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A TWO-PERIOD MODEL OF EMISSION ABATEMENT AND ALLOWANCE BANKING UNDER UNCERTAINTY†

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By

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ABSTRACT

This paper deals with the effects of uncertainty and risk aversion on market outcomes for SO_2 emission allowance prices and on electric utility compliance choices. The 1990 Clean Air Act Amendments (CAAA) provide about twice as many SO_2 allowances to be issued per year in Phase I (1995-1999) than in Phase II. Also, considering the scrubber incentives in Phase I, there is likely to be substantial emission banking for use in Phase II. Allowance prices may increase over time at a rate less than the return on alternative investments with allowances being banked only by risk averse electric utilities. Speculators are likely to be willing to sell allowances in forward markets, which will lower current market prices of allowances relative to a situation with only risk averse utilities in the market. The Argonne Utility Simulation Model (ARGUS2) is being revised to incorporate the provisions of the CAAA acid rain title and to simulate SO_2 allowance prices, compliance choices, capacity expansion, system dispatch, fuel use, and emissions using a unit level data base and alternative scenario assumptions.

1. INTRODUCTION AND OVERVIEW

There is a great deal of confusion regarding the viability and effects of the market for SO_2 emission allowances to be established under the 1990 Clean Air Act Amendments (CAAA), Title IV, on Acid Rain Controls. It has even been questioned whether electric utilities, after being allocated emission allowances free-of-charge, will be willing to trade or sell these emission allowances. A futures market in SO_2 allowances would lower transactions costs in acquiring allowances for future use and would provide more choices to affected parties on risks to be born. The Chicago Board of Trade (CBOT) is proposing a futures market in SO_2 allowances.

The CAAA enacts a 2-phased acid rain control program. In Phase I (1995-1999) allowances are distributed by the U.S. EPA at about twice the annual rate as in Phase II. Some of these Phase I allowances will be saved (i.e., banked) for use in Phase II. Also incentives and extensions under the CAAA, as well as state regulations, will increase the adoption of Flue Gas Desulfurization (FGD) in Phase I and hence will lead to greater Phase I emission reductions and banking. In each year of Phase I, the difference between allowance allocations and utility emissions in that year is an increment to banked allowances for future use.

Most of this paper focuses on the intertemporal banking decision by electric utilities which are the ultimate users of SO_2 emission allowances. A major determinant of the banking decision by an individual firm is the expected evolution of the market price path for SO_2 allowances, and the risks that the allowance price may increase more or less than expected. The current allowance market price is the price at which electric utilities can purchase allowances for current use or banking and the price necessary to induce some other utilities to sell some of their stock of allowances.

It is argued here that an electric utility may have reason to bank allowances as a hedge against risk. As an important example, consider the cost at which electric utilities will be able to generate electricity in the future with advanced technologies which do not emit SO_2 in significant quantities (e.g., renewable technologies, clean coal technologies). These costs are not well known so costs are best represented as a probability distribution. If the costs of these future electricity supplies turn out to be low, the welfare of the electric utility is expected to be greater except for one aspect: any SO_2 emission allowances it has banked will depreciate in value due to the penetration of low SO_2 emitting new capacity. On the other hand, if the cost of clean advanced technology is higher than expected, conventional coal fired plants will be utilized more heavily, increasing the market demand for and the price of SO_2 emission allowances. Hence holding emission allowances is a hedge against technological risk. This investment is also a hedge against the risk of failure in demand side management. The stock of allowances banked by a utility is an asset whose return will be negatively correlated with the electric utility's overall welfare. Hence the value of emission allowances may reflect a premium for electric utility risk diversification. This risk premium is defined as the excess of the current market price over the present value of the expected future spot price at some date when the allowances are needed.

However, even if utilities are risk averse, other market participants could drive the current market allowance price down to the present value of the expected future spot price. If the current price were higher than this, a speculator (whose stock portfolio does not contain higher than average shares in the electric utility sector) could earn an expected return by selling a forward contract to the utility, which the utility would view as an alternative to banking allowances for future use. The forward contract would guarantee delivery of SO_2 emission allowances at a specified future date at a price which is determined in advance by the market for futures contracts. Utilities wishing to bank allowances for the future would not need to pay more than the present value of the forward contract price, since the forward contract is equivalent to banking. The forward contract price could be bid down to the expected value of the future spot price since any higher forward price would provide speculators with a positive expected value on their investment.

[The relationship of the forward contract price to the expected future spot price could be further pursued using the tools of the Capital Asset Pricing Model (CAPM), since the overall stock market value is likely to be positively correlated with the availability of low cost, low emitting energy alternatives and allowance prices are negatively correlated with availability of these new energy alternatives. Hence, in theory there could be systematic portfolio risk reduction by holding emission allowances. The application of the CAPM model is left for future research.]

