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Modelling a mixed system of air pollution fee and tradable permits for controlling nitrogen oxide: a case study of Taiwan*

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A mixed-integer non-linear programming model that minimises the total regulatory costs of controlling nitrogen oxide is used to investigate how a newly proposed permit trading scheme in Taiwan, which incorporates the features of banking and a non-one-to-one trading ratio, may affect firms' emission reduction strategies and permit trading decisions. Compared to the previous regulation where only an air pollution fee is used, the new regulation that requires a reduction in emissions by 10 per cent from the emission level in the year 2000 for a 5 year period will increase the costs by 77 per cent, which is equivalent to US$9.87 million. The design of banking and the increasing returns to scale characteristic of pollution control among firms might lead to an uneven reduction in emissions in each year. Setting a lower reservation rate for banking would, however, help maintain a more stable environmental quality without a significant loss to the government in terms of air pollution fee revenue.

Key words: air pollution fee, banking, mixed-integer non-linear programming, nitrogen oxide, tradable permits.

1. Introduction

A tradable permit system has been widely used in many countries for pollution control (e.g. the Acid Rain Trading Program in the U.S. and the Greenhouse Gas Emission Trading Scheme in the European Union). Theoretically, the system can reach a given environmental target in a cost-effective way under certain assumptions such as full information and zero transaction costs (Montgomery 1972). A series of empirical studies has also indicated that substantial cost savings could be achieved by implementing a tradable permit system (e.g. Atkinson and Lewis 1974; Maloney and Yandle 1984; Krupnik 1986; Johnson and Pekelney 1996). Encouraged by the successful experience of the U.S. Acid Rain Trading Program, the Environmental Protection Agency (EPA) in Taiwan has planned to establish its first permit trading program together with the current air pollution fee regulation in the Kaohsiung and Pingtung counties in Southern Taiwan, the major bases for heavy industries, to reduce nitrogen oxide (NO_x) emissions in the year 2005. By modelling a framework which incorporates the features of the proposed mixed system

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of permit trading and air pollution fees, this study aims to analyse how the regulation may affect firms' emission reductions and permit trading behaviour.

In the past 30 years, various modifications have been made regarding permit trading to meet the needs of control agencies. For example, the design of banking or borrowing has changed firms' behaviour in relation to emission control (e.g. Cronshaw and Kruse 1996; Rubin 1996; Hagem and Westkog 1998; Leiby and Rubin 2001; Phaneuf and Requate 2002). However, to maintain air quality, a discount rate (banking ratio) or a limitation on use over a given lifetime may be applied to the banking permit. In the permit trading system used for NO_x control in the Eastern U.S., the control agency has set up a 'flow control' mechanism which restricts the aggregate level of banking to limit the year-to-year variability in emissions. Under this system, if the total amount of banked emissions by all sources exceeds 10 per cent of the total allowable emissions for the year, a 2-for-1 discount will be applied to the use of the extra banked allowances (Krupnick *et al.* 2000). Similarly, in the Emission Reduction Market System (ERMS) for Volatile Organic Material control adopted in Chicago, the unused permits can only be banked for 1 year (Illinois Environmental Protection Agency 1996).

In addition to banking and borrowing, some studies have focused on emission trading that is not on a one-to-one basis but is governed through exchange or trading ratios determined by spatial factors such as the timing of emissions and the magnitude of wind flows when the pollutant is non-uniformly mixed (e.g. Tietenberg 1995; Ermoliev *et al.* 2000). The ambient permit system (APS) that takes into account the geographical difference in each pollution source is a definite example of such a design. However, the APS cannot be easily adopted for practical use due to the fact that firms need to hold enough permits for each receptor. Since implementing a trading system with spatial considerations is complicated, simplified versions such as a pollution-offset system (e.g. Krupnick *et al.* 1983; McGartland and Oates 1985) and an exchange rate emission trading system are proposed (e.g. Klaassen *et al.* 1994; Forsund and Navdal 1998). However, in the research by Krupnick *et al.* (1983), an exchange rate that considers location effects among firms is set endogenously and is also not easy to use in practical applications. To overcome the implementation difficulty, Krupnick *et al.* (2000) have proposed another exogenously determined exchange rate system based on the mean of the random variable used for meteorological uncertainty. For some areas, such as the Kaohsiung and Pingtung counties in this study where no appropriate probability density function can be applied due to the highly unstable weather conditions, however, the control agency in Taiwan has further simplified the trading ratio system into one in which all transactions take place at the same exchange rate. The rate is set higher than one to maintain air quality. Even if the heterogeneity of the firms' location effect might be overlooked or even overemphasised, what matters is that control agencies could gain ease of implementation. In addition, actual transaction costs will be lower if firms have to participate only in a single market with the same trading ratio as others.

