EFFICIENCY LOSS AND TRADABLE PERMITS

by

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Introduction

Theoretically, using incentive-based policies, such as a tradable permit system, for pollution control has been shown to be cost-effective (Baumol and Oates, 1988). A series of empirical studies have indicated that substantial cost-savings could be achieved by implementing a tradable permits system. (e.g. Atkinson and Lewis 1971; Maloney, and Yandle 1984; Krupnik 1986; Johnson and Pekelney 1996). Atkinson and Titenberg (1991), on the other hand, pointed out that actual savings from trading programs might be lower than expected due to a sequential and bilateral trading process and non-uniformly mixed pollutants. Burtraw, Harrison and Turner (1998) argued that divergence between the cost-minimizing and the observed pattern of permit trading may be due to the informal structure of many trading programs, incomplete assignation of permits and uncertainty of the trading program length. One added advantage of using tradable permits is that any initial misallocation of pollution permits can be remedied through trading. In the case of perfect competition and full information, initial allocation of permits has no role in the market equilibrium formation and the same environmental goal can be achieved under any allocation as long as the total number of permits issued remains the same (Montgomery 1972).

Beside the actual trading costs, preliminary works for establishing a trading program may also increase the cost of permit trading. For example, a new program requires agreement on (1) the universe of covered sources, (2) baseline emission levels, (3) the emissions cap and planned rate of decline, (4) the allocation of emission allowances and (5) standardize monitoring and measurement techniques for determining each source’s emissions. These administration costs may be substantial when the number of affected sources is large. Experience with the Regional Clean Air Incentives Market (RECLAIM) and the Acid Rain program shows that obtaining the agreement on these points can take several years.

Another factor that may also reduce the potential cost-saving of permit systems is the indivisibility and irreversibility of investment on control equipment. This factor is largely neglected in the permit trading literature. Usually, emissions can be reduced by using less polluting inputs, cleaning up after emission is generated at the end-of-the-pipe or installing better and cleaner technologies which lower emissions during the production process. For some equipments, the amount of pollution reduction depends only on the control capacity of that equipment and firms’ actual pollution level. Once the equipment has been installed, it will always perform at a constant removing rate without incurring extra operating costs as long as the emission levels are within the capacity range. That is, firms’ actual emission reduction levels depend on their pollution levels and pre-determined equipment capacity (or size). Firms' decisions on whether adopting a control equipment and how much the capacity of the equipment should be are the key factors determining the amount of pollution reduction. However, the control capacity of an equipment may not always be divisible (continuous). In reality firms can adopt a control equipment with appropriate size that closely matches their quantity of pollution and environmental standards. Therefore, when the amount of reduced emission from the installed equipment exceeds the standard, the trading market will be in excess supply of permits. The efficiency loss from offering too many permits than needed may result from over investment on equipment (or discontinuity of control capacity). Using the Kaohsiung and Pingtung county as an example, the major base for heavy industries in Taiwan, this study tries to estimate the possible efficiency loss that may arise from over investment on control equipment if a permit trading system was used to regulate Nitrogen Dioxide (NO_x) emissions in this area.

The efficiency loss may be substantial in a trading market for NO_x control. The costs of NO_x control technologis can be categorized into two groups, namely capital-based and control-based. Cichanowicz et. al. (1991) indicated that the cost associated with the use of a *Low* NO_x *Burner* (LNB) may comprise 95% to 99% capital and 1% to 5% operating and management expenses. Firms cannot adjust their emission reduction levels once a certain size of LNB has been adopted. On the contrary, *Selective Catalytic Recircular* (SCR) -another equipment often used for NO_x control, would be approximately 40% to 50% capital and 50% to 60% operating and maintaining expense. When SCR is installed, firms are allowed to adjust their emission reduction levels through switching catalyst as long as the emission levels are within the SCR's control capacity. That is, pollution can be further reduced by paying higher variable costs. Even though the control efficiency and flexibility of SCR is higher than LNB, high installing and operating costs of SCR have limited their use only to certain industries (such as petroleum refinery).