Banking allowances for future use is equivalent to holding forward contracts for allowances. The amount of banked allowances (or forward contracts) that the utility will choose to hold will depend on current market prices for allowances (or the present value of forward prices) and their relationship to expected future spot market prices and the variance in these future spot prices.

If the future spot market price were known, banking an allowance would amount to holding an asset which did not pay interest; the return is based on the capital gain on the asset. Allowance market prices would then have to rise at the rate of interest paid by other assets. However, risk averse utilities may be willing to hold allowances when their expected return is less than the rate of interest because allowances are an asset which can lower the overall risk in a utility's portfolio. As current market prices are bid down by speculators willing to sell allowances using forward contracts, utilities will be willing to hold more allowances or forward contracts because these become better investments at lower prices and provide risk diversification for the utility. This paper will elaborate on this theory to determine the quantity of allowances that electric utilities may be willing to bank and forward contracts they may be willing to buy.

This paper is organized into four sections. Section 2 presents a simple two-period model for the emission allowance prices, banking, and emission control with uncertain technical advance. Interfirm and intertemporal efficiency conditions are compared with the behavior of risk neutral utilities. Section 3 uses this simple two-period model to analyze risk averse utilities. In section 4 the general equilibrium is compared (1) with banking, but no forward contracts and (2) with a futures market.

2 EFFICIENCY CONDITIONS UNDER UNCERTAINTY

In this section, the pattern of emission reductions across firms and time is derived which minimizes the expected value of total discounted costs. It is then shown that a market for tradable emission allowances induces individual risk neutral firms to behave in a manner so that the efficiency conditions are met.

The important role of futures markets will not become evident until Sect. 3, in which electric utilities are allowed to be risk averse. Then electric utilities may wish to hold allowances plus forward contracts exceeding the supply of banked allowances. It will be shown in Section 3 that in the absence of forward contracts, the supply of banked allowances could command a premium price and the intertemporal efficiency condition might not be met.

2.1 Interfirm and Intertemporal Efficiency

Assume that emissions from the ith firm in period t, E_{ti}, are proportional to electricity generation if there are no abatement controls: $E_{ti} = Bg_{ti}$. This situation of no controls probably refers to the burning of local high sulfur coals. (Although the notation does not indicate it, the coefficient b could be firm specific.) Let η_{ti} be the fractional emission reduction by firm i in period t from this uncontrolled state. Therefore,

$$E_{ti} = (1 - \eta_{ti})bG_{ti}. \tag{1}$$

The cost of emission abatement technology is represented by a continuous, differentiable function increasing more than proportionally with η. For a given fractional reduction η, abatement costs are assumed to be proportional to the size of the emissions source, Bg. That is, emission abatement costs are given by

$$C_{ti} = f(\eta_{ti})bG_{ti} \tag{2}$$

where $f' > 0$ and $f'' > 0$. (The function $f(\cdot)$ could also be firm specific.) The interpretation of the function $f(\eta_{ti})$ is the abatement cost per unit of coal-fired generation aggregated for all coal-fired units under the ownership of the electric utility company. Marginal abatement costs, MAC_{ti}, are defined as $(-Dc_{ti}/De_{ti})$ and from (1) and (2), we have

$$MAC_{ti} = f'(\eta_{ti}) \tag{3}$$

To keep the model simple, consider only two periods corresponding to Phase I and Phase II of the 1990 CAAA. The type of uncertainty we considered here is the amount of non-coal generation available to meet electricity demand in Phase II. That is, how much non-SO_2 emitting new technologies will be available 15 years from now? How much natural gas will be available for electricity generation? Will existing nuclear plants built in the 1970's still be available? Will demand side efficiency measures be achieved as a substitute for electricity supply? Considerable uncertainty surrounds all these major energy issues. The outcomes of these uncertainties are taken as exogenous in this model. Of course, there are other important uncertain variables which will affect the tightness of Phase II emission allowance markets such as economic growth, the quantity of low sulfur coal reserves and the cost and performance of clean coal technologies (CCT). The outcome for low sulfur coal reserves and CCT will shift the shape of the abatement cost function, as shown in Section 5. A somewhat more general model of management's precautionary motives is presented in Section 4, but many of the key uncertainties are represented by the model introduced in this section.