Our review of the literature on location effects under permit trading reveals no literature that emphasises the trading ratio issue mentioned above and which also incorporates the possibility of banking, due to difficulties in modelling. Nor do they offer an operational framework to analyse how the discounted banked permits and the non-one-to-one trading ratio can be designed. This study proposes a conceptual and operational framework by integrating both the design of the banking system and the feature of a non-one-to-one trading ratio.

2. KPERMS – background

The Kaohsiung and Pingtung counties are the main areas where the electricity and gas, paper, fabric and metal, manufacturing, petroleum refining and chemical industries are concentrated. The emission of NO_x from these highly polluting industries has led to serious health damage over the past 20 years. In contrast to the command and control policy adopted in the early days, an air pollution fee was introduced in 1995 to ensure that the air quality in Taiwan could reach a level comparable to that of developed nations. This unit air pollution fee is determined by geographical indicators such as wind, temperature, the amount of rainfall and the adoption or use of certain pre-approved technology. Based on an EPA report (2006), the average annual air pollution fee collected in Taiwan is around \$6.5 million[1] and has become an important financial source for many counties. Around the time the air pollution fee was imposed, NO_x emissions decreased by a significant amount (EPA 2006); however, due to the rapid economic growth in the past 10 years, the annual NO_x emission levels have started to increase and now are around 52 000 tons (Executive Yuan 2006). Thus, the EPA has proposed a new concept referred to as 'total emission control' that tries to control the quantity of NO_x through a tradable permit system. The target of this newly proposed regulation, referred to as the Kaohsiung–Pingtung Emission Reduction Market System (KPERMS), is to reduce NO_x emissions by 10 per cent in each year based on the year 2000 baseline emission levels. Thus, each firm needs to reduce its emissions by at least 10 per cent in each year in accordance with its baseline for the year 2000. When firms fail to sufficiently reduce their emissions, they have to buy permits in the market to fulfil the reduction requirements. If the newly proposed permit trading system can be implemented successfully in this area, the same regulation will be applied to other areas in Taiwan.

KPERMS is not a pure permit trading scheme. Instead, it is a mixed regulatory system. That is, even though firms are allowed to trade emission rights, they still have to pay for the pollution they have emitted. However, the draft of the trading rules (EPA 2002) indicates that firms that are regulated by such

[1] All price-related information used in this study is measured in US dollars.

a mixed system can have a preferential air pollution fee rate for at most five years. The purpose behind incorporating the current air pollution fee is to maintain the revenue for government use, but not to act as a 'trigger price' as suggested by Roberts and Spence (1976) and Pizer (2002) due to the uncertainty of compliance costs among firms. Unlike those 'emission allowance systems' such as the U.S. Acid Rain program and the ERMS, KPERMS is an emission credit system in which firms can only apply for an emission reduction credit (ERC) if the amount of reduced NO_x emissions is higher than the 10 per cent reduction target. Each unit of ERC allows firms to offset 1-ton of NO_x emissions. However, the amount of excess emission reduction needs to be adjusted first through an exchange coefficient which is currently set at 1.2 by the EPA as the amount of ERCs for which firms can apply. For example, if the amount of the reduced NO_x emissions of a firm is 12 tons higher than the 10 per cent target, then it can only apply for 10 units of ERCs after the adjustment. The unused ERCs can be sold or banked for future use, but they can only be kept for 5 years. In addition, each banked ERC needs to be discounted by a reservation coefficient prior to future use. For example, one unit of ERC from the past year can only be used to offset 0.8 tons of NO_x emissions this year under a 0.8 reservation coefficient. The banked ERCs need to be adjusted by the same rate each year. Thus, the longer the ERC has been banked, the smaller the amount of NO_x that it can offset. Currently, no agreement has been reached regarding the value of the reservation rate in the KPERMS draft. For the purposes of the simulation, this study assumes a coefficient of 0.8.

