Abstract

Banking has been an important component of sulfur dioxide (SO₂) emissions trading in the U.S. Acid Rain Program and it is commonly included as a desirable feature of emissions trading programs. This paper evaluates the performance of this temporal dimension of the SO₂ allowance market based on the five years in which the SO₂ bank was built up and the first year of draw-down that can now be observed. According to aggregate data on actual prices, emissions and allowance allocations, we find that the evolution of the SO₂ bank is nearly optimal from an ex-post perspective (i.e., after the initial market uncertainty was resolved). Furthermore, given the significant heterogeneity across firms we argue that if the bank is reasonably efficient then the overall market must also be efficient.
1. Introduction

The most prominent feature of the U.S. Acid Rain Program (Title IV of the 1990 Clean Air Act Amendments) is the significant bank that has been accumulated during 1995-99, the first five years of the program, which constitute Phase I. During this period, a total of 38.09 million allowances were distributed—thereby limiting cumulative emissions over these years to that amount—but only 26.44 million allowances were used to cover emissions. The difference, 11.65 million allowances, is the amount of banked allowances at the end of Phase I. This bank is significant by any measure. Thirty percent of the allowances made available to cover emissions in these years were not used. Equivalently, the reduction in emissions during Phase I was about twice what was required to meet the cap.¹

There is no surprise in the fact that banking occurred during Phase I. The two-phased structure of Title IV and the provision allowing unlimited carry-over of unused allowances made banking virtually certain. Phase II, beginning in the year 2000, differs from Phase I in both the stringency and scope of the required emission reductions. In Phase I, units larger than 100 MWₑ capacity and with 1985 emission rates of 2.5 #/mmBtu or higher were required to be subject to Title IV in Phase I and to reduce emissions to an average emission rate equal to 2.5 lbs. SO₂ per mmBtu of heat input (#/mmBtu) times average 1985-87 (baseline) heat input.²

The Phase II limit is approximately half the 2.5 rate of Phase I: the lesser of 1.2 #/mmBtu or the unit’s 1985 emission rate times baseline heat input and all fossil-fired generating units greater than 25 MWₑ became subject to Title IV regardless of historical emission rates. This structure created a significant difference in expected marginal abatement costs that would occur at midnight, December 31, 1999, if banking were not

¹ A reasonable estimate of counterfactual emissions from all the units receiving allowances during Phase I is 48 million tons. The difference between this estimate of what emissions would have been without Title IV and observed emissions from these same units is about 21 million tons, or a little more than twice what would have been required to meet the cap of 38 million tons.

² As detailed in chapter 3 of Ellerman et al. (2000) and Joskow and Schmalensee (1998), numerous exceptions to the basic principle of allocation occur, but the over-all cap was maintained by the operation of the “ratchet” provision.
permitted. However, with unlimited carry-over and a positive discount rate, the accumulation of a bank during Phase I and its subsequent use in the first years of Phase II was widely expected even before Phase I began.

Although banking was expected, the prospective size of the bank was the subject of considerable disagreement. Early estimates ranged from two to ten million tons and as Phase I began in 1995, one consulting firm created a small sensation by predicting a bank as large as 15 million tons. The size of the Title IV bank is now known, 11.65 million tons, but the more interesting issue is the efficiency of the temporal pattern of abatement implied by that bank, or what we call temporal efficiency in this paper. The accumulation phase of the banking period is over and, with the year 2000 data now available, the first year of the draw-down of the bank can be observed. In sum, sufficient data now exists to form an interim assessment of the temporal efficiency of this feature of emissions trading under Title IV.

The rest of the paper is organized as follows. In Section 2 we present a model of optimal banking and discuss what temporal efficiency implies in the context of Title IV. We use the model to deploy alternatives banking trajectories for different parameter values and contrast them with the actual banking path from 1995 through 2000. In Section 3 we use the capital asset pricing model (CAPM) and allowance price data from 1995 through 2000 to estimate the discount rate employed by allowance market participants. In Section 4 we discuss the optimality of the evolution of the bank from an ex-ante and ex-post perspective. Final remarks are in section 5.

