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This dissertation addresses three topics on applied microeconomics. First, we investigate issues of market power and tax incidence in the U.S brewing industry. Since alcohol consumption can be addictive, we derive a structural econometric model of addiction from a dynamic oligopoly game. This model identifies the degree of market power in a dynamic setting and allows us to test the hypothesis that federal tax incidence differs from state excise tax. Results indicate that beer producers have a modest market power and an increase in federal excise tax is more effective to reduce consumption than state excise taxes.

Second, we estimate the effect of sulfur dioxide(SO_2) emissions regulations on the productivity growth and opportunity cost of 261 phase I generating units. The Clean Air Act Amendment(CAAA) of 1990 required units to reduce emissions to 2.5 pounds per mmBTU fuel input in the phase I period(1995-99). We calculate Luenberger productivity indicators using directional technology distance function for 209 units in 1990-1999. There is more potential to reduce pure technical inefficiency since it is the main source of inefficiency in phase I period. Productivity declined, but it is not significantly different from the productivity

growth of pre-phase I. So environmental policy is successful to reduce SO_2 emission without sacrificing productivity growth. Opportunity cost declined, but the opportunity cost of scrubber and "other" strategy increase.

Third, we estimate the regulatory effect on strategy choice of 257 phase I units using multinomial logit model. We assume behavioral cost is a function of shadow input prices, output, SO_2 emissions and regulatory variables. Results suggest regulation significantly affect choices. Units located in high-sulfur coal states are more likely to choose scrubber, allowance or "other" strategy through shadow capital price effect. Allowance trade and sales restriction negatively affect allowance, scrubber or fuel switch strategy. Non-private units are more likely to choose allowance strategy while private units are likely to choose less uncertain scrubber and fuel switch. Units subject to stringent local regulation are more likely to choose "other" strategy and scrubber and units with substitution/compensation boilers are more likely to choose allowance and "other" strategies.

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Dong Woon Noh, Author

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Essays on Applied Microeconomics

1. INTRODUCTION

This thesis consistes of three essays. The effective tax policy to reduce the excessive beer consumption is analyzed in the first essay. Actual sales tax rates on beer have declined dramatically over time and are currently well below optimal rates. So the excessive beer consumption derived from inappropriate tax imposes substantial negative externalities on society. Beer industry is characterized by imperfect structure and addictive consumption. So dynamic model is used to analyze the oligopoly pricing behavior and excise tax incidence in the U.S. brewing industry. Primary goal is to determine whether or not the incidence of state and federal taxes differ to reduce the excessive beer consumption. Two-stage simultaneous equation model is used to estimate beer consumption equation and industry supply relation equation for beer industry in 1953-1995.

In the second essay, the extent to which sulfur dioxide(SO_2) emissions regulations affect the productivity growth of phase I electric generating units in 1990-99 period is analyzed. The The Clean Air Act Ammendment(CAAA) of 1990 required phase I generating units to reduce sulfur dioxide(SO_2) emissions to 2.5 pounds of SO_2 emission per million BTU of fuel input during the phase I period(1995-1999). All units chose one compliance strategy to reduce sulfur dioxide(SO_2) emissions. Since the target level of sulfur dioxide(SO_2) emissions reductions was achieved in the first year of phase I period, it seems that the US environmental policy was successful to achieve the policy goal. Directional technology distance function with directional vector of one(g_y=1, g_b=-1, g_x=-1) is used to estimate Luenberger productivity indicator for 209 phase I generating units in 1990-99. The effect of the SO_2 emissions regulations on productivity growth, the opportunity cost of SO_2 emissions regulation and the effect of SO_2 emissions regulation on productivity growth potential are estimated.