Denote the fraction of non-SO_2 emitting generation which penetrates firm i by the random variable θ_i. The expected value of total discounted cost for two periods and all firms is given by

$$EX\{TDC\} = \sum_i f(\eta_{1i})bG_{1i} + \sum_{\theta 1}\cdots\sum_{\theta N}\left(\sum_i f(\eta_{2i})(1-\theta_i)bG_{2i}\right)Pr(\Theta)/(1+r) \tag{4}$$

where Θ is the vector $[\theta_1,...,\theta_N]$ for N firms and where 1/(1+r) is the discount factor.

Phase I annual allowances will be about twice as great as Phase II annual allowances. The CAAA provides for banking some of the Phase I allowances for use in Phase II. The relevant emission constraints are modeled as follows:

$$\sum_i ALLOW_{1i} \geq \sum_i E_{1i} = \sum_i (1-\eta_{1i})bG_{1i} \tag{5a}$$

$$\sum_i ALLOW_{1i} + ALLOW_2 \geq \sum_i E_{1i} + \sum_i E_{2i} = \sum_i [(1-\eta_{1i})bG_{1i} + (1-\eta_{2i})(1-\theta_i)bG_{2i}] \tag{5b}$$

It is assumed that the Phase II compliance choice is made after the uncertainty is revealed on the mix of Phase II capacity. Hence, the stringency of compliance in Phase II is conditional on the θ_i and η_{1i}. That is, the η_{2i} is determined ex post. The problem that will be faced in period 2 will have the η_{1i}'s and Θ given, and the η_{2i}'s are chosen to minimize $\sum_i f(\eta_{2i})(1-\theta_i)bG_{2i}$ subject to constraint (5b). Solving this problem yields

$$f'(\eta_{2i}) \equiv MAC_{2i} = \lambda_2 = MAC_{2j} \tag{6}$$

for all firms i and j where λ_2 is the LaGrange multiplier associated with the constraint (5b). That is, second period controls are selected to equate MAC_2 across firms, i.e., interfirm efficiency. The emission reductions in period 1, η_{1i}, are chosen to minimize the expected value of total discounted costs, (4), with the understanding that the η_{2i}'s will be chosen ex post to satisfy (6) and the constraint (5b). Minimizing (4) with respect to period 1 reductions subject to the period 1 inequality constraint (5a) yields:

$$f'(\eta_{1j})bG_{1j} + \sum_{\theta 1}\cdots\sum_{\theta N}\sum_i f'(\eta_{2i})\left(\frac{\partial \eta_{2i}}{\partial \eta_{1j}} \mid \Theta\right)(1-\theta_i)bG_{2i}Pr(\Theta)/(1+r) - \lambda_1 bG_{1j} = 0 \tag{7}$$

The term $f'(\eta_{2i})$ is the common MAC_2 in period 2 and λ_1 must be zero if strict inequality holds in (5a), i.e., banking. The problem is to evaluate the term $\frac{\partial \eta_{2i}}{\partial \eta_{1j}} | \Theta$ which is done in Appendix A. The result yields the efficiency condition

$$MAC_{1k} = MAC_{1j} \geq EX\{MAC_{2r}/(1+r)\} \tag{8}$$

with equality expected to hold since constraint (5a) is not expected to be binding (i.e., banking in Phase I). That is, MAC_1's are equated across all firms in period 1 (i.e., interfirm efficiency) and this common value, if there is banking, is the expected value of the common value for the MAC_2's in period 2, discounted to the present. The relationship that $MAC_1 = EX\{MAC_2/(1+r)\}$ is the intertemporal efficiency condition under banking. So, if there is intertemporal banking, emissions are controlled in Phase I up to the point where the MAC_1 equals the expected value of MAC_2 in Phase II, discounted to the present time. This condition determines how much emission reduction is efficient in each period. The quantity of emission banking is thereby determined, given annual allowances. However, it would not be economic to bank emissions, if the emission constraint (5a) were sufficiently stringent and held with equality, in which case it must be true that MAC_1 in Phase I is greater than $EX\{MAC_2/(1+r)\}$.

2.2 Markets for Allowances with Risk Neutral Electric Utilities

The interfirm and intertemporal efficiency conditions have now been derived for emission reductions. Here it is shown that if firms are risk neutral and if there is a competitive market in tradeable emission allowances, then the emission reductions chosen by individual firms will satisfy the efficiency conditions and hence minimize the expected value of total discounted costs. Each firm i is assumed to be sufficiently small to take allowance prices as given, ie. the firm does not have market power in the allowance market.