Based on the hearing held by the EPA in 2002 for implementing the KPERMS in the Kaohsiung and Pingtung counties, most firms in this area expressed reservations regarding the mixed system of pollution control. This is not only because permit trading is a new concept for them, but also because the new regulation will require them to further reduce their current emission levels. Furthermore, they only recently experienced a regulatory change from command and control to the air pollution fee in 1995. If the trading system had begun to operate in 2005, this would have meant that the NO_x control policy would have been dramatically changed twice in the past 10 years. Thus, the implementation of the system has been postponed on several occasions and is still uncertain.[2]

3. The model

In order to capture the special features of the KPERMS and determine an efficient technology adoption and trading pattern, a mixed-integer non-linear programming (MINLP) model is developed for the simulation. The model

[2] Based on a telephone interview with a Mr Wu at the EPA, the program could be implemented as early as late 2007.

reflects the perspective of a social planner in achieving the targeted emission reduction levels in the most economical way. The objective of the model of the social planner is to minimise the total regulatory costs of all firms which consist of the emission control and the air pollution fees. Each firm can either choose to reduce its NO_x emissions to comply with its emission reduction requirement and sell excess permits, or else buy the 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 regarding the individual producer's cost structure. This means implicitly that all participants cooperate both with each other and with the social planner in adopting the socially optimal solution. Clearly, this is not a true representation of reality, but the purpose here is to determine a socially optimal solution which provides a benchmark against other alternatives.

When different exchange and reservation coefficients are set to transfer emission reductions and banked permits into real ERCs that can be actually traded in the market, we need to distinguish whether or not ERCs in trading markets are generated in the current year or from previous banking. To accomplish this, we create two separate 'imaginary' markets referred to as the 'fresh' and 'banking' markets for ERC transactions. The fresh market is composed of ERCs generated from the current period, while the banking market is designed only for ERC transactions from previous years. Firms can participate in either market to meet the environmental standards.

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

$$\sum_F \sum_Y \delta^Y \left[TC_F(X_{F,Y})\right] + \sum_F \sum_Y \delta^Y \left[t_F(b_F - X_{F,Y})\right] \qquad (1)$$

subject to

$$D^f_{F,Y} + X_{F,Y} \geq k(S^f_{F,Y} + B^f_{F,Y}) + M^f_{F,Y} \qquad \text{for all } F \text{ and } Y \qquad (2)$$

$$D^b_{F,Y} + r(B^f_{F,Y-1} + B^b_{F,Y-1}) \geq S^b_{F,Y} + B^b_{F,Y} + M^b_{F,Y} \qquad \text{for all } F \text{ and } Y \qquad (3)$$

$$M^f_{F,Y} + M^b_{F,Y} = h_{F,Y} b_{F,Y} \qquad \text{for all } F,\ Y \qquad (4)$$

$$X_{F,Y} - h_{F,Y} b_{F,Y} = U^f_{F,Y} - V^f_{F,Y} \qquad \text{for all } F,\ Y \qquad (5)$$

$$U^f_{F,Y} \leq cZ^f_{F,Y} \qquad \text{for all } F,\ Y \qquad (6)$$

$$V^f_{F,Y} \leq c(1 - Z^f_{F,Y}) \qquad \text{for all } F,\ Y \qquad (7)$$

$$k(S^f_{F,Y} + B^f_{F,Y}) = U^f_{F,Y} \qquad \text{for all } F,\ Y \qquad (8)$$

$$S^f_{F,Y} D^f_{F,Y} = 0 \qquad \text{for all } F,\ Y \qquad (9)$$

$$S^b_{F,Y} D^b_{F,Y} = 0 \qquad \text{for all } F,\ Y \tag{10}$$

$$\sum_F (D^f_{F,Y} + D^b_{F,Y}) = \sum_F (S^f_{F,Y} + S^b_{F,Y}) \qquad \text{for all } Y \tag{11}$$

$$X_{F,Y} \le b_{F,Y} \qquad \text{for all } F,\ Y \tag{12}$$

$$Z^f_{F,Y} = 0, 1 \qquad \text{for all } F,\ Y \tag{13}$$

$$X_{F,Y}, D^f_{F,Y}, D^b_{F,Y}, S^f_{F,Y}, S^b_{F,Y}, B^f_{F,Y}, B^b_{F,Y}, M^f_{F,Y}, M^b_{F,Y}, U^f_{F,Y}, V^b_{F,Y} \ge 0. \tag{14}$$

The notation used in the model is described below:

F and Y denote the firm and the year, respectively; δ is the discount factor, while the upper script f and b associated with the variables denote whether or not the variable is in conjunction with the fresh or banking markets; $X_{F,Y}$ is the amount of reduced pollution by firm F in year Y using the current best available control technology (BACT); $TC_F(X_{F,X})$ is the total cost function of NO_x control by firm F using BACT; t_F is the unit air pollution fee paid currently by firm F in year 2004; $b_{F,Y}$ is the amount of pollution generated by firm F in year Y if no regulation is imposed and can be viewed as the firm's baseline emission level; k and r are the exchange and reservation coefficients set by the EPA; c is an exogenously assigned constant; $D_{F,Y}$, $S_{F,Y}$ and $B_{F,Y}$ are the amounts of ERCs bought, sold and banked, respectively, by firm F in year Y; $M^f_{F,Y}$ and $M^b_{F,Y}$ are the required emission reduction levels set by firms in the artificial fresh and banking market; $M_{F,Y}$ which is the sum of $M^f_{F,Y}$ and $M^b_{F,Y}$ is the required reduction emission level set by the control agency for firm F in year Y; $h_{F,Y}$ is the required reduction ratio set by the EPA; $U_{F,Y}$ and $V_{F,Y}$ are the positive and negative deviation variables used to control firms' ERC buying and selling behaviour; and $Z_{F,Y}$ is a binary variable. All variables written in upper case represent endogenous variables, while those written in lower case are exogenously assigned.

The objective function (1) represents the total regulatory cost of emission control to firms. The first term is the cost resulting from the emissions reduction, while the second term represents the air pollution fee paid by each firm during the planning process. Equations (2) and (3) regulate the annual emission level for each firm in the fresh and banking markets. This means that, at the end of each year, each firm must either reduce its emissions by an adequate amount or have sufficient ERCs on hand to offset the difference between the required and actual NO_x reduction levels in order to satisfy the EPA's regulation. The left-hand side of Equation (2) represents the supply side of ERCs in the fresh market. The emission reduction credits come from the firms' emission reduction activities or from purchases made through market transactions. These two sources determine the possible supply of ERCs. The right-hand side of Equation (2) is the demand side for ERCs. For any firm, it includes the amount of ERCs sold, banked and used by the firm to cover the required emission reduction. If the total supply of ERCs is greater than or equal to the total demand for ERCs, then the overall emission standard will be met. Since the amount of the emission reduction needs to be adjusted first through an exchange coefficient before becoming an ERC, the coefficient k is used to adjust the difference between the emission reduction level and the number of ERCs.

Similar to Equation (2), Equation (3) is the emission constraint for firms in the banking market. The left-hand side of constraint (3) is the sum of ERCs bought, the banked ERCs from the previous trading season, and the banked ERCs directly from the banking market itself. In addition, regardless of whether the banked ERCs are from the previous year or the banking market itself, they need to be adjusted by a reservation coefficient r. A lower value of r implies that less unused ERCs can be carried for future use. The right-hand side of this constraint implies that those banked or bought ERCs in the banking market can be sold or used to meet the required emission reduction level set by a firm. Since firms are free to meet their emission standards in each market, Equation (4) implies that the sum of these two endogenously determined standards needs to satisfy the real government regulatory target.

In Equation (2), the amount of supplied and banked ERCs in the fresh market will only be positive when $X_{F,Y} > h_{F,Y}b_{F,Y}$. However, when a firm has no ERC for sale or banking, it may either not be engaging in any emissions reduction ($X_{F,Y} = 0$) or may only be reducing its emissions by less than the required amount ($X_{F,Y} < h_{F,Y}b_{F,Y}$). Since the model allows firms to freely choose the required reduction levels in each market, constraints (5)–(8) are established to avoid the situation where firms choose a lower emission standard in the fresh market and supply an amount of ERCs that is not in compliance with the KPERMS rules during the problem-solving process. To accomplish this, constraint (5) first defines the gap between the firms' actual emission reductions and the required reduction levels. When the difference $X_{F,Y} - h_{F,Y}b_{F,Y}$ is positive, $U^f_{F,Y} > 0$ and $V^f_{F,Y} = 0$. Conversely, $V^f_{F,Y} \geq 0$ and $U^f_{F,Y} = 0$. Constraints (6) and (7) then restrict the value of these deviation variables to be determined by the product of a constant c and a binary variable ($Z^f_{F,Y}$). When the binary variable $Z^f_{F,Y}$ equals 1, the positive deviation variable ($U^f_{F,Y}$) must be positive, and the negative deviation variable ($V^f_{F,Y}$) must be 0. Therefore, the left-hand side of constraint (5) must be positive. This implies that firms will have ERCs for sale or banking. In other words, when $Z^f_{F,Y}$ is 0, $U^f_{F,Y}$ is 0 and $V^f_{F,Y}$ must be positive. This will lead to the left-hand side of constraint (5) being negative, and will mean that firms' actual emission reduction levels are lower than the required levels and that no ERCs can be generated. Constraint (8) then ensures that when a firm reduces its emission by more than the required amount, it can have the right quantity of ERCs for sale and banking.