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3 A report from the General Accounting Office published in December 1994 (USGAO, 1994) projected a Phase I bank of two million tons. An earlier and more thorough analysis by EPRI published in August 1993 (EPRI, 1993) predicted a bank “between 5 and 10 million tons, with our current projections at the higher end of the range.” RDI, a coal and electric utility consulting firm, forecast a 15 million ton bank in mid-1995 as the first emission reports became available. A later EPRI report (EPRI, 1997) written with the benefit of the 1995 compliance data stated: “The bank size by 2000 is surprisingly uncertain—from 10 to 15 million short tons.”
2. An Optimal Banking Program

2.1 The theory

An optimal banking program is one that is temporally efficient, which means that firms avail themselves of opportunities to equalize the present value of marginal abatement costs for the current period and all relevant future periods. In the context of Title IV, where banking but not borrowing is allowed, firms would reduce more than required in the current period in order to bank allowances for use in later years whenever marginal abatement costs are expected to increase at a rate greater than the discount rate.

Temporal efficiency needs to be carefully distinguished from spatial efficiency, which involves the equalization of marginal abatement costs among geographically disparate sources in the same period of time. The evidence suggests that firms with affected units in Phase I have achieved a high degree of spatial efficiency. The volume of trading among firms has been significant, and although prices vary considerably through time, at any one point in time, the law of one price prevails.

As is well established in the literature (Rubin, 1996; Schennach, 2000), the essential condition for an optimal banking program is that marginal abatement costs, $mc$, rise at the discount rate, $r$, over the banking period, the end of which is denoted by $\tau$ (since we have not introduced uncertainty yet $r$ would correspond to the risk-free rate)

\[ mc_{t+1} = mc_t e^{rt} \quad \forall \; t \in [0, \tau] \]

A further condition is that the cumulative number of allowances issued during the banking period equal cumulative emissions over the same period of time. If the cap is binding, then the number of allowances, $a$, is less than what counterfactual emissions would be without the cap, $u$, and actual emissions will be equal to counterfactual emissions less the abatement, $q$, required to comply with the cap. This identity will not apply for any year within the banking period, but it will obtain for the banking period as a whole.

This condition can be expressed as
These cumulative sums are determined by the cap, the growth rate in emissions absent the cap, and the marginal abatement cost function, which relates the quantity of abatement to the prices, or marginal costs, obtaining over the banking period as required by equation 1. The annual cap is specified by the legislation and counterfactual emissions can be modeled as emissions at $t = 0$ increasing at some growth rate, $g$.

Determining the quantities of abatement requires an assumption about the aggregate cost functions. We assume that marginal abatement cost depends on aggregate abatement in the form of a power function:

$$mc_t = \alpha_t q_t^\gamma$$

The scaling parameter, $\alpha_t$, takes the subscript 1 during the years 1995 through 1999 and the subscript 2 thereafter. Two time-differentiated cost functions exist because Phase II expands the scope of Title IV to include additional generating units and abatement opportunities. The exponent, $\gamma$, reflects the curvature of the relationship, which in this form, expresses the constant elasticity between price and quantity. We assume that this parameter is the same for both the Phase I and Phase II aggregate cost functions.

The end of the banking period, when $t = \tau$, is a particularly important point in time for any banking program. Emissions will be equal to allowances for each period of time thereafter. The shortfall of allowances from counterfactual emissions will define the quantity of abatement at that point in time and thereby the marginal cost of abatement and the price of allowances. This characteristic makes $\tau$ a reference point or anchor for the entire banking period.

As a result, equations 1 and 3 can then be restated as a function of the price and quantity of abatement at $\tau$.
(1a) \[ mc_i = mc_i e^{-r(t-	au)} \quad \forall t \in [0, \tau] \]

and

\[
q_t = \left( \frac{\alpha_2}{\alpha_1} \right) q_\tau e^{-r(t-	au)} \quad \text{for} \quad 0 \leq t \leq T \\
q_t = q_\tau e^{-r(t-	au)} \quad \text{for} \quad T \leq t \leq \tau
\]

where \( T \) denotes the end of Phase I. Substituting these equations into equation 2 and integrating yields an equation for an optimal banking program

\[
a_t T + a_2 (\tau - T) = u_0 \left( \frac{e^{\gamma T} - 1}{g} \right) + u_0 \left[ \frac{e^{\gamma t} - e^{\gamma T}}{g} \right] - \\
\left( u_0 e^{\gamma T} - a_2 \right) \left[ \frac{1}{r} \left( \frac{\alpha_2}{\alpha_1} \right)^{\frac{1}{\gamma}} e^{-r(t-	au)} e^{\gamma T} \right] + \left( 1 - e^{-r(\tau-T)} \right)
\]