The allowances banked by firm i are given by its initial allocation of allowances less its emissions and less the allowances it sells on the market. Note that a negative $SELL_{1i}$ variable represents the purchase of emission allowances. For example, firms wishing to bank more allowances than it has available will initially purchase allowances (i.e., $SELL_{1t}$ will be negative.)

$$BANK_i = ALLOW_{1i} - (1-\eta_{1i})bG_{1i} - SELL_{1i} \geq 0 \tag{9a}$$

A firm can choose zero banking or positive banking as indicated by the inequality constraint (9a). In the second period all unused allowances are sold (or any needed allowances are purchased):

$$SELL_{2i} = ALLOW_{1i} + ALLOW_{2i} - (1-\eta_{1i})\ bG_{1i} - (1-\eta_{2i})\ (1-\theta_i)bG_{2i} - SELL_{1i} \tag{9b}$$

or, using (9a),

$$SELL_{2i} = ALLOW_{2i} - (1-\eta_{2i})(1-\theta_i)bG_{2i} + BANK_i$$

The discounted costs for firm i are based on its cash flow given by

$$DC_i = f(\eta_{1i})bG_{1i} - PA_1SELL_{1i} +$$

$$f(\eta_{2i})(1-\theta_i)bG_{2i}/(1+r) - PA_2(\Theta)SELL_{2i}/(1+r) \tag{10}$$

where PA_t is the price of allowances in period t. The demand for period 2 allowances, and hence their price $PA2_2$, will depend on the amount of coal-fired generation, which is an inverse function of the components of the vector Θ. Substituting (9a) and (9b) into (10) yields:

$$DC_i(\eta_{1i}, BANK_i, \Theta) = f(\eta_{1i})bG_{1i} + PA_1(1-\eta_{1i})bG_{1i}$$

$$- PA_1ALLOW_{1i} + PA_1BANK_i + f(\eta_{2i})(1-\theta_i)bG_{2i}/(1+r)$$

$$- PA_2(\Theta)ALLOW_{2i}/(1+r) + PA_2(\Theta)(1-\eta_{2i})(1-\theta_i)bG_{2i}/(1+r) - PA_2(\Theta)BANK_i/(1+r) \tag{11}$$

Think of DC_i as a function of Θ but not η_{2i}, since once the outcome of Θ is revealed, the period 2 decision for η_{2i} will be a function of Θ. That is, minimizing DC_i with respect to η_{2i}, given Θ, yields the necessary condition

$$MAC_2 = f'(\eta_{2i}) = PA_2(\Theta) \quad \text{for all i.} \tag{12}$$

In Phase II the allowance price $PA_2(\Theta)$ is revealed and emissions are reduced for each firm i up to the point where MAC_2 equals the emissions price. In Phase I, DC_i can be minimized with respect to η_{1i} for a fixed amount of banking, i.e., given $BANK_i$, yielding

$$MAC_1 = f'(\eta_{1i}) = PA_1 \quad \text{for all i.} \tag{13}$$

Note that a firm's least cost compliance choice η_{1i} is independent of the firm's decision to bank allowances, since there is a market for allowances. Firms choose their emission reductions based on the market price of emissions and not on their particular need for allowances relative to their emissions.

The risk neutral firm seeks to minimize the expected value of its discounted costs:

$$EX\{DC_i(\eta_{1i},BANK_i,\theta)\}=f(\eta_{1i})bG_{1i}+PA_1(1-\eta_{1i})bG_{1i}-PA_1ALLOW_{1i}+PA_1BANK_i \quad (14)$$

$$\sum_{\theta 1}\ldots\sum_{\theta N}[f(\eta_{2i}(1-\theta_i)bG_{2i}-PA_2(\Theta)ALLOW_{2i}+PA_2(\Theta)(1-\eta_{2i})(1-\theta_i)bG_{2i}-PA_2(\Theta)BANK_i]Pr(\Theta)/(1+r)$$

Minimizing (14) with respect to $BANK_i \geq 0$ yields the condition

$$PA_1 \geq EX\{PA_2(\Theta)/(1+r)\} \quad (15a)$$

with equality holding if banking is positive:

$$PA_1 = EX\{PA_2(\Theta)/(1+r)\} \qquad \text{if } BANK_i > 0 \quad (15b)$$

No banking in Phase I might be associated with Phase I regulations of comparable or greater stringency to Phase II regulations. However, in the 1990 CAAA, Phase II regulations are considerably more stringent, causing banking to be expected.

Condition (15b) is similar to the Hotelling condition in the theory of exhaustible resources. Risk neutral firms are indifferent between selling an allowance in Phase I for a price PA_1 or banking the allowance and selling it in Phase II for an expected price r percent greater than PA_1. Condition (15b) takes into account the time value of money. Note that the condition $PA_1 < EX\{PA_2/(1+r)\}$ should never occur. If it did, banking allowances would earn a higher return than other assets and all firms would seek to buy allowances, driving up the price PA_1 until (15b) were to hold.