Technology adoption is an important decision variable for firms. The cost per unit abatement depends largely on the extent to which the emission control equipments are utilized. Thus, the costs per unit of abatement are determined endogenously and simultaneously with technology adoption, equipment utilization, and permit buy/sell decisions. The fixed cost issue was not properly dealt with in the permit trading literature. Most studies used the marginal analysis approach, that incorporates a constant variable cost (including the operating costs and annualized fixed costs) for each permit unit, assuming that firms can control the amount of pollution reduction. However, when a particular technology is not used with its full potential or the life of the permit trading program is shorter than the lifetime of emission reducing devices installed, the traditional marginal cost approach would underestimate both the cost and the market price of permits. Hence, they tend to underestimate the costs of abatement faced by firms and overstate the cost-savings resulting from permit trading programs. If an emission reduction technology (or equipment) is expensive, many firms would opt to buy emission permits rather than install that technology unless the equipment has a long lifetime.

This study presents a methodology that incorporates the independent, optimizing behavior of individual participants of a new trading market in Taiwan. To accomplish this objective, a price endogenous dynamic mathematical programming model will be developed that simulates the firms' behavior and determines the efficiency loss, optimal technology adoption and permit trading decisions.

KPERMS - Background

Kaohsiung and Pingtung county is the main area where the electric and gas, paper, fabric and metal, manufacturing, petroleum refining and chemicals industries are concentrated. Its booming industrial activities in the past 20 years have made the county a major base for Taiwan's industrial development. However, the emission of NO_x from these highly polluted industries has often caused the air quality fail to meet the standards and lead to serious health damages. As opposed to the early days' command and control policy, Taiwan has adopted an incentive-based instrument to revise the air pollution control regulations in recent years. For example, an air pollution fee was introduced in 1995 to ensure that air quality in Taiwan can reach a comparable level to that of developed nations. In addition, the Environmental Protection Administration (EPA) of Taiwan has further promulgated that, in 2007 Kaohsiung-Pintung area will launch the first tradable permit system for NO_x control. The program is so called the Kaohsiung-Pintung emission reduction market system (KPERMS).

The EPA plans to set gradually tightening emission standards and continues to promote improvement of air quality through KPERMS. However, the affected sources are very concerned about the new trading program. This is because improved emission reduction technologies are sometimes very expensive to install[1] and are typically lumpy or indivisible. Thus, no contentious agreement has been made so far about the details of KPERMS such as the target reduction levels, duration of permits and extension to which firms should be included in the program.

Even though the draft of KPERMS has not been finalized, it is natural to assume that this program will follow the features of the existing programs such as RECLAIM and Acid Rain Program. Thus, in this study we assume that the future trading program

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[1] Chu (1998) present examples with installation costs over one million $US.

will also be a “cap and trade” regime and the “grandfathering” rule will be used for initial permit allocation. We assume that each firm will be required to reduce its emission by 10% of its baseline, which is determined by the firms’ NO_x emission levels in the year 2000, Each permit, called *Emission Reduction Credit* (ERC), gives the firm the right to emit one ton of NO_x. When the firm’s actual emission is lower than the initial permit allocation or the emission reduction is greater than the required amount, the firm is allowed to sell the unused permits. Unused permits cannot be banked for future use to prevent the possibility of a hot spot problem in this area. In order to lower possible transaction costs and to avoid monopoly, we further assume that mandatory participants of this system are those firms with historical annual NO_x emissions of 5 tons or above. Smaller firms that are excluded from KPERMS will be regulated under the current air pollution fee system.

The Model

In order to determine an efficient technology adoption and trading pattern, a mixed-integer programming model is developed. The model reflects the perspective of a social planner who wants to achieve the targeted emission reduction levels in the most economical way. The objective of the social planner’s model is to minimize the total emission control cost, including variable costs of technology use and fixed costs of installing equipments, by all firms. Each firm can either choose to install an expensive but more efficient technology to comply with its emission reduction requirement and sell excess permits or buy required permits from other participants in the market. The model assumes that all these decisions are controlled by the social planner who has full information about the individual producers’ cost structure. This means implicitly that all participants cooperate among themselves and with the social planner to adopt the socially optimum solution. Clearly this is not a true representation of the reality, but the purpose here is to determine a socially optimum solution which provides a benchmark against other alternatives.