The two terms on the left-hand-side of (4) state the number of allowances available in Phase I and during the years of Phase II that constitute the draw-down phase of the banking period. The first two terms on the right-hand-side give cumulative counterfactual emissions for units affected during Phase I and for all units during Phase II up to the end of the banking period. The complicated last term on the right-hand side states the cumulative emission reductions over the entire banking period. The term in parentheses outside the brackets is \( q_\alpha \) the amount of abatement required at \( t = \tau \), and the two terms in the brackets are indices of cumulative abatement, normalized to \( q_\alpha \) for Phase I and for the Phase II part of the banking period, respectively. Thus, for any set of parameter values, equation (4) allows to solve for \( \tau \) which in turn allows to compute the optimal emissions and bank trajectory over time.

Because the SO\(_2\) market is part of an uncertain world, when comparing optimal banking programs with the actual data is important to understand how the presence of
uncertainty and irreversibility alters the solution of (4) and consequently the expected optimal emissions and bank trajectories. Besides the uncertainty that may have existed before the SO2 market developed,\(^4\) it is reasonable to think that the industry marginal cost \((mc_t)\) and unrestricted emissions \((u_t)\) may somehow depart from their expected values from period to period. Assuming that firms are risk neutral and that this uncertainty can be captured by independent random shock to \(mc_t\) and \(u_t\),\(^5\) optimal emission and bank paths can be approximated to their certainty equivalent paths after making \(r = r_f + \rho\) (where \(r_f\) is the risk-free rate and \(\rho\) is the risk premium specific to holding allowances) and including a carry-over (or inventory) at the end of the banking period.

As explained by Schennach (2000), under the presence of uncertainty prices are still expected to rise at the discount rate \(r\) during most of the banking period. When firms approach the end of the banking program, however, prices are expected to rise at a lower rate because the probability that they hit (or fall below) the optimal carry-over level in the next year is no longer zero.\(^6\)

### 2.2 Numerical simulations

Equation (4) allows us now to simulate (certainty equivalent) optimal banking paths for different parameters values. All of the terms in (4), except \(r\), \(\chi\) and \(\tau\) are known or can be reasonably estimated from observed data. For the allowance allocations \(a_1\) and \(a_2\) we annualize the total number of allowances allocated during each phase to obtain \(a_1 = 7.62\) million allowances and \(a_2 = 9.94\) million allowances.\(^7\) \(T = 5\) by design. Initial counterfactual emissions for units affected in Phase I only \((u_0')\) and for all Title IV units \((u_0)\) can be observed for the units entering in Phase II and closely estimated for the units first affected in 1995 based on heat input in the initial year and observed emission rates

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\(^4\) We study this type of uncertainty in Section 4. In our model, the effect of this uncertainty can be captured by assuming that firms had to make irreversible investments before the true values of either \(u_0\), \(\alpha\) or both were revealed.

\(^5\) In particular we assume that \(u_t = u_0e^{\theta t} + \eta_t\) and \(mc_t = (\alpha + \eta_t)q_t^\gamma\), where \(\theta_t\) and \(\eta_t\) are i.i.d., \(E[\theta_t] = E[\eta_t] = 0\), \(E[\theta_t^2] > 0\) and \(E[\eta_t^2] > 0\).

\(^6\) Note also by including a carry-over at the end of the banking period the certainty equivalent emissions path increases and gets closer to the true expected emissions path (see Schennach, 2000).

\(^7\) See Ellerman et al. (2000) for detail on allowance allocations.
shortly before 1995. Based on Ellerman et al. (2000) we assume \( u_0' = 9.07 \) and \( u_0 = 15.79 \). Based on EPA’s forecast study (Pechan, 1995) and EPRI (1995) we assume that the rate of growth of these counterfactual emissions is \( g = 0.65\% \). Finally, \( (\alpha_1/\alpha_2)^{1/\gamma} \) was obtained from reduction data in 2000. Since all units faced the same allowance price in 2000, \( (\alpha_1/\alpha_2)^{1/\gamma} = q_2/q_1 = 1.209 \), where \( q_1 \) and \( q_2 \) are reductions in 2000 from Phase I and all units, respectively.

