price for 1995 vintage permits seems a sufficient approximation for the value of these extension permits. Based on the 1994 permit price of $150, the capital investment in scrubbers should be adjusted down by 15%, to $173/ton.

The O&M costs of scrubbing in 1995 were $79/ton (Ellerman, et al., p. 43). This includes $14/ton in "fixed" O&M costs (primarily personnel and regular maintenance) and $65/ton for "variable" costs (materials, waste disposal, and

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model, because, for simplicity, we have excluded the "fuel switching" option for compliance.

parasitic power loss from scrubber operation). In the context of this model, both types of O&M cost are conditional on the state in period 1: if the down state implies that scrubbers will not be used, then no O&M costs will be incurred.

Thus, the cost of compliance using scrubbers was $173 + $79 per ton, or $252/ton. The cost of compliance using permits was $150/ton (based on 1994 permit sales). The binomial options pricing model predicts that, in a competitive equilibrium, the permit price would fall somewhere between $173/ton and $252/ton. Additional explanation is still required for the permit price to be as low as it is. This could be occurring because of non-market incentives to scrub instead of buy permits (see, for example, Bailey (1998a)), and, of course, the fact that the assumptions of the basic model do not accurately represent the electricity market. Furthermore, the price comparison may be inaccurate because of time discrepancies in the data.

It is possible that expectations of reduced prices for low-sulfur coal were already affecting permit prices by 1994. Although the number of trades in permits in 1993 make it difficult to attach too much validity to the price of permits at that time, the Emissions Exchange did begin reporting that permits were being traded at prices at or above $170. Also, two private transactions in the summer of 1993 reported prices of $178 and $203 (Ellerman, et al., 1997, p. 27). It is instructive to redo the calculations using the more conservative lower value of $178. The scrubber capital cost adjustment for extension permits changes to 17.8%, giving a cost of compliance of \$167 + \$79 per ton, or \$246/ton. Note that, with these values, the price of permits, \$178/ton, is consistent with the predictions of the binomial options pricing model.

We interpret the aggregate evidence for the US Acid Rain Program to be consistent with the binomial options pricing model. A complete empirical analysis will require that model allow for heterogeneous since the data indicates that costs vary considerably across firms. The effects of regulation must also be included. The analysis presented here, however, suggests that it would be more accurate to develop such features in an options pricing model, rather than a conventional static production model.

Policy implications

Proper policy planning requires an accurate analysis of how firms value the right to pollute. The model developed above shows that there is a wedge between the price of permits and the cost of alternative abatement options. The implication of this result is that abatement costs are not an accurate measure of the value of the right to pollute. This comes from the fact some of the investment in abatement equipment is purchased as an option to account for future price fluctuations in electricity. While investment in abatement generally has a social benefit (from reduced pollution), this benefit does not occur when the abatement equipment is not used. In other words, there is some strictly private benefit to abatement investment (at least in the presence of alternative compliance options, such as marketable permits). When planners attempt to weigh the costs and benefits of pollution control, it is important that they not overvalue the cost of abatement investment, since some of that cost has a corresponding private benefit to the firm.

Before implementing a program to control pollution, an evaluation must be made to determine what is the correct level of control. The economic analysis to date is correctly based on the concept that the optimal level of pollution to allow is the quantity at which the marginal benefit of pollution exactly offsets the marginal cost of pollution. This is exactly what happens in a market equilibrium (see figure 4). In a static model, the marginal benefit of permits to pollute is correctly identified with the marginal cost of abatement, and the marginal cost is simply the marginal social cost (a valuation of environmental damage).

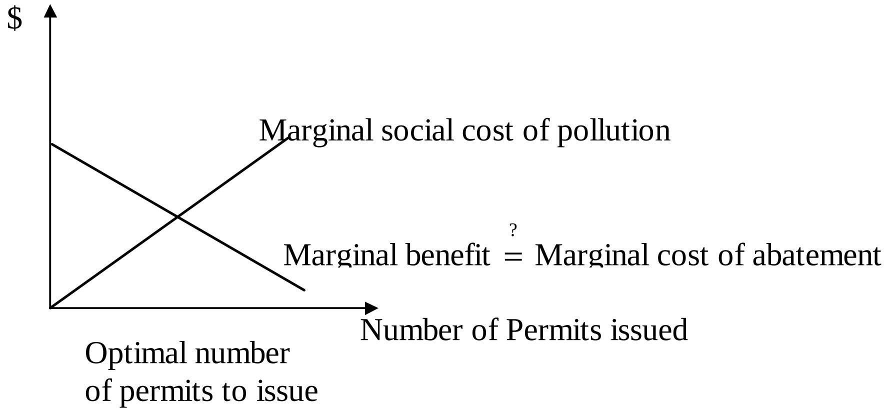

Figure 4: Static analysis of optimal number of permits to issue

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Permits that can be banked represent a qualitatively different commodity than permits that must be used in the current period. The binomial options pricing model provides a means for correctly determining the relationship between the marginal cost of abatement and the marginal benefit of permits. The model presented in this paper is based on constant marginal abatement costs, which makes the relationship between the price of permits and the cost of abatement very clear. The marginal benefit curve is lower than the marginal abatement cost curve. The optimal number of permits (and the expected sale price of permits) is lower than the quantity that would result if the policy maker incorrectly used the marginal abatement cost curve (see figure 5).