3. RISK AVERSE ELECTRIC UTILITIES AND THE ROLE OF FUTURES MARKETS

3.1 Emission Banking in the Absence of Forward Trading

In this section, the analysis is extended to the more interesting cases in which electric utility firms, hereafter referred to as firms, are risk averse. By risk averse, we mean that the firm's objective is to maximize the expected value of an increasing, concave utility function depending on its discounted net income. Although our model does not provide for all the components of a firm's net income, it is noted that a firm's SO_2 abatement costs would be a subtraction from net income. Further, exogenous technical advance in non-coal generation as described by a higher outcome for the random variable θ_i should also increase, or at least not decrease, the firm's discounted net income. Hence, we define the utility function for the firm i as $U_i(Y_i)$, where

$$Y_i = g_i(\theta_i) - DC_i \cdot \tag{16}$$

The firm seeks to maximize

$$EX\{U_i\} = \sum_{\theta 1} \ldots \sum_{\theta n} U(g(\theta_i) - DC_i)Pr(\Theta) \tag{17}$$

where $DC_i(\eta_{1i}, BANK_i, \Theta)$ is given by (11). Differentiating (17) with respect to η_{1i} yields (13), i.e., $MAC_1 = PA_1$. *Therefore, the criterion for reducing emissions is the same even under risk aversion.* Differentiating (17) with respect to $BANK_i$ yields the following expression denoted here by z and involving the marginal utility of income, $MU_i = \partial U_i/\partial Y_i$,

$$z \equiv \frac{\partial EX\{U_i\}}{\partial BANK_i} = \sum_{\theta 1} \ldots \sum_{\theta n} (-MU_i)[PA_1 - PA_2(\Theta)/(1+r)]Pr(\Theta) \tag{18a}$$

$$= COV\{MU_i, PA_2\}/(1+r) - EX\{MU_i\}[PA_1 - EX\{PA_2\}/(1+r)] \tag{18b}$$

It may turn out that an infinite amount of banking is optimal. This is true in the risk neutral case if $PA_1 < EX\{PA_2\}/(1+r)$. For the risk averse case, expected utility in (17) continues to increase with more banking if z is always positive. For example, referring to (18b) if $PA_1 = EX\{PA_2\}/(1+r)$ and if $COV\{MU_i, PA_2\}$ is positive, then z will be positive. For a maximum expected utility to exist, it is clear that PA_1 must exceed $EX\{PA_2\}/(1+r)$ by a sufficient amount to offset the positive term $COV\{MU_i, PA_2\}$. However, if PA_1 is too high, no banking of allowances is economic and the constraint $BANK_i \geq 0$ begins to bind. Hence, there must exist a range of allowance prices over which an interior maximum exists. At the amount of banking which yields a maximum z = 0 and

$$PA_1 = EX\{\frac{MU_i}{EX\{MU_i\}} PA_2(\Theta)/(1+r)\} = \frac{COV\{MU_i, PA_2\}}{(1+r)EX\{MU_i\}} + \frac{EX\{PA_2\}}{1+r} \tag{19}$$

Hence, if MU_i is positively correlated with $PA_2(\Theta)$ (which is discussed below), it must be true that

$$PA_1 > EX\{PA_2(\Theta)/(1+r)\} \tag{20}$$

This is one of the main results of the paper: *risk averse firms will be willing to hold, in fact, will desire to hold, a stock of banked allowances, even when the expected return on these assets in isolation is less than their opportunity cost, which is r%.* The reason, of course, is that one must look at the firm's entire portfolio, not just one type of asset in isolation, and compare the return on the portfolio as a whole. Emission allowances help an electric utility hedge against risk and hence lower the overall risk in its portfolio.

To see this, suppose that the outcome in year 2000 for θ_i is higher than its expected value, $EX\{\theta_i\}$. The θ_i refers to the fraction of non-coal electricity generation in the future: hydroelectric, biomass, other renewable sources, gas, oil, nuclear, as well as demand-side efficiency measures. Underlying the outcome for θ_i are a set of other random variables affecting both θ_i and other firms' components of Θ. These underlying random variables are technological success with non-coal sources, public acceptance, the amount of available resources such as natural gas, and the stringency of other regulations pertaining to these sources. Because of these common underlying random variables, the θ_i will be positively correlated with the other components of Θ. The effects of a higher Θ vector for the electric industry is less need for SO_2 allowances, so $PA_2(\Theta)$ will tend to decrease. For the specific firm i, a higher θ_i will lower its coal-based generation, and directly lower its abatement costs.