Equations (9) and (10) require that firms not act as both buyers and sellers in the same trading market. The purpose in adding this constraint is that it offers more information for solving this complicated MINLP model. However, these two constraints do not rule out the possibility that a firm may play

Table 1 Best available control technology and its average cost function for NO_x reduction

Technology	Industry	Control efficiency (%)	Average cost function for emission reduction ($10 000 per ton)
LNB + OFA	Electricity generation	50	$y = 5.62 \times 10^{-11}x\ 2 - 0.12 \times 10^{-5}x + 6.69 \times 10^{-3}$
SCR	Steel rolling	80	$y = (4.88 \times 10^{-2}) \cdot x^{-0.49}$
	Steel and iron casting	–	–
	Petroleum refining	–	–
LNB	Petrochemicals	35	$y = (2.23 \times 10^{-3}) \cdot x^{-0.367}$
	Others	–	–

LNB, low NO_x burner; OFA, over fire air; SCR, selective catalytic reduction.
Notes: y represents the average abatement costs of reducing x tons of NO_x emissions. Multiplying both sides of the equations by x yields the total cost functions used in the economic model.

different roles in each market. Equation (11) represents the equilibrium constraint for the permit trading market. It requires that the total supply of permits from both markets equal the total demand. Since our model contains binary variables, the shadow price information may or may not be able to represent the equilibrium permit price. The related price issue under a discrete modelling structure will be further explored in the next section. Constraint (12) implies that a firm cannot reduce its emissions below its baseline emission level. Constraint (13) is for binary variable $Z^f_{F,Y}$. The last constraint (14) requires that the endogenous variables be non-negative.

4. Data

The data required in the social planner's model, which includes the total emissions in the year 2000 for the projected KPERMS participants, the technical description of the KPERMS sources (EPA 2001), and the costs of add-on control technologies available to these sources (Table 1), is provided by the EPA (Chu 1998). The emission dataset covers 42 large firms which had emission levels of more than 30 tons of NO_x in 2000.

According to the EPA's technical report (Chu 1998), Low NO_x Burner (LNB) is regarded as the BACT for the electricity-generating, petrochemical, papermaking, cement-manufacturing and fertiliser-producing industries. Selective Catalytic Reduction (SCR), on the other hand, is the most cost-effective equipment for the steel-rolling, steel- and iron-casting and petroleum-refining industries. For the electricity-generating industry, LNB is often used with the 'over-fire air' (OFA) process to increase the efficiency of pollution control. Therefore, this study assumes that LNB, OFA and SCR are the only forms of add-on[3] equipment that will be used by firms. Although the potential cost-saving

[3] 'Add-on' systems refer to equipment installed downstream of an air pollution source to control its emissions.

from permit trading arises due to the heterogeneity of pollution control technologies among firms, the survey in the technical report (Chu 1998) indicates that more than 98 per cent of firms in this area had already adopted LNB, OFA and SCR on some of the existing equipment following the imposition of air pollution fees in the year 1995, combined with the fact that the government had identified the NO_x control equipment as BACT on several occasions and in different publications (e.g. EPA 1996, 2003; Industrial Development Bureau 2002). This gives us reason to believe that the equipment will still be chosen by firms based on cost minimisation considerations. According to the estimated cost functions for LNB, OFA and SCR shown in Table 1, the average abatement costs will tend to decline as more emissions are reduced. That is, firms will face increasing returns to scale (IRTS) with regard to emission controls.

The unit air pollution fee paid by each firm in 2004 in the model is based on a mail survey. This is because the information is confidential for both the EPA and the firms. To increase their willingness to disclose these numbers, firms were only asked to write the average of what they paid in 2004.[4] The average unit air pollution fee obtained from the survey turned out to be \$148.7 per ton, and this ranged between \$77 and \$310 per ton. However, there was no way to test the accuracy of the data.

5. Results

By applying the collected data, this study simulates the firms' emission reduction strategies in KPERMS for five years under a 6 per cent discount rate through the solver SBB, CPLEX and SNOPT offered in the General Algebraic Modelling System (GAMS).[5] The reason for choosing a five-year duration is to avoid the difficulty of modelling a more complicated case where the ERC might have expired. In addition, the capability of the current software for solving the MINLP problem also has its limitations. One thing that needs to be kept in mind is that constraints (9) and (10) give rise to improper convexity in the model. Even though the supplementary information from the solvers' status based on the GAMS may indicate that the model works well, computational problems may still occur when applying this model to other problems with different cost structures, baseline emission levels, trading rules or even the solvers used. In addition, since there is just one firm from each of the food, papermaking, cement-manufacturing and fertiliser-producing industries, they will be categorised under 'other' industries in the following discussion.

[4] In Taiwan, firms need to report their emission levels four times a year. Within a year, they may have different air pollution fee rates depending on factors such as a firm's location or whether or not a clean input such as gas is used for production.