Given the data above, a discount rate, \( r \), and an estimate of elasticity, \( \gamma \), equation (4) can be solved numerically to determine optimal \( \tau \).\(^8\) Note that to solve for \( \tau \) we just need an estimate of \( r/\gamma \) rather than \( r \) and \( \gamma \) separately. Given \( \tau \) and a representative price along the price paths, the prices and quantities for the optimal banking program corresponding to that discount rate and elasticity assumptions can be computed. For example, Figure 1 shows the price paths for optimal banking programs associated with \( r/\gamma \) of 3\%, 6\% and 10\%, and 15\% (where \( r \) is in nominal terms) and the price of October 2001 is taken as an equilibrium price.\(^10\)

The time \( \tau \) for each discount rate is indicated by the kink in the price path, when prices cease rising at the discount rate and increase at a lower rate characterizing the post-banking period. This rate, which is assumed to be 2\% per annum in Figure 1, would depend upon the rate of increase in counterfactual emissions (0.65\%), the elasticity of the marginal abatement cost curve, and the rate of inflation. As seen in Figure 1, higher discount rates are associated with shorter banking periods, lower initial prices, and greater increases in marginal abatement cost during the banking period.

In this simulation of Title IV, the optimal banking programs associated with \( r/\gamma \) of 15\%, 10\% and 6\% have initial prices of $66, $93, and $122, respectively, and they end during the years 2003, 2004, and 2007, respectively. In the distant future, when all plausible banking programs would have ended, here assumed to be 2007, the price would be the same since the quantity of abatement would be the same regardless of discount

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8 We relax this value later in the paper.
9 We leave for next section the effect of the carry-over at the end of the banking period on the simulation results that we present below.
10 This is equivalent as to consider rates \( r \) of 3\%, 6\% and 10\%, and 15\% and a linear marginal cost (\( \gamma = 1 \)). Note also that to the extent that the October 2001 price ($184) does not represent the true equilibrium, the price paths in Figure 1 will be shifted up or down.
rate. The differing prices for 2007 in Figure 1, from $250 to $265, result from using the October 2001 price, $184, as the point of normalization. If we assumed that the end of 2007 price were known to be $265 and worked backwards, the indicated price for October 2001 would be $185, $184, and $193 for the 6%, 10%, and 15% programs, respectively.

The quantity duals for these optimal banking programs are shown in Figure 2. In this figure, the bold line indicates the quantity of abatement associated with no banking (or alternatively with a very high discount rate). The amount of abatement rises continually within Phases I and II, as a result of the banking and the increase in counterfactual emissions after $\tau$, and there is a large increase of abatement with the start of Phase II. The discount rate is inversely related both to the quantity of abatement during the fixed period of Phase I and to the length of the draw-down period in Phase II.

Yet another way to depict optimal banking programs is to plot the evolution of the end-of-year bank as done in Figure 3. The dots extending only through the end of 2000 is the observed bank and the line that fits the dot series represents the profile of an optimal banking program with $r/\gamma$ equal to 3% (e.g., 3% nominal discount rate and linear marginal cost).¹¹

The size of the accumulated bank at the end of Phase I varies significantly with $r/\gamma$, ranging from 4 million allowances with $r/\gamma=15\%$ to 11.55 million allowances with $r/\gamma=3\%$, very close the actual end-of-Phase I bank of 11.65 million allowances. Moreover, the rate of accumulation during Phase I and the rate of draw-down in the first year of Phase II are very close to what would occur in a 3% program and where the bank is completely drawn-down beyond 2010. Although the latter figure is somehow out of line with current expectations, the fact that there are infinite combinations of $r$ and $\gamma$ for which $r/\gamma=3\%$, in the absence of independent estimates of $r$ and $\gamma$ it is not possible to say a priori whether the evolution of the SO$_2$ bank has been reasonably optimal or not.