To establish a positive correlation between MU_i and $PA_2(\Theta)$, we note that the marginal utility for firm i, MU_i, is a <u>decreasing</u> function of the firm's income. Suppose that the underlying random variables mentioned above tend to raise the components of Θ and hence lower PA_2. Then we need to show that raising the values of Θ components will tend to <u>increase</u> income. To start, consider the costs of generation to the firm if the θ_i outcome were higher. The costs of generation would tend to be lower, and presumably net income would be higher for a higher θ_i, due to the underlying random variables such as greater technical progress, larger than expected gas resource base, or less stringent regulations than expected. Hence generation costs would be lower. Abatement costs, measured here by DC_i, would also be lower, again presumably raising net income. Abatement costs will be lower if θ_i is higher because there is less coal-fired generation to clean up or to cover with allowances. So far all the direct terms discussed have been in the direction of a positive correlation between MU_i and PA_2. Now we consider the indirect effects on a firm's income due to market changes in the $PA_2(\Theta)$ and the resulting response in η_{2i}, which is the solution to (12) : $f'(\eta_{2i}) = PA_2(\Theta)$. These indirect effects are presumably small but there may be many of them due to many firms j, each with random variable θ_j. To calculate these indirect effects formally, one differentiates DC_i with respect to θ_j and substituting in $\frac{\partial \eta_{2i}}{\partial \theta_j} = \frac{\partial PA_2}{\partial \theta_j}/f''(\eta_{2i})$, since (12) must hold. Due to the envelope theorem, many of these terms cancel. The effect of a higher θ_j, and hence lower PA_2, on lowering the firm's emission reduction, η_{2i}, will save abatement costs just equal to the market value of the increased emissions. Hence, it can be shown that

$$\frac{\partial Y_i}{\partial \theta_j} = -\frac{\partial DC_i}{\partial \theta_j} = \frac{\partial PA_2}{\partial \theta_j} SELL_{2i} \tag{21}$$

where $\partial PA_2/\partial \theta_j < 0$. If firm i banks insufficient allowances for Phase II of the CAAA, so that it must buy allowances on the market in Phase II, then $SELL_{2i}$ is negative and $\partial Y_i/\partial \theta_j$ will be positive, contributing to the positive correlation between MU_i and PA_2 (Θ). However, it is more likely that the risk averse utility will want to be in a position of banking allowances so that it will expect to be selling some of these excess allowances once the uncertainties are resolved in Phase II. If $SELL_{2i}$ is positive, then $\partial Y_i/\partial \theta_j$ is negative. Then these indirect effects on income through the effect on the market price $PA_2(\Theta)$ will not be a contributor to the positive correlation between MU_i and $PA_2(\Theta)$. However, since the direct effects analyzed here imply a positive correlation, leading to more incentives for banking allowances, it is not surprising that the analysis finds an indirect partially offsetting effect, that the market value declines for excess allowances expected to be eventually sold.

In summary the necessary condition (19) determines the optimal value of $BANK_i$ where firm i is a price taker (i.e., PA_1 is taken as given and PA_2 is taken as an exogenous distribution). The firm increases its banked allowances up to the point where the expected value of the distribution of PA_2 weighted by the positively correlated variable

$$w_i = MU_i/EX\{MU_i\} \tag{22}$$

and discounted to the present, equals the current price PA_1. Note that the amount of banking will affect the distribution of the weights w_i. Taken in isolation, banking lowers the firm's expected net income because it has a lower expected return than alternative investments available. This lower expected income raises the expected value of MU_i.

We now examine more concretely the optimal banking for firm i. To work a tractable case we take a specific functional form for the utility function. The U(Y), an increasing, concave function of the firm's net income, is taken to be parabolic over the range of variability of income considered here. Hence, the second derivative of U with respect to income is taken to be the constant (-H) over the relevant range of income. For concreteness marginal utility of income is represented by

$$MU_i = K - HY_i \tag{23}$$

Calculate $\partial z/\partial BANK_i$ where z is the derivative of expected utility with respect to banking given by (18):

$$\frac{\partial z}{\partial BANK_i} = \sum_{\theta 1} \dots \sum_{\theta N} \frac{\partial^2 U_i}{\partial Y_i^2} \frac{\partial DC_i}{\partial BANK_i} [PA_1 - PA_2(\Theta)/(1+r)] Pr(\Theta) \tag{24}$$

$$= - H \cdot EX\{[PA_1 - PA_2(\Theta)/(1+r)]^2\}$$

using the expression (11) for $DC_i(\eta_{1i}, BANK_i, \Theta)$. Hence

$$\frac{\partial z}{\partial BANK_i} = \frac{\partial^2 EX\{U_i\}}{\partial BANK_i^2} = - H \cdot [(PA_1 - EX\{PA_2/(1+r)\})^2 + VAR\{PA_2\}/(1+r)^2] < 0 \tag{25}$$