The regulatory effect on the choice of compliance strategy is estimated in the third essay. The Clean Air Act Amendments(CAAA) of 1990 introduced market-based emission reduction system. It is expected that the phase I generating units will achieve the least-cost compliance strategy. There were several types of regulation that may affect the sulfur dioxide(SO_2) emissions reduction compliance strategy choice. If the regulatory variables affect the strategy choice, then the least-cost to reduce emission will not be achieved. The generating unit level's data is used since emission regulation was applied to each generating unit. Multinomial logit model is used to estimate the regulatory effect on the compliance strategy choice. Multinomial logit model is appropriate model since all phase I generating units choce one strategy among several available strategies.

2. EXCISE TAXES AND IMPERFECT COMPETITION IN THE U.S BREWING INDUSTRY

2.1 Introduction

Identification of market power and estimation of the tax incidence in imperfectly competitive markets are fundamental issues in the fields of industrial organization and public economics. Since taxes and market power affect consumption, these issues are especially policy relevant in markets where substantial externalities are present. In the market for alcoholic beverages, for example, it is generally accepted that excessive consumption imposes substantial negative externalities on society. In the U.S. brewing industry alone, recent estimates indicate that the external costs of drunk driving and health care were approximately 19.9 billion dollars or $3.31 per gallon of beer [Kenkel (1996)]. This estimate of the external costs of beer drinking is considerably above the current excise tax rate of about $0.83 per gallon.

Most of the recent empirical work on tax incidence in imperfectly competitive markets where externalities are present have been confined to the market for cigarettes. Several studies find evidence that cigarette firms have significant market power in the U.S. and Europe [Barnett et al. (1995), Tremblay and Tremblay (1995a), Delipalla and O'Donnell (2001), and Farr et al. (2001)]. In addition, Barnett et al. (1995) find that the tax burden on U.S. consumers is greater for federal than for state excise taxes on cigarettes. A likely explanation for this result is the presence of bootlegging. That is, since some consumers may be able to avoid a state tax increase by shopping in a neighboring state that has a lower tax rate, it will be difficult for retailers to pass along all of a state tax increase to consumers. In addition, if bootlegging is more costly across federal than state boundaries, then the consumer tax burden will be greater for a federal than for a (single) state tax increase. In any case, this is an interesting result that should motivate further investigation and verification.

Previous research on the market for alcoholic beverages has focused on issues of market power and optimal sales or excise tax rates. Regarding taxes, recent estimates indicate that the optimal sales tax on alcoholic beverages is between 40 and 100 percent [Phelps (1988), Pogue and Sgontz (1989), and Kenkel (1996)].[1] Actual tax rates have declined dramatically over time and are currently well below these optimal rates, however. Kenkel reports that the average tax rate for alcoholic beverages in the U.S. was over 50 percent of the market price (net of taxes) in 1954 and declined to below 25 percent during the 1990s.[2] Figure 1 illustrates that in spite of a 100 percent increase in the federal excise tax rate on beer in 1992, the current real rate is substantially below that of the 1950s. When

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[1] Kenkel generates the 100 percent estimate but also finds that the optimal tax rate would be much lower if consumers were better informed about the health risks of alcohol consumption and if the penalty for drunk driving were increased.

[2] Of course, industry leaders claim that these taxes are excessive and support legislation to reduce taxes on alcoholic beverages. For example, the beer industry supports a bill before the House of Representative (HR 1305) to cut beer excise taxes in half [www.rollbackthebeertax.org/legislation/].

viewed as an average sales tax, total excise taxes on beer were about 55 percent of the market price in 1954 but are only about 28 percent in 1997 [Tremblay (2002)]. The little research that has been done on market power has been confined to the U.S. brewing industry. Most recently, Greer (1998) argues that the brewing industry is oligopolistic, and Tremblay and Tremblay (1995b) find empirical support for the hypothesis that beer producers have market power. To date, however, the issue of tax incidence has not been empirically investigated for alcohol markets.