[5] SBB, CPLEX and SNOPT are solvers that can be used for MINLP, mixed integer programming and non-linear programming problems. They were developed by M. Bussieck of GAMS and A. Drud of AKRI Consulting and Development, ILOG and P. Gill University of San Diego, along with W. Murray and M. Saunders at Stanford University.

Table 2 Simulation results with a 1.2 exchange coefficient and 0.8 reservation coefficient

	Year 1	Year 2	Year 3	Year 4	Year 5
Emission level without regulation (tons)	72 618	72 618	72 618	72 618	72 618
Required reduction (tons)	7262	7262	7262	7262	7262
Actual total NO_x reduction (tons)	16 596	5979	7032	7323	8352
Number of traded ERCs (tons)	3741	4164	6323	6296	6342
Total banked ERCs (tons)	7155	3545	1551	203	0
ERC price ($/tons)	28.2	35.2	44.0	55.0	68.8
Total air pollution fee after the regulation ($ million)					4.36
Total regulatory costs ($ million)					9.87

At the 0.8 reservation coefficient, the simulation results (Table 2) reveal a total regulatory cost of $9.87 million. Of this, $4.36 million is for air pollution fees, and $5.51 million is for the NO_x reduction. Firms in the petrochemical and electricity-generating industries play a major role in supplying the ERCs in the market, while most firms in the petroleum-refining, steel-rolling and other industries take on the role of buyers. If, instead of implementing the proposed mixed system, the control agency decides to stick with the current air pollution fee regulation and does not require any NO_x reduction, the total fee expended by firms will be $5.59 million during the five-year planning horizon. Therefore, switching from the current pure fee regulation to the new system will raise the total costs by 77 per cent.

In the first year, it is found that 3741 units of ERCs were traded; however, the amounts of the transactions went up to 4164, 6323, 6296 and 6342 from year 2 to year 5, respectively. On the other hand, the amounts of the banking from year 1 to year 5 were 7155, 3545, 1551, 203 and 0 tons, respectively. Thus, even if the reservation coefficient imposes a penalty on firms with NO_x reductions and banking, the IRTS property of pollution control will still encourage some firms to reduce their emissions by more than the required amount and to bank them for future use. However, zero banking in year 5 may be due to the setting of a five-year planning horizon. The social planner under a trading program with a limited life might ask firms to only generate an 'exact' amount of ERCs for cost minimisation purposes.[6] Although the target NO_x emission reduction level is initially 7262 tons (Table 2), the setting of exchange and reservation coefficients leads to an annual average reduction level of 9056 tons. That is, NO_x emissions are reduced by a further 8970 tons during the five-year planning horizon. While an over-reduction in emissions by firms might be beneficial to the environment, since some of the banked ERCs are withdrawn to offset the emissions, the actual NO_x reduction in some years (such as years 2 and 3 in Table 2) are seen to be below the

[6] One exception is when the unit air pollution fee is set at high levels. Some firms might be willing to reduce emissions more than the required amount and to let those banked ERCs expire at the end of year 5 in order to reduce their air pollution fee expenditure.

required level. This also implies that we should expect worse air quality in these years due to the way in which the bankings are designed.

The shadow price information that is discounted by 6 per cent in each year from the equilibrium constraint in the GAMS indicates that the trading prices from year 1 to year 5 are \$28.2, \$35.2, \$44, \$55 and \$68.8 per ton, respectively. However, these shadow prices may or may not be interpreted as equilibrium prices due to the discontinuity of the model (Gomory and Baumol 1960). To check whether or not these prices can accurately reflect the imputed value of the scarce resource, such as tradable permits in this study, another economic model based on firms' cost minimising behaviour under a perfectly competitive permit market is used. In this model, each firm tries to minimise its own regulatory costs while acting as a permit price taker in the market. The shadow prices derived from the social planner's model are then plugged into the model from the firms' perspective to determine if their behaviour conforms to that required by the social planner. The results of the simulation indicate that the firms behave just as the social planner wanted them to. Therefore, the shadow price reported by the GAMS solver can be interpreted as the equilibrium price, at least in this case. To determine if these prices are affected by discounting the banked ERC, the results of the sensitivity analysis conducted using different reservation coefficients are reported in Table 3. These results indicate that the permit price is relatively stable under a zero reservation rate. When banking is discounted, the prices in general would exhibit an increasing trend from years 1 to 4. If the coefficient is set under 0.7, the price will be over 100 in year 4 and will then drop by a large amount in the last year. This is because some firms (from the petrochemical industry), which originally acted as permit buyers, are now asked by the social planner to reduce their emissions by only a smaller amount to meet a more stringent banking rule, and incur relatively higher regulatory costs under the IRTS characteristic. Thus, we can conclude that the permit prices are very sensitive to the setting of the reservation coefficient.