Let's begin by evaluating z when $BANK_i = 0$. Recall the firm is a price taker in PA_1 and the PA_2 distribution. Suppose

$$PA_1 > EX\{\frac{MU_i \cdot PA_2(\Theta)}{EX\{MU_i\}} / (1+r)\} \tag{26a}$$

where the random variable MU_i has a distribution based on the parameter value $BANK_i = 0$. Then it is optimal not to bank because the expected lower capital gains on holding allowances offset the risk hedging advantages of banking. However, suppose instead that

$$EX\{\frac{PA_2(\Theta)}{1+r}\} < PA_1 < EX\{\frac{MU_i \cdot PA_2(\Theta)}{EX\{MU_i\}} / (1+r)\} \tag{26b}$$

when $BANK_i = 0$. This condition implies z in (18) is positive when $BANK_i = 0$. Since $dz/dBANK_i < 0$, we must decrease z to find the root, $z = 0$, by increasing banking. The root, $z = 0$, maximizes $EX\{U_i\}$ given by (17). The second order condition for a maximum holds (see Eq. (25)). Using a Taylor Series expansion, a first order approximation to the optimal banking is

$$BANK_i = \frac{-z_o}{\partial z/\partial BANK_i} \quad (27a)$$

where z_o is z in (18) evaluated at $BANK_i = 0$.

$$BANK_i = \frac{-COV\{Y_i, PA_2(\Theta)/(1+r)\} - [K/H - EX\{Y_i\}][PA_i - EX\{PA_2(\Theta)/1+r)\}]}{[PA_1 - EX\{PA_2(\Theta)/(1+r)\}]^2 + VAR\{PA_2(\Theta)\}/(1+r)^2} \quad (27b)$$

The sign of the numerator in (27b) can be shown to be positive if and only if (26b) holds, evaluated at $BANK_i = 0$. The covariance of Y_i and PA_2 is taken to be negative based on a positive correlation between MU and PA_2. The term $[K/H - EX\{Y_i\}]$ is positive since MU is positive. The term $[PA_i - EX\{PA_2(\Theta)/(1+r)\}]$ is positive or else there would be an incentive for infinite banking as discussed earlier. Eq. (27b) shows that banking decreases with a higher PA_1 and increases with a higher $COV(Y_i, PA_2)$, $EX\{PA_2\}$, H, and $EX\{Y_i\}$ .... all of which are in the expected directions. For example, higher risk aversion is measured by a higher value of H, which increases banking.

A caution should be made on the use of Eq. (27b). If $BANK_i$ turns out to be large, the linear approximation assumption underlying (27b) may no longer be valid, requiring the solution to the more general Eq. (19). This warning would hold, for example, if the positive term $(PA_1 - EX\{PA_2\}/(1+r\})$ were small.

Eq. (27b) shows the sensitivity of the optimal banking to the curvature of the utility function. Greater curvature parameter H implies more risk aversion. For some value of H sufficiently small, (27b) shows that $BANK_i$ will be zero (provided $PA_1 > EX\{PA_2\}/(1+r)$). Larger values of H will increase banking. Since the degree of risk aversion may not be known, it might be useful to do a set of sensitivity calculations solving Eq. (19) for optimal banking under different parameter assumptions. Note that Eq. (27b) again emphasizes that the banking decision is independent of the emission reduction decision. The banking decision is a financial asset decision and hence depends on rates of return, risks facing the firm, and the degree of risk aversion by the decision makers.

3.2 Forward Contracts as a Substitute for Emission Banking

From an individual firm's point of view forward contracts are viewed the same as banking. Hence the firm's constraint set is unchanged and its behavior is unaffected, provided that there are no marketwide effects. However, there are expected to be market effects in which the initial allowance price PA_1 is bid down by the introduction of forward contracts. These market effects will be discussed in the next section.

A forward market modifies the firm's constraint in the second period; (9b) becomes

$$SELL_{2i} = ALLOW_{2i} - (1-\eta_{2i})(1-\theta_i)bG_{2i} + BANK_i + FBUY_i$$

including a term for the purchase of forward contracts. (If $FBUY_i$ is negative, the firm is a net seller of forward contracts.)

In our simple model, forward contracts are a perfect substitute for banking, and hence sell at the same present value price. The buyer pays for a forward contract in period 2 at price $PA_1(1+r)$ which in present value terms is PA_1. This is the identical present value price as buying an emission allowance in period 1 on the cash market and banking that allowance for use in period 2. Alteratively selling a forward contract has a present value PA_1 which is the same present value price as selling the allowance in period 1 on the cash market.