In this paper, we use a dynamic model to analyze the oligopoly pricing behavior and excise tax incidence in the U.S. brewing industry. Previous empirical studies of tax incidence in imperfectly competitive markets ignore dynamic effects, which is inappropriate for markets for cigarettes and alcohol where addiction is important. Our primary goal is to determine whether or not the Barnett et al. (1995) result, that the incidence of state and federal taxes differ, holds for another industry. The brewing industry is an ideal candidate for such a study because an excise tax can be an effective policy instrument to mitigate the negative exernalities associated with alcohol consumption. In addition, beer consumption is of vital concern, since it accounts for about 88 percent of all alcoholic beverage consumption in the U.S. [*Modern Brewery Age* (1993, 1-2)]. Our empirical results confirm that beer is addictive and that the Barnett et al. result holds for the U.S. brewing industry.

2.2 The Theoretical and Empirical Model

Because the consumption of alcoholic beverages can be habit forming and/or addictive, a brewing company's problem is a dynamic one. That is, sales decisions today affect not only current profits but also the level of addiction, demand, and profits in future periods. To model the firm's problem, consider a market with n firms that compete in discrete time periods. The inverse market demand for beer in period t, $p_t(Q_t, \varphi_t, z_t)$, is a function of current consumption, Q_t, the degree of habit or addiction, φ_t, and a vector of other exogenous variables, z_t. With addiction, an increase in Q_t leads to an increase in φ_{t+1} and, therefore, market demand in the next period. Firm i's unit costs in period t, $c_t(\mathrm{w}_t, x_t, T_t)$, are a function of a vector of input prices, w_t, the quantity of a fixed input, x_t, and a control variable for the state of technology, T_t. In this case, firm i's problem in time period $t = 0$ is to choose the level of output (q_{it}) in each period that maximizes its discounted stream of current and future (after-tax) profits, Π_0. More formally, the firm's problem is to choose the output level in each period that maximizes the following:

$$\Pi_0 = \sum_{t=0}^{\infty} \delta^t[p_t(Q_t, \varphi_t, z_t)\, q_{it} - c_t\, (w_t, x_t, T_t)q_{it} - (\tau_{ft} + \tau_{st})q_{it}] \tag{1}$$

subject to the constraints on the structure of the dynamic updating rule regarding addiction, on the initial value of addiction, and on output feasibility. In terms of notation, δ is the discount factor ($0 \leq \delta < 1$), τ_{ft} is the federal excise tax rate, and τ_{st} is the average state excise tax rate.

Assuming a solution exists, the problem can be described for any time period k ($0<k<\infty$) by a Bellman equation.[3] This is based on the notion of a value function, defined as $V_t = \sup \Pi_t$ for period t. Given this notation, the Bellman equation for this problem in period k is:

$$V_k = \max\ [p_k(Q_k, \varphi_k, z_k)\ q_{ik} - c_k\ (w_k, x_k, T_k)q_{ik} - (\tau_{fk} + \tau_{sk})q_{ik} + V_{k+1}\ ] \qquad (2)$$

subject to the constraints described above. Note that this notation implies that the firm has selected the optimal output levels from period $k+1$ on. Because of the presence of addiction, however, an output change in period k will affect the optimal path of output in future periods. Thus, when choosing the optimal output level in period k, the Bellman equation demonstrates that the firm must trade off today's net returns with the present value of future net returns (V_{k+1}). This is illustrated in the first order condition for this problem:

$$[p_k - \theta\ q_{ik} - c_k\ (w_k, x_k, T_k) - (\tau_{fk} + \tau_{sk})\ ] + \frac{\partial V_{k+1}}{\partial q_{ik}} = 0 \qquad (3)$$

where θ is an index of market power. The bracketed term is the standard first-order condition to the firm's static problem in the absence of addiction. With addiction, however, greater production today affects the firm's competitive

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[3] See Novshek (1993) for a discussion of dynamic programming techniques and several economics applications.

environment in both current and future periods. The impact on future periods is described by the last term on the left-hand side of equation (3).