The results obtained from the sensitivity analysis in Table 3 also show that a reservation rate that is close to 1 will tend to encourage more banking and lower the total regulatory costs. However, it will give rise to a more uneven emission reduction pattern and higher air quality uncertainty. On the other hand, if we lower the reservation coefficient from 1 to 0.5, the total regulatory costs will only be increased by 4 per cent from \$9.7 to \$10.1 million. At the same time, the amount of banked ERCs will decrease by 35 per cent, while the total amount of the reduction in NO_x will increase by 14 per cent due to the change. Larger emission reductions under lower reservation coefficients will also imply better environmental quality and less air pollution fee revenue. However, the results indicate that the fee revenue will only be reduced by 2 per cent. In addition, less banking is accompanied by a more evenly distributed emission control pattern during the five-year planning horizon (Table 3). Therefore, the control agency should consider setting a lower reservation rate to maintain a more stable air quality.

Table 3 Sensitivity analysis

Reservation coefficient	Total regulatory costs ($ million)	Number of traded ERCs (tons)	Total banked ERCs (tons)	Total air pollution fee ($ million)	Actual total NO_x reduction (tons)	Amount of reduction in NO_x (tons) (ERC price)				
						Year 1	Year 2	Year 3	Year 4	Year 5
1	9.70	26 067	15 607	4.39	42 344	16 596	5535*	6149*	7032*	7032*
						(74.6)	(74.6)	(74.6)	(74.6)	(74.6)
0.9	9.79	26 546	13 880	4.37	43 984	16 596	5535*	6987*	7032*	7834
						(31.0)	(34.4)	(38.6)	(42.5)	(47.2)
0.8	9.87	26 866	12 454	4.36	45 282	16 596	5979*	7032*	7323	8352
						(28.2)	(35.2)	(44.0)	(55.0)	(68.8)
0.7	9.94	27 093	11 038	4.34	46 246	16 596	6056*	7323	7728	8543
						(64.3)	(91.8)	(131.2)	(187.4)	(66.8)
0.6	10.01	27 206	10 370	4.33	47 231	16 596	6496*	7520	8076	8543
						(23.0)	(38.3)	(63.8)	(106.4)	(66.9)
0.5	10.1	27 367	10 107	4.32	48 297	16 596	7032*	7970	8155	8543
						(21.8)	(43.6)	(87.1)	(174.3)	(66.8)

ERC, emission reduction credit.
Note: All price information (shown in parentheses) represent discounted prices. * indicates that the actual emission reduction level is lower than the target.

Table 4 Total air pollution fee under various preferential rates

Discount applied to air pollution fee rate	Total regulatory costs ($ million)	Total air pollution fee ($ million)	Actual total NO_x reduction (tons)	Number of traded ERCs (tons)	Total banked ERCs (tons)
0% off	9.87	4.36	45 282	26 866	12 454
20% off	8.99	3.49	45 092	26 829	11 649
40% off	8.12	2.62	45 055	26 824	11 498
60% off	7.25	1.75	44 975	26 719	11 189
80% off	6.37	0.87	44 924	26 858	10 934
100% off	5.5	0	44 924	26 897	10 934

ERC, emission reduction credit.

Table 5 Simulation results based on a one-to-one trading ratio

	Base case	Scenario 1	Scenario 2
Exchange coefficient	1.2	1	1
Reservation coefficient	0.8	1	1
Air pollution fee rate	Year 2004 fee rate	Year 2004 fee rate	0
Total air pollution fee ($ million)	4.36	4.5	0
Total regulatory costs ($ million)	9.87	6.21	1.7
Total required NO_x reduction (tons)	36 309	36 309	36 309
Actual total NO_x reduction (tons)	45 282	36 309	36 309
Number of traded ERCs (tons)	26 866	32 689	32 689
Total banked ERCs (tons)	12 455	0	0

ERC, emission reduction credit.

Based on the current KPERMS draft, we have no information on the preferential fee rate for firms in the program. Thus, we further simulate a case where various preferential air pollution fee rates are applied to the firms when the exchange and reservation coefficients are set at 1.2 and 0.8, respectively. The results (Table 4) show that even when all firms are exempted from any pollution fee (100 per cent off), the difference in terms of the total reduction in emissions in the case where firms pay the year 2004 fee rate is only 357 tons. This implies that the firms' emission reduction behaviour is not affected much by the preferential fee rate that we assumed in the study. In addition, it has almost no impact on the amount of banked ERCs and their corresponding trading volume in the market. However, the total pollution fee revenue will decline sharply by $4.36 million if the mixed system is transferred to a pure permit trading scheme. Therefore, if the control agency wishes to use the fee rate as a tool to encourage a greater reduction in emissions, it should consider differentiating the rate among firms regardless of whether it gets involved in emission control activities.