A mathematical representation of the social planner’s model is given as follows:

$$\text{Min`} \quad \sum_F \sum_Y \sum_T \delta^Y (v\cos t_T \cdot USE_{FYT} + f\cos t_T \cdot D_{FYT}) \qquad (1)$$

such that**:**

$$BUY_{FY} + \sum_T D_{FTY} \cdot emis_{FT} \cdot baseline_{FY} = SELL_{FY} + SURPLUS_{FY} + emis\lim_{FY}$$

for all F, Y (2)

$$\sum_F BUY_{FY} = \sum_F SELL_{FY} \quad \text{for all } Y \qquad (3)$$

$$\sum_y D_{FYT} \le 1 \quad \text{for all } F \text{ and } T \qquad (4)$$

The notation used in the model is described below:

F, T, N, Y denote firm, technology, length of the planning horizon, and year, respectively; δ is the discount factor;

$f\cos t_T$ is the fixed cost of installing technology *T;*

$v\cos t_{FT}$ is the variable cost of installing technology *T* by firm *F;*

USE_{FTY} is the utilization rate of technology *T* by firm *F* in year *Y;*

BUY_{FY} and $SELL_{FY}$, are the amounts of ERCs bought and sold by firm *F* in year *Y;*

$SURPLUS_{FY}$ is the amount of ERCs that cannot be sold (or expired) by firm *F* in year *Y*;

$emis\lim_{FY}$ is the required reduction of NO_x by firm *F* in year *Y*;

$emis_{FT}$ is the NO_x reduction if technology *T* is used by firm *F;*

$baseline_F$ is the baseline emission level of firm *F*;

D_{FYT} is a binary variable indicating whether or not technology T is adopted by firm F in year T;

USE_{FTY}, BUY_{FY}, $SELL_{FY}$ and $SURPLUS_{FY}$ are all variable that are greater than or equal to zero.

The objective function (1) represents the total cost of emission control. The first term in the summation is the total variable cost resulting from the use of all technologies adopted by the firms, while the second term represents the total fixed cost of installing required equipments during the planning horizon. Variable costs are defined as costs per ton of pollution reduction. It is determined by each firm's utilization rate of a given technology and depends on the efficiency of that technology which may vary from firm to firm. Firms will incur no variable costs when LNB is installed. The fixed cost involves annualized fixed costs assuming that most producers would finance expensive equipments through bank loans and pay the total cost in partial installments. Emission control equipments are durables and can be used beyond the planning horizon. To reflect the cost and benefit situation during the planning horizon, annual costs are incorporated in the model. Note, however, that annualized fixed costs would be incurred throughout the entire planning horizon once equipments are installed. The parameter $emis_{FT}$ measures the abatement efficiency defined as the percentage emission reduction provided by technology *T* for firm F.

Equation (2) regulates the annual emission level for each firm. It means that at the end of each year, in order to satisfy the EPA's regulation, each firm must have enough ERCs in hand to match its seasonal emission level. ERCs can be generated by installing cleaner technology or by purchasing through market transactions. These two sources on the left hand side of (2) constitute the supply side of ERCs. The permits generated thereby can either be used to fulfill the required reduction, or sold to other firms. However, unsold permits may create an excess supply in the market which is captured by the variable $SURPLUS_{FY}$. When $SURPLUS_{FY}$ equals zero, then the trading market will be in equilibrium (or cleared). If $SURPLUS_{FY} \succ 0$ this implies that the environmental quality is over achieved. This is because firms may have generated more ERCs than needed. Since firms cannot adjust their emission reduction level once LNB is chosen, the model may not be solved without adding this variable. For any firm, it includes the amount of ERCs sold and used by the firm to cover the required emission reduction by the EPA.

Equation (3) implies that the total buy and sell of ERCs have to be balanced. However, this equation is unlike the equilibrium constraint employed in the permit trading studies presented in the literature. It can only be interpreted as an equilibrium constraint if the variable $SURPLUS_{FY}$ in equation (2) is zero.

Equation (4) is a technical constraint which ensures that each technology can be installed only once during the planning horizon. Once an equipment is adopted it can be used for the remaining years.

Data:

The database required in the social planner's model, including total emissions in the year 2000 for the projected KPERMS participants, technical description of the KPERMS sources and control efficiency of add-on control technologies available to these sources, is provided by the EPA. The emissions data set covers 42 firms which account for approximately 52% of the region's NO_X emissions from point sources. Since the actual total emission level in the entire Kaoshiung-Pingtung county is about two times higher than the value used in this study (due to the unavailable data for excluded firms), the minimum total cost of the program will be extrapolated to determine the total cost for the entire area.

Other cost and engineering data used in the simulation come from engineering studies by the EPA. KPERMS is assumed to be a 5-year program, therefore using the same baseline emission level to project future actual emissions may not be fully representative. In the simulations we used the past emission records to estimate potential emissions for the period 2007-2011. Since each firms' past emission records show no certain upward or downward trend, we assumed that the actual emission levels in the planning horizon would follow a uniform distribution whose lower and upper bounds are the extreme values observed during 1995-2000.