¹¹ The year-by-year accumulation of the bank in Phase I is calculated as if the total number of allowances issued for Phase I were issued in five equal annual vintages. In fact, a greater proportion of the total Phase I vintage allowances were distributed during the first two years; however, with a cumulative cap the year-by-year allocation in Phase I would make little difference. For this analysis, the assumption of equal annual installments gives a truer picture of the rate at which the end-of-Phase I bank was accumulated.
3. CAPM Estimate of the SO₂ Discount Rate

All we know at this point about $r$ is that it cannot be lower than the risk-free rate $r_f$; the discount applied to U.S. Treasury notes of maturities comparable to plausible holding periods for allowances. If inventory behavior is assumed to follow a first-in, first-out pattern, most allowances would be held for a period of time ranging from five to 10 years. From the end of 1993 to the end of 2000, the interest rate for U.S. Treasury notes of maturities from five to ten years ranged from low of about 4.5% in late 1998 and early 1999 to a high of around 7.5% in late 1994 and the average yield for notes of 5, 7 and 10 year maturities were 5.97%, 6.06%, and 6.09%, respectively.

Accordingly, if we believe that marginal abatement costs are linear in quantities, i.e., $\gamma = 1$, then the quantity data about banking would indicate that the actual bank is inefficiently big even if $r$ happens to be equal to 6%. If, on the other hand, we believe that marginal abatement costs are rather quadratic, i.e., $\gamma = 2$, then the quantity data would be consistent with an optimal bank if we find that parties banking SO₂ allowances consider them to be as risk-free as a Treasury note. If so, then allowance prices should be increasing in price at an annual rate of about 6%. Figure 4 provides an index of SO₂ allowance prices since August 1994 when trading became sufficient to closely bound price quotes at any given point in time.

It would be possible to select points from this data to yield a 6% rate of increase, or even lower. For instance, the rate of increase from October 1994 until October 2001 is about 3.5%. However, the SO₂ allowance market was very new in 1994-95 and there are substantial reasons to believe that early prices did not fully reflect all the factors bearing on allowance value. Allowance prices experienced an unexpected and pronounced decline during 1995, the first year of Phase I; however, since early 1996, a definite upward trend in prices can be observed, as would be predicted by theory, albeit with a notable deviation in 1998 and 1999.

As explained elsewhere (Ellerman and Montero, 1998; Ellerman et al., 2000), a combination of events—expectations of high prices in the early years when there were no reliable market price indicators, the lead times required for investment decisions in scrubbers and for low-sulfur coal contracts for Phase I affected units, and the
irreversibility of investing and contracting decisions—led to the collapse of SO₂ allowance prices in the first year of Phase I. However, prices did not collapse to zero. A bottom was found, which has not been revisited, that could be interpreted as the lower price level warranted by Title IV’s cumulative constraint on SO₂ emissions once the initial over-commitment to abatement was recognized.

Sufficient time has passed since this initial correction in prices to form an estimate of the return being required by the market for holding allowances. If holding SO₂ allowances is riskier than investing in Treasury bills, the price behavior of SO₂ allowances over time should reveal a discount rate \( r \) higher than 6% to compensate for the extra risk associated with these assets.

To estimate the discount rate of allowances we use the capital asset pricing model (CAPM)

\[ r_a = r_f + \beta_a (r_m - r_f) \]

where \( r_a \) is the expect return (i.e., discount rate) on allowances, \( r_f \) is the return on a risk-free asset (e.g., Treasury bill), \( r_m \) is the expected return on the market portfolio and \( \beta_a = \sigma_{am}/\sigma_m^2 \), where \( \sigma_{am} \) is the covariance between the allowance return \( r_a \) and the market return \( r_m \) and \( \sigma_m^2 \) is the variance of the market return.

We estimate \( \beta_a \) using allowance and market data from January 1996 through 2000. We use monthly returns based on end-of-the-month quotes. For allowances we use price data from Fieldston (EATX/SOPI) and for the market we use different stock market indexes. Statistical results, which are in Table 1, indicate that in all cases \( \beta_a \) is not significantly different from zero. As a further test, we estimate \( \beta_a \) for a series of shorter periods of time using the three stock indexes combined. Results, which are in Table 2, indicate again that \( \beta_a \) is not significantly different from zero. These results provide strong evidence that investors treat allowances as risk-free assets.

\[ 12 \] While over a long period of time the market risk premium, i.e., \( r_m - r_f \), has averaged 8.4% a year (Brealy and Myers, 1991), today it is argued that this value is smaller.
4. **Is the Evolution of the SO$_2$ Bank Optimal?**

Having found that $r = 6\%$, in this section we discuss the optimality of the SO$_2$ bank. Although in equation (4) we do not make any explicit distinction between short-run and long-run marginal cost functions, we introduce such distinction here to address the fact that SO$_2$ abatement is very capital intensive.