Lastly, we simulate two other scenarios for comparison purposes (Table 5). In Scenario 1 where both the exchange and reservation coefficients are set to 1, the results indicate that the total regulatory costs will decline to $6.21 million and will be 37 per cent lower than in the case where the exchange and reservation coefficients are 1.2 and 0.8, respectively (the first column in Table 5). In Scenario 2, not only is 1 used for both of these coefficients, but a pure permit trading scheme with no air pollution fee is also assumed. The total regulatory costs in this case decrease only to \$1.7 million. In addition, since no firm has any desire to bank ERCs under either of these scenarios, this implies that a balanced emission reduction pattern is expected. However, the air quality will still fluctuate if ERCs are bought by firms that cause more damage as a result of their emissions. Since the total costs under this one-to-one trading ratio are much lower, the control agency should consider giving up the possible location effects at this moment in time if its major concern is to raise the firms' willingness to accept the new regulatory system.

6. Conclusion

Based on a social planner's perspective of minimising the total regulatory costs for NO_x control, a MINLP model that mixes air pollution fees and permit trading is developed to simulate a newly proposed regulatory scheme in Taiwan. The results indicate that the firms' total costs for NO_x control will be increased by 77 per cent if the regulation is switched from the current air pollution fee to the proposed mixed system, with the exchange and reservation rates being set at 1.2 and 0.8, respectively. Firms in the petrochemical and electricity-generating industries are the major ERC suppliers in the market, while firms in the other industries are the buyers. Although the annual required reduction level is only around 7262 tons, the exchange coefficient used in ERC trading leads to an average reduction level of 9056 tons within a 5 year planning period. However, if firms are allowed to carry more ERCs for future use, the IRTS characteristic of pollution control leads to uneven reduction activities in each year. The situation becomes even more severe when the reservation coefficient is set close to 1. Based on our simulation, a lower reservation coefficient would encourage more emission reduction and lead to a smooth reduction pattern without the government losing too much pollution fee revenue. In addition, the firms' total regulatory costs would only be raised by a relatively small amount under these circumstances. Due to the fact that the environmental quality could be further improved by an over-reduction in NO_x emissions, a lower reservation rate could be set to maintain a more stable air quality.

Compared with the air pollution fee rate, the reservation coefficient used in banking plays a more important role in determining the firms' emission reduction level. Based on the current setting, a change in the fee rate will affect the tax revenue, but will have virtually no impact on the amount of the pollution reduction. Since firms in the petrochemical and electricity-generating industries maintain almost the same emission reduction levels under various air pollution fee rates, the lower fee rates will only benefit those firms that are not committed to any form of pollution control. Therefore, if the objective of the control agency is to obtain a greater reduction in emissions or to encourage firms to use a more efficient control technology, it should then try to use a more differentiated fee rate schedule to encourage the firms to reduce their emissions. For example, lower fee rates can be applied to firms with higher emission reduction levels. Although banking may offer a certain degree of flexibility in regard to controlling emissions, the results of the simulation indicate that this will lead to unstable air quality in our mixed system when a reservation coefficient close to 1 is applied to the unused ERCs at the same time as a-non-one-to-one trading base. On the other hand, setting both the exchange and reservation coefficients to 1 can effectively eliminate the firms' desire to resort to banking even under the assumption of IRTS for emission control (Scenarios 1 and 2). However, the finding of zero banking may be due to the firms' ability to generate ERCs in our dataset. If some large polluting firms can reduce their emissions to zero at one time and supply enough permits through banking for several trading seasons, we should still expect some banking under the IRTS property. Therefore, how environmental quality or firms' emission reduction strategies might be affected by banking permits will depend on the interaction of several factors such as trading rules, the cost structure of emission controls, the firms' baseline emission levels, or whether or not an air pollution fee is also used.

Apart from the policy implications derived from the simulation, this study contributes to the existing permit trading literature by proposing an operational framework that can deal simultaneously with both the exchange rate and the banking of permits. By weighting all the intended goals such as maintaining the current air pollution fee, encouraging greater emission reductions, or achieving a more stable air quality, the control agency can easily find an appropriate combination of the parameters in the model by analysing firms' reactions to the policy changes.

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