According to the EPA's technical report (1998), LNB is considered as the best available control technology for power generation, paper, petroleum refining and chemical industries. SCR, on the other hand, is the most cost-effective equipment for steel and some petroleum refining industries compared with other add-on control equipment. Therefore, this study assumes LNB and SCR as the only add-on[2] equipments that will be used by the firms. Based on each firm's size and emission records, the available size of LNB or SCR is determined up front. Thus, firms only have to make Yes/No decisions on technology adoption. The total cost of these control systems includes fixed costs and variable costs. Fixed costs are the costs of purchasing and installing equipment and are defined as total capital investment costs by the EPA's NO_x control cost manual (1998). Variable costs incorporate the required labor and fuel costs for running the machine. A capital recovery factor (CRF)[3] with a 6 percent interest rate and 10-year machine life is used to calculate the annualized fixed and variable costs.

Results

Two scenarios are considered in the simulation. The first scenario assumes that the actual emission levels for firms in the 5-year planning horizon, i.e. 2007-2011, are the same as their year 2000 baseline emissions. The second scenario assumes that the actual emission levels will vary and are estimated using the previous emission records. Besides the 10% reduction rule from the baseline level, we further simulate a condition in which 20% reduction is required in both scenarios. The purpose of the 20% reduction rule is to evaluate the economic cost of a more stringent environmental standard.

In the first scenario where the emission level is stable and the 10% reduction rules is applied, about 10,184 units of ERC (9 % of the total ERCs issued by the EPA) would be traded each year. Most KPERMS participants would be buyers in the market. Only two firms, Taiwan Power and Taiwan Plastic companies, would adopt new control equipment and become the only suppliers in the market. Both of these firms would install LNB for NO_x Control. However, they would generate more ERCs than the market demand, which leads to an excess supply of 498.1 units of ERC. Since the market is not cleared, the social planner's model would not result in a market equilibrium. Excess supply of permits also implies that the environmental standards are over-achieved. The total discounted abatement cost for the KPERMS over the 5-year planning horizon would be approximately $3.7 million. Since the firms' emission levels, annualized fixed and variable costs are the same during the planning

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[2] "Add-on" systems are equipments installed downstream of an air pollution source to control its emissions.

[3] Capital Recovery Factor = $\frac{r \cdot (1+r)^n}{(1+r)^n - 1}$ where *r* is interest rate and *n* is the use life for each equipment.

Table 1: Results of the Social Planner’s Model in year 1

	10% reduction	20% reduction
Estimated Emission Level (ton)	72,859.3	72,859.3
Required NO_x reduction (ton)	7,285.9	14571.9
Total ERCs issued (ton)	65,573.4	58287.5
No. of ERCs traded (ton)	5,868.7	9274.9
No. of unused ERCs (ton)	498.1	43.2
No. of buyers in the market	42	40
No. of sellers in the market	2	4
No. of firms with technology adoption	2	4
Annual abatement cost (in million)	0.74	1.2

horizon, their behavior were the same through year-1 to year-5. Table 1 presents the simulation result for the first trading season only.

When the required reduction rate is increased to 20%, the excess supply was reduced to only 43.2 tons. Two more firms from petroleum refining industries adopt new control equipments. The trading volume and total annual abatement cost were increased by 58% and 62%. Thus, a more stringent regulation rule on emission would dissipate the excess supply of ERCs.

Applying the 10 % reduction rule in the second scenario, where firms’ actual emission levels were extrapolated based on their historical trends, the volume of traded ERCs was estimated as 17,458 units in the first year, which corresponds to roughly about 27 percent of the total ERCs issued (65,573.4 units). In the first trading season, 20 firms would be permit buyers while the other 24 firms would be sellers in the market. Among those 24 sellers, four firms adopted new technology. The firms

Table 2: Results of the Social Planner's Model (10% reduction)