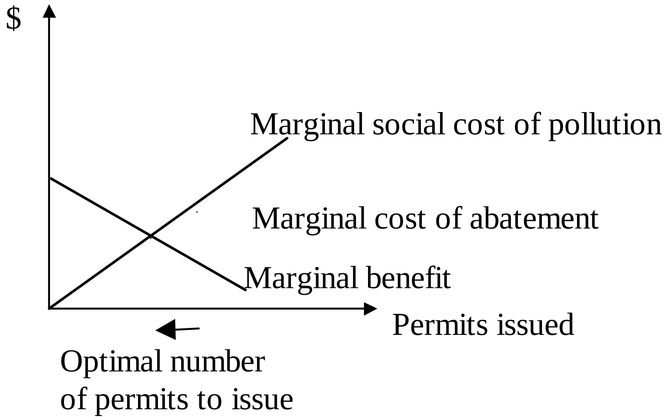

Figure 5: Dynamic analysis of optimal number of permits to issue, using options pricing model

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The brief graphical analysis demonstrates that, while an estimate of the cost of abatement may be valuable information, it may not be the correct information to use as an estimate of how much firm's would value permits to emit pollution. Furthermore, the consequences of using incorrect information may be substantial. For example, the figures drawn from the U.S. Acid Rain Program suggest that permit prices may be 60%-75% lower than marginal abatement costs. Imagine for a moment that determination of the 8.7 million-ton allotment of permits was based on marginal analysis, using an accurate estimate of marginal abatement cost as an incorrect measure of marginal benefit. With any approximately linear marginal social cost curve, the correct number of permits would have been between 5.2 million and 6.5 million, and the welfare loss associated with the incorrect allocation of permits would be in the range of $80-$180 million[14].

In a realistic policy setting, the actual decision-making process may bear little resemblance to the abstract model shown in figure 5. Regardless of how the decision is made, however, the process will be improved by correct information. The results developed here indicate that planners may be using incorrectly valuing the benefits of allowing firms to emit pollution by using abatement expenditures as

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[14] These estimates are based on linear social marginal costs and linear marginal abatement costs. With this assumption, the percentage difference in the price is the same as the percentage difference in the optimal quantity. Welfare loss is simply the area between the marginal social cost of pollution and the marginal benefit of permits, over the range between the actual number of permits and the optimal number of permits.

a measure of that benefit. The option value of abatement expenditures provides a private benefit to the firm that policy planners should not include in their analysis.

Conclusion

The generation of electricity by coal-fired power plants is an excellent example of a common situation; it is a polluting industry for which a primary abatement measure requires irreversible investment under uncertainty. Bankable permits in such situations are qualitatively different from permits that must be used immediately. As such, any analysis comparing the value that firms place on these permits with the value firms place on abatement measures must account for the effects of uncertainty and irreversible investment.

The results of this analysis indicate that the expected equilibrium relationship in most cases of interest is with the price of permits substantially lower than the marginal cost of abatement. A full empirical analysis is not provided here, but a brief look at the data available from the US Acid Rain Program is revealing. Even the very simple model presented here correctly predicts a discrepancy in the price of permits and the cost of abatement, although the magnitude of the discrepancy appears to be larger than the model predicts. A more extensive model that accounts for heterogeneity and market power in the electricity production industry is required for a full-scale empirical analysis.

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This approach will also be relevant for environmental policy. The contribution presented here addresses the marginal benefit side of the analysis. Any accurate welfare treatment will require a more complete analysis of the relationship between marginal environmental damage and marginal social cost for bankable permits. One issue not considered in this analysis is the correct valuation of the social cost of pollution (represented by issued permits) when the time that the pollution will be emitted is not known. Permits issued today can be used either now or later: does the timing of the use of permits influence the consequent marginal damage?

Another policy-relevant economic question where this model may find application is whether the characteristics of an individual firm are related to the firm’s choice of compliance method. For example, do firms with lower marginal costs tend to prefer purchasing permits or investing in abatement, relative to firms with higher marginal costs? Additional refinements to the model could also relate compliance options to regional differences in the uncertainty surrounding downstream market prices (or input costs). Both of these questions would be relevant for addressing concerns about the geographic distribution of permit use, and the possibility of pollution “hot spots” developing because of a permit market.

This work adds to the ongoing improvement of theoretical models used in environmental economics, in much the same way that researchers have developed better ways of addressing dynamic situations by using dynamic models. In situations with uncertainty and irreversible investment, the binomial options pricing model is an obvious choice. The specific model presented here represents a new and interesting application of this methodology that will continue to be productive with further development.

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