This general structure encompasses several important oligopoly games. For example, if firms play a finitely-repeated simultaneous move game where output is the strategic variable, then the Cournot-Nash outcome in each period is a mutual best reply for each firm. In this case, $\theta = -\partial p_t \,/\, \partial Q_t$. Alternatively, if firms play a finitely-repeated simultaneous move game where price is the strategic variable, then a Bertrand-Nash outcome in each period is a mutual best reply for each firm. In this setting, $\theta = 0$. Finally, if all n firms play an infinitely repeated game and identify a trigger strategy that effectively supports collusion, then a collusive outcome is the mutual best reply for each firm, which occurs when $\theta = n(- \ p_t / \ Q_t)$.

Following Bresnahan (1989), one can rewrite equation (3) in aggregate form. After rearranging terms, this generates the subsequent dynamic version of the industry supply relation.[4]

$$p_t = c_t(w_t, x_t, T_t) + \tau_{ft} + \tau_{st} + \theta\, Q_t - \sum_{t=1}^{n} \frac{\partial V_{t+1}}{\partial q_{it}} \qquad (4)$$

[4] This approach implicitly assumes that marginal cost is the same for all firms and that the market power parameter is either a constant or a measure of average industry conduct. In the next section, we find that market power parameter appears to be stable. See Bresnahan (1989), Genesove and Mullin (1998), and Corts (1999) for further discussion of the strengths and weaknesses of the new empirical industrial organization approach.

where Q_t is industry output. This synthesizes the new empirical industrial organization approach to modeling oligopoly markets with Pindyck's (1985) approach to modeling a dynamic monopoly market. As in the static case, exerted market power increases with θ.

The empirical model consists of a system of equations describing the market demand function and the industry supply relation. Like Barnett et al. (1995) and Farr et al. (2001) for cigarettes, we assume a linear market demand function.

$$Q_t = \alpha_0 + \alpha_1 p_t + \alpha_2 p_t^{cola} + \alpha_3 p_t^{whis} + \alpha_4 Inc_t + \alpha_5 Q_{t-1} + \alpha_6 Dem_t + \varepsilon_{t,D} \quad (5)$$

where p^{Cola} is the price of cola, p^{Whis} is the price of whiskey, *Inc* is disposable income, and ε_D is an additive error term.[5] Because marketing experts find that the primary beer drinking population is between 18 and 44 years old [*Beer Industry Update* (1992)], a demographics variable (*Dem*) is included in the demand function. It is defined as the proportion of the total population in this age group, and market demand should increase with this variable. Lagged consumption controls for habit or addiction by letting $\varphi_t = Q_{t-1}$. This assumes a partial adjustment or myopic model of addiction.[6]

[5] Although Tremblay (1985) finds that advertising has a significant impact on the firm demand for beer, there is no empirical evidence to support the hypothesis that advertising affects the market demand for beer [Lee and Tremblay (1992), Nelson (1999), and Coulson et al. (2001)]. This is consistent with markets that are covered, as in Tremblay and Martins-Filho (2001) and Tremblay and Polasky (forthcoming). As a result, advertising is excluded from the demand function. Empirical results from a model that includes advertising in demand are discussed in the next section.

[6] Unfortunately, a rational addiction model is not identified with time-series data when price and output are endogenous [Chaloupka (1991)]. In any case, Akerlof (1991) provides an excellent

Because of its flexibility and ease of calculation, we use a variation of the Generalized Leontief functional form to describe the marginal cost function [Diewert (1974)]. Following Tremblay (1987), Elyasian and Mehdian (1993), and Kerkvliet et al. (1998), costs are assumed to be a function of two variable input prices (labor and materials), one fixed input (capital), and a time trend to control for technological change (*T*). This generates the following restricted marginal cost function:

$$c_t = \beta_1 w_t^l + \beta_2 w_t^m + \beta_3 (w_t^l w_t^m)^{1/2} + \beta_4 K_t + \beta_5 T_t \qquad (6)$$

where w^l is the price of labor, w^m is price of materials, and K is the quantity of capital.