	Year 1	Year 2	Year 3	Year 4	Year 5	Total
Estimated Emission Level (ton)	97,531.8	84,505.2	82,091.8	82,338.6	96,995.1	443,462.5
Required NO_x reduction (ton)	31,958.4	18,931.7	16,518.4	16,765.2	31,421.7	115,595.4
Total ERCs issued (ton)	65,573.4	65,573.4	65,573.4	65,573.4	65,573.4	327,867.0
No. of ERCs traded (ton)	17,458	9,752.2	15,280.7	16,763.2	13,945.8	73,199.9
No. of unused ERCs (ton)	0	13,652	10,924.6	3,641.1	2,170.7	30,388.4
No. of buyers in the market	24	22	27	28	24	-
No. of sellers in the market	20	22	17	16	20	-
No. of firms with technology adoption	4	4	4	4	4	4
Annual abatement cost (in million)	3.31	3.08	2.91	2.75	2.59	14.64

investing in technology adoption in scenario-1 would again invest in control equipment in this scenario. The other two firms with new technology adoption were also from petroleum refinery and electric generating industries. Since the market is cleared in the first trading season, no firm with technology adoption would face an efficiency loss.

Starting with year-2, some firms would not be able to sell their unused ERCs and the market was not cleared. Since the firms' actual emission levels were determined differently, the unused ERCs were either from firms that adopted new equipment or from firms whose emission levels were lower than their initial ERC allocation levels. The amount of unused ERCs in year-2 was 13,652 tons, which is roughly 21% of the total issued ERCs. The substantial excess supply situation continued in year-3, although not being as severe (10,924 tons) due to the low actual

Table 3: Results of the Social Planner’s Model (20% reduction)

	Year 1	Year 2	Year 3	Year 4	Year 5	Total
Estimated Emission Level (ton)	97,531.8	84,505.2	82,091.8	82,338.6	96,995.1	443,462.5
Required NO_x reduction (ton)	39244.4	26217.7	23804.3	24051.1	38707.6	152,025.1
Total ERCs issued (ton)	58287.5	58287.5	58287.5	58287.5	58287.5	291,437.5
# of ERCs traded (ton)	16175.4	8538.3	12458.5	17265.8	11100.5	65,538.5
# of unused ERCs (ton)	0	6366	3538.6	0	0	9,904.6
# of buyers in the market	24	25	30	29	28	-
# of sellers in the market	20	19	14	15	16	-
# of firms with technology adoption	5	5	5	5	5	5
Annual abatement cost (in million)	4.99	4.61	4.35	4.13	3.91	21.99

emission level by firms, but it was much lower in year-4 and year-5 where 3,600 and 2,200 tons of ERC, respectively, could not be sold. The total abatement cost of the program was about $14.64 million under this scenario. Since the social planner’s model assumes perfect information and full cooperation among the firms, this cost corresponds to the minimum control cost for meeting the required NO_x reduction.

When the 20% rule is applied, the results indicate that the total abatement cost would increase to 22 million (Table 3). However, the total trading volume would be reduced significantly. Compared with the 10% rule, one more firm (in petroleum refining industry) would adopt new control technology (which was SCR) . Due to the higher abatement requirement, excess supply was eliminated except in years two and three. In the remaining years the market was in an equilibrium condition.

The reason for the discrepancy between the findings of previous permit trading studies and this study is the existence of fixed costs associated with equipment installation in the example described here. In this case marginal analysis is not valid, and a large amount of installation cost may be incurred even for a small amount of permits to be generated. Neither the marginal nor the average cost may be equalized across firms. In the particular case of KPERMS, fixed costs constitute an important component of the problem, therefore the initial permit allocation may matter and can be used as a policy tool to improve not only equity among firms but also economic efficiency.

Efficiency Loss

Unused ERCs may be interpreted as an efficiency loss. Such ERCs have two sources - one from firms that adopt new technology and the other from firms with higher initial allocation of permits than their actual emission levels. In this study, we only focus on the unused ERCs that stem from ove- investment of control equipment. Thus, efficiency loss will not be incurred by the firms whose unsold ERCs come from their own initial endowment.

Due to the special features of LNB, the firms cannot fully control the amount of NO_x reduction once the equipment is installed. Thus, some firms may over-comply the reduction target when they cannot sell all of their available permits. The efficiency loss is then defined as the costs of generating those unused ERCs[4]. Table 2 shows that the Taiwan-Power and Taiwan Plastic companies are the two firms that would incur this type of efficiency loss in most cases. When the firms' emission levels were constant and the 20% rule was employed, the total efficiency loss would be smaller because the number of unsold ERCs in this scenario would be small. When the firms' emission levels were extrapolated differently and the 20% rule was used, we found that the total unsold ERCs would be much lower than that in the 10% rule. However, the unsold ERCs in this case come mainly from China Petroleum company that adopts SCR which leads to a large efficiency loss.