4.1 **Long-run equilibrium analysis**

Let us consider first the case in which SO$_2$ abatement is fully reversible so there is no difference between long-run and short-run curves except for the entry of new firms, which has been negligible in the SO$_2$ market. Simulation results in Section 2 indicate that for the SO$_2$ bank to be optimal the marginal cost curve must be quadratic in quantities, i.e., $\gamma = 2$. Previous cost studies indicate that the long-term marginal cost curve is linear, if not slightly concave, for a wide range of values (EPRI 1995, Ellerman et al., 2000).$^{13}$

Based on our best estimates for counterfactual emissions ($u'_0$ and $u_0$), discount rate ($r$) and elasticity ($\gamma$) our results provide evidence for excessive banking from a long-run equilibrium perspective. In this case, the bank at the end of Phase I ($B_T$) should have been only 8.12 million allowances and not 43% bigger (or 11.65 million allowances) as we actually observed. If as a result of periodic random shocks on $u_t$ and $mc$, we add a large carry-over level of 20% (i.e., 2 million allowances) of the annual allocation of 9.97 million allowances, $B_T$ goes up only to 8.64 million. The large bank can only be supported if we (unreasonably) believe that firms are planning to keep an inventory at the end of the banking period around 13.6 million allowances.

4.2 **Short-run equilibrium analysis**

In the real world markets are rarely in long-term equilibrium and firms make irreversible capital investments based on expectations about the future that not

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$^{13}$ Ellerman et al. (2000) found that $\gamma = 1$ for Phase I units in the 0-400 range and EPRI (1995) found that $\gamma = 1$ for all units in the 0-500 range.
necessarily hold true. As discussed by Ellerman et al. (2000, Chapter ), this situation has been particularly notorious in the SO₂ program as firms had to make long-lived investments in abatement technologies and some long-term fuel commitments well in advance of the first compliance year (i.e., 1995) when future allowance prices and abatement costs were still uncertain. In 1993, these irreversible investments seemed economical because allowances prices were expected to be in the 250-300 range; well above their actual levels. Because of the unexpected availability of cheaper low sulfur coal from PRB (Ellerman and Montero, 1998), allowance prices turned out to be much lower than expected and many of the irreversible investment made by Phase I utilities in 1993 looked uneconomical ex-post.\(^{14}\)

As a result, the changes in quantity of abatement that we observe reflects movements along a more inelastic, short-run cost function than the unrestricted, and implicitly fully reversible long-run, cost function that we have used in our analysis so far. As illustrated in Figure 5, standards production theory suggests that when there is over investment prices and quantities move along a steep short-run marginal cost curve \((\gamma > 1)\) until prices reach some critical value \(P_c\) after which becomes optimal to install new capital according to the long-run marginal cost curve \((\gamma = 1)\).

Although equation (4) does not make any distinction between short-run and long run cost functions, it is easy to adjust our model (see the appendix) to simulate ex-post optimal banking programs for a given short-run marginal cost (i.e., \(\alpha_{\text{SR}}\) and \(\gamma_{\text{SR}}\)) and a critical price \(P_c\). The long-run curve is still assumed linear, i.e., \(\gamma_{\text{LR}} = 1\), although its slope may be lower (or higher) after the initial cost and price uncertainty was resolved. The short-run curve was estimated by regressing average annual prices on aggregate reduction during Phase I.\(^{15}\) Actual prices and fitted marginal cost curves are presented in Figure 6. The best fit is obtained for \(\alpha_{\text{SR}} = 1\) (imposed) and \(\gamma_{\text{SR}} = 3.55\) (see fitted MC). If we do not impose any constraint \(\alpha_{\text{SR}} = 0.24\) (although not significantly different from 1) and \(\gamma_{\text{SR}} = 4.59\) (see fitted MC (2)).

\(^{14}\) In terms of our model, \(u_o\) and \(\alpha_i\) revealed to be much lower than expected after the SO₂ started.