The firm's discounted costs DC_i are still given by (11) with $FBUY_i$ a perfect substitute for banking. Then discounted costs are given by DC_i (η_{1i}, $BANK_i$, + $FBUY_i$, Θ). Hence, the risk averse firm will choose the sum $BANK_i$ + $FBUY_i$ to satisfy the optimality condition (19). A firm which finds it optimal not to bank will also not want to buy forward contracts.

4. THE ALLOWANCE MARKET RESPONSE TO A FUTURES MARKET

Suppose that there did not exist a futures market or other forward transactions. Further, suppose that electric utility firms are risk averse. Then the market allowance prices are likely to satisfy (19) so that $PA_1 > EX\{PA_2\}/(1+r)$.

Now suppose that there exists a futures market and additional participants enter the market who are less risk averse and have capital to invest in a portfolio which might include participating in the futures market for allowances. This is sometimes called speculative capital. Sometimes it is referred to as distributing the risk to those who are willing to bear the risk most efficiently. These non-utility investors estimate positive expected returns in selling forward contracts, since the future price of the forward contract $PA_1(1+r)$ is greater than $EX\{PA_2\}$. In theory, risk neutral speculators may even desire to sell an infinite amount of forward contracts until this price differential is bid down to zero. However, speculators may not be totally risk neutral and they may be at some disadvantage in their knowledge of the complex determinants of the Phase II price of allowances (utilities may be better at this), so the supply of forward contracts may not be infinite and PA_1 may not be bid down all the way to $EX\{PA_2\}/(1+r)$.

In conclusion, a formal cash market in tradable allowances in Phase I of the CAAA will make the compliance choices more efficient. A formal futures market will have additional effects. A supply of futures contracts which utility firms can buy on the market will be a substitute for banking. This increased supply of a banking substitute will bid down the Phase I price of allowances PA_1 until risk averse utility firms are willing to hold both the banked allowances and the forward contracts which speculators desire to sell. By bidding the present value price PA_1 down closer to $EX\{PA_2\}/(1+r)$ increases economic efficiency in terms of lowering total social costs.

The emission constraints in the CAAA of 1990 will still hold, i.e., Eq. (5) will still hold. However, there will be less emission reduction in Phase I. Recall that emissions are reduced up to the point where the marginal abatement cost equals the allowance price, PA_1. A lower PA_1 also lowers emission reductions. As a consequence, Phase II emission reductions will need to be greater. However, this temporal reallocation of emissions still satisfying the provisions of the CAAA, lowers the present value of total compliance costs. For those who have a strong environmental protection motive, it is noted that these social cost savings can be applied to increase the benefits of environmental protection in other areas.

It is also seen here that whereas the banking decision is a financial decision for the firm, independent of the firm's emission reduction decision, at the market level there is no longer independence. That is, a lower initial price PA_1 due to the existence of forward contracts will both lower aggregate Phase I emission reductions and lower aggregate banking.

APPENDIX A

If emissions were reduced slightly more in period 1, emissions would not need to be reduced as much in period 2, given Θ. Mathematically, this is seen by differentiating (6), yielding

$$f''(\eta_{2i})\frac{\partial \eta_{2i}}{\partial \eta_{1j}} | \Theta = \frac{\partial \lambda_2}{\partial \eta_{1j}} | \Theta \qquad \text{(A-1)}$$

Also differentiating the constraint (5b) with respect to η_{1j} given Θ yields

$$-bG_{1j} - \sum_i (\frac{\partial \eta_{2i}}{\partial \eta_{1j}} | \Theta)(1-\theta_i)bG_{2i} = 0 \qquad \text{(A-2)}$$

Substituting (A-1) into (A-2) yields

$$-bG_{1j} - (\frac{\partial \lambda_2}{\partial \eta_{1j}} | \Theta) \sum_i [(1-\theta_i)bG_{2i}/f''(\eta_{2i})] = 0 \qquad \text{(A-3)}$$

which provides the solution for $\frac{\partial \lambda_2}{\partial \eta_{1j}} | \Theta$. Substituting this term into (A-1) yields

$$\frac{\partial \eta_{2i}}{\partial \eta_{1j}} | \Theta = \frac{-bG_{1j}/f''(\eta_{2i})}{\sum_k [(1-\theta_k)bG_{2k}/f''(\eta_{2k})]} \qquad \text{(A-4)}$$

Now substitute (A-4) into (7). Recognizing that $f'(\eta_{2i})$ is the MAC_2 and is independent of i, this common value for MAC_2 across firms can be factored out of Eq. (7), yielding (8).

END

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