The efficiency loss found here is not because of a bilateral trading process and/or insufficient information for finding trading partners, but it is due to not having full control ability of the installed equipment. In order to eliminate the efficiency loss, we further simulate two cases where banking is allowed. In the first case, we assumed that unused ERCs could be banked for one year. In the second case, no limit was imposed on the useful life of ERCs. The simulation results all indicated that extending the ERC life would not lower the efficiency loss. This is because firms adopting new technology were the same with or without banking. Thus, banking would only defer the efficiency loss from one year to another during the planning horizon.

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[4] Efficiency loss is equal to the unit abatement cost (annualized fixed costs of equipment divided by total NO_x reduction.) multiplied by the amount of unused ERCs.

Table 4: Estimated Efficiency Loss (million) under two scenarios

		Year 1	Year 2	Year 3	Year 4	Year 5	Total
Scenario 1- 10%	Taiwan Power(LNB)	0.06		0.06		0.05	0.17
	Taiwan Plastic(LNB)		0.01		0.01		0.02
	Total	0.06	0.01	0.06	0.01	0.05	0.19
Scenario 1- 20%	Taiwan Power(LNB)	0.003		0.003		0.002	0.008
	Taiwan Plastic(LNB)		0.001		0.001		0.002
	Total	0.003	0.001	0.003	0.001	0.002	0.01
Scenario 2 – 10%	Taiwan Power(LNB)		0.63		0.17		0.80
	Taiwan Plastic(LNB)			0.04			0.04
	Total		0.63	0.04	0.17		0.83
Scenario 2 – 20%	China Petroleum(SCR)		1.12				1.12
	Total		1.12				1.12

Incorporating smaller firms into KPERMS might be another solution for the reducing efficiency loss, as this would increase the effective demand. The firms excluded in the trading program analysis here are currently subject to the air pollution fee regulation. If smaller firms can be incorporated in the market, then the relatively smaller demand for ERCs from these firms can successfully reduce the excess ERCs. Therefore, the government may consider a more flexible regime that allows smaller firms to switch conveniently between the permit trading system and the air pollution fee system when the price of those excess permit is lower than the fee they face.

Conclusion

An economic analysis of the KPERMS, which aims at reducing the air pollution in the Kao-shiung and Ping-tung county using a tradable permits system, is presented in this study. Two issues were of particular interest: i) investigate the economic impacts of the program on participating firms, and ii) analyze possible efficiency loss due to indivisibility of technology installation of firms in the permit market. A social planner's model is developed to determine the socially optimum pollution abatement and trading strategy. An important feature that makes this study unique is the incorporation of discrete (binary) decision variables, namely technology adoption decisions, in an optimization model (a mixed integer program) that simulates the firms' decision-making behavior. This characteristic is important because in the case of KPERMS the pollution control equipments are in general expensive and one-time fixed costs constitute an important component of the total costs and hence the firms' decision-making. Therefore, the model is a more realistic representation of the actual decision problem than the conventional modeling approach seen in the permit trading literature where abatement costs involve variable costs only based on the simplifying assumption that once adopted the abatement technologies will be utilized at full capacity. In reality, the average cost of abatement under alternative technology options is endogenously determined depending on the firms' decisions regarding the number of permits generated, purchased or sold or banked, all of which are determined by permit prices over the duration of the emission trading program.

The result shows that when control equipment decisions are indivisible, an efficiency loss may arise due to over-investment. The option of banking unused ERCs to future periods would not eliminate the excess supply in the particular case study (KPERMS) presented here. Rather, it would only defer the efficiency loss to a future period. Whether a more stringent environmental standard can eliminate excess supply and decrease the efficiency loss depends on the number of firms participating in market, the firms' emission levels, available control technologies and required reduction rates. When the number of firms is large and their choices over control equipment vary widely, such losses may disappear and the empirical findings obtained from the discrete analysis presented here would correspond more closely to those that would be obtained from a continuous analysis typically used in the traditional permit trading literature. In that case, the excess supply would diminish and the permit trading market would be close to equilibrium. In reality, each trading market focuses on one pollutant and the best available control equipment for that pollutant usually does not vary much. In that case the firms' behavior in terms of choosing their control equipment would be more or less homogenous. However, even when the number of participants in the permit market is large, the efficiency loss may still occur.

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