\(^{15}\) The price series is 83.67, 100.08, 128.5, 159.42 and 198.75 and the emissions reduction series is 3.74, 3.74, 3.80, 3.98 and 4.39.
Using the cost parameters that best fit the data and different values of $P_c$ varying from 200 to 300 we can now compare the actual bank to ex-post optimal banking programs.\(^{16}\) Results are in Figure 7. For $P_c = 250$, for example, the size of the optimal bank at the end of Phase I ($B_T$) is 12.29 million allowances, which is only 5.5% bigger than the actual bank at that moment. Although a $P_c$ in the 250-300 range may seem appropriate because reflects the (expected) price that made the last irreversible investments economical before the SO2 program started in 1995, we believe from recent announcements to bring online new scrubbers that $P_c$ is rather close to $200.\(^{17}\) If so, Figure 7 shows that the actual SO2 is remarkably close to an ex-post optimal banking program. In fact, $B_T$ is 11.66 million allowances for $P_c = 200$; identical to the size of the actual bank of 11.65 million allowances. Furthermore, this optimal ex-post bank ends in 2009, which again is consistent with current expectations.\(^{18}\)

The results presented in Figure 7 do not change much if we relax some of the values used for the cost and unrestricted emissions parameters and add a reasonable carry-over level at the end of the banking period $\tau$. For simplicity let us focus on changes in $B_T$.\(^{19}\) For example, if we let $\gamma^\text{SR}$ take the lower and upper values of the 95% confidence interval, 3.4 and 3.7 respectively, $B_T$ becomes 12.24 and 11.07, respectively. If instead we use the alternative fitted marginal cost curve depicted in Figure 6 and let $\alpha^\text{SR}_1 = 0.24$ and $\gamma^\text{SR} = 4.59$, $B_T$ becomes 11.80. If we vary the growth rate of counterfactual emissions $g$ between 0.15% and 1.5%, $B_T$ varies from 10.89 to 12.20. Finally, we can study the effect of uncertainty by assuming different carry-over levels. If, as before, we assume a 20% carry-over level, $B_T$ increases to 11.89. Because these sensitivity analysis show that the actual and optimal bank paths do not differ in more than 5%, our analysis provide strong evidence on the (ex-post) optimality of the SO2 bank.

\(^{16}\) Note that we still assume that $\gamma_1 = \gamma_2$ and $(\alpha_1/\alpha_2)^{\gamma_1} = 1.209$ for either the short-run or long-run curves.

\(^{17}\) [Add note with recent announcements].

\(^{18}\) If we assume instead that the growth rate of counterfactual emissions is either $g = 1\%$ or $0.2\%$, results barely change. In the first case, the optimal bank at the end of Phase I increases only to 11.94 million allowances and it ends one year sooner in 2008. In the second case, i.e., $g = 0.2\%$, the optimal bank at the end of Phase I decreases to 11.36 million allowances and it ends in 2009.

\(^{19}\) Because banking paths do not cross the biggest differences in absolute terms occur at $T$. 

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5. Discussion and Concluding Comments

The U.S. Acid Rain Program has become justifiably famous for its provisions concerning both spatial and temporal emissions trading. The owners of affected units have made abundant use of both provisions. In this paper we have evaluated the intertemporal dimension of the allowance market. We develop a model of an optimal banking program which we test using readily available data on prices and quantities (i.e., emissions). Based on reasonable assumptions concerning the curvature of the aggregate abatement cost functions and the evolution of counterfactual emissions, we find that the evolution of the bank appears to be largely inefficient from an ex-ante perspective. We argue that had agents correctly predicted allowance prices at the time they committed to irreversible investments, the size of the (ex-ante) optimal bank at the end of Phase I should have been 8.12 million allowances vis-à-vis the 11.65 million allowances actually observed.

In the real world, however, markets are rarely in long-term equilibrium and firms make irreversible capital investments based on expectations about the future that not necessarily hold true. Because this situation has been particularly notorious in the SO2 program as firms had to make long-lived investments in abatement technologies and some long-term fuel commitments well in advance of compliance when future allowance prices and abatement costs were uncertain, we also develop a model of an ex-post optimal banking program given a certain amount of capital in place. Using readily available data on prices and quantities we find that the actual SO2 bank is remarkably close to an ex-post optimal bank; result that is robust to changes in parameters values.

One can argue that an (ex-post) efficient SO2 bank does not necessarily implies that the overall SO2 market is efficient in the sense that there may be some firms that are not participating in the market. Although it is difficult to support this claim based on the broad market participation documented by Joskow et al. (1998) and Ellerman et al. (2000), it remains a possibility since by construction the aggregate cost curves in our models do not need to coincide with the least-cost curves. However, Montero (2002) demonstrates that less than full market participation is inconsistent with optimal banking if for at least one of the non-participating firms occurs that either its own discount rate is
different than the market discount rate \((r)\) or the end of its own banking program differs from the end of the “market” bank \((\tau)\).\(^{20}\) Because the latter condition holds when counterfactual emissions are heterogeneous across firms, as occur in the SO\(_2\) program (Ellerman et al. 2000), we argue that our analysis not only provides evidence of an efficient bank but also of an overall efficient SO\(_2\) market.

**References**


\(^{20}\) If the latter, Montero (2002) shows that the path of the observed bank is always above the path of the optimal path during the built-up period.


Montero, J.-.P. (2002), Testing efficiency in an emissions permits market, mimeo, MIT.


APPENDIX

In this appendix we provide the solution to the ex-post optimal banking program, which is relevant when the optimal amount of capital invested ex-ante $K_{EA}$ is higher than the optimal amount of capital that to be invested ex-post (i.e., after the uncertainty about prices was resolved).

Let $\alpha^j_{SR}$ and $\gamma^j_{SR}$ be the cost parameters of the short-run marginal cost curve during phase $j = 1, 2$ for an amount of capital $K_{EA}$; $\alpha^j_{LR}$ and $\gamma^j_{LR}$ the cost parameters of the long-run marginal cost curve during phase $j = 1, 2$ (as before I assume that $\gamma^1_{SR} = \gamma^2_{SR} = \gamma^R_{SR}$ and $\gamma^1_{LR} = \gamma^2_{LR} = \gamma^R_{LR}$); and $t_c$ the critical time at which becomes optimal to install new capital ex-post (in terms of figure 6 this is the time at which the allowance prices reach $P_c$). I assume that $t_c > T$.

Following the same steps as in Section 2, the optimal evolution of emission reductions is

\[
q_t = \begin{cases} 
\left( \frac{\alpha^2_{LR}}{\alpha^1_{SR}} \right)^{1/\gamma^R_{SR}} q_t \gamma^R_{SR} e^{-r(t-t_c)} & \text{if } 0 \leq t \leq T \\
\left( \frac{\alpha^2_{LR}}{\alpha^2_{SR}} \right)^{1/\gamma^R_{SR}} q_t \gamma^R_{SR} e^{-r(t-t_c)} & \text{if } T < t \leq t_c \\
q_t e^{-r(t-t_c)} & \text{if } t_c < t \leq \tau 
\end{cases}
\]

where $\tau$ is the end of the banking period and $q_\tau = u_0 e^{g \tau} - a_2$ is the corresponding amount of abatement. Plugging (A1) into (2), we can obtain an expression similar to (4) that solves $\tau$. 

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FIGURE 3

Optimal banking programs

Million Allowances

Year

1995 1997 1999 2001 2003 2005 2007 2009 2011 2013 2015

FIGURE 4

SO2 Allowance Prices, 1994-2001

(Current Vintage)
FIGURE 5

Ex-post Marginal Cost Curve

$/q

\[ LRMC, SRMC \]

\[ \gamma = 1 \]

\[ \gamma > 1 \]

FIGURE 6

Phase 1 Short Run Marginal Cost

Reductions (million tons)

nominal values

- actual price
- fitted MC
- lower 95%
- upper 95%
- fitted MC (2)
FIGURE 7

Optimal Banking with Irreversibility

- Act Bank
- Bank\(\text{Pc} = 200\)
- Bank\(\text{Pc} = 250\)
- Bank\(\text{Pc} = 300\)
Table 1. Beta for Allowances (βₐ)

<table>
<thead>
<tr>
<th>Market Index</th>
<th>Coefficient</th>
<th>Standard Error</th>
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<tbody>
<tr>
<td>NYSE</td>
<td>-0.215</td>
<td>0.297</td>
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<tr>
<td>AMEX</td>
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<td>0.244</td>
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<td>NYSE&amp;AMEX</td>
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<td>0.298</td>
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<tr>
<td>NASDAQ</td>
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<tr>
<td>NYSE&amp;AMEX&amp;NASDAQ</td>
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<td>0.261</td>
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</tbody>
</table>

Notes: 60 Observations

Table 2. βₐ for different periods

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<tr>
<td>Jul 94-Jun 96</td>
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<td>Jan 95-Dec 96</td>
<td>-0.213</td>
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<td>Jul 95-Jun 97</td>
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