Identification of the industry supply relation requires additional structure on the dynamic effects described in the first order condition. Following Roberts and Samuelson (1988) and Jarmin (1994), aggregate dynamic effects that occur in future periods are represented by a constant, λ_0.[7] Given this assumption and equations (4) and (6) above, the dynamic industry supply relation can be written as:

$$p_t=\beta_1 w_t^l+\beta_2 w_t^m+\beta_3(w_t^l w_t^m)^{1/2}+\beta_4 K_t+\beta_5 T_t+\lambda_0+\lambda_1\tau_{ft}+\lambda_2\tau_{st}+\theta Q_t+\varepsilon_{t,S} \qquad (7)$$

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defense of the myopic addiction model. See Greene (1997, pp. 798-799) for a description of this model.

[7] One needs to be cautious when interpreting the sign of this constant term, as it may control for more than just dynamic effects. For example, it could also capture optimization errors made by firms in the industry or a constant term associated with market power or the marginal cost function.

where $_{s}$ is an additive error term. If bootlegging is more likely across state than national boundaries, making it more difficult for beer producers to pass along state than national excise taxes to consumers, then $\lambda_1 > \lambda_2 > 0$.

2.3 Regression and Simulation Results

The market demand equation (5) and the industry supply relation (7) are estimated using two-stage least squares.[8] The data consist of 43 annual observations at the industry level from 1953-1995. Table 1 provides a list of variables, their mean values, and their standard deviations. A description of the data and their sources can be found in the Data Appendix.

The empirical results are reported in Table 2. Regarding demand, the parameter estimates have the expected signs and all are significant except for the parameter associated with the price of whiskey. Demand has a negative slope, cola and whiskey are substitutes for beer, and beer is a normal good. In addition, current demand increases with a greater population of young adults and for higher levels of past consumption. This latter result provides empirical support for the presence of addiction and for the dynamic representation of the intertemporal link in the demand function. Elasticity estimates evaluated at the sample means of each variable are provided in Table 3. In general, these elasticity estimates are within the ranges found in previous studies.[9]

On the supply side of the market, all of the parameter estimates have the expected signs and all are significantly different from zero except the parameter

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[8] We tested and corrected for first-order autocorrelation in the supply relation. No autocorrelation was detected in the demand equation.

[9] In a review of six previous studies of the demand for beer, Tremblay (2002) finds that the price elasticity of demand ranges from -0.142 to -0.889, the cross-price elasticity for whiskey ranges from 0.140 to 0.285, and the income elasticity ranges from -0.545 to 0.760.

on the state excise tax variable. The results indicate that technology has changed over time, a result that is consistent with Tremblay (1987) and Kerkvliet et al. (1998). Although the market power parameter is positive and significant, its value is close to zero, suggesting that the degree of exerted market power in brewing is modest. This result is consistent with the work of Tremblay and Tremblay (1995a) and the fact that accounting profit rates are low in brewing relative to the manufacturing sector as a whole.[10] Finally, we find that federal excise taxes have a greater impact on the supply price than state excise taxes, a result consistent with that of Barnett et al. (1995) for cigarettes.

In order to better understand the effect of federal and state excise taxes, we use the parameter estimates of the model to simulate the impact of a one dollar increase in the federal and the state excise tax rates per (31 gallon) barrel. Table 4 presents the short- and long-term effects of these simulated tax increases when all exogenous variables are held constant at their mean values. The results demonstrate that the equilibrium price of beer rises more for a federal than a state tax increase. Thus, consumers bear a greater tax burden when excise taxes are increased at the federal level.[11] Again, this can occur if there is greater

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[10] For example, *Brewers Almanac* (1998, 33) reports that the average profit-to-sales ratio is 2.723 percent for brewing and 4.823 percent for all manufacturing during the 1960-1994 time period.

[11] This result is possible because states have very different tax rates and change their rates at different times. In 1997, for example, the average state tax rate was $7.84 per barrel, while North Carolina set its tax rate at $15.00 per barrel and Wyoming set its tax rate at $0.62 per barrel. One would expect the tax incidence to be the same for a dollar increase in the federal tax rate and a dollar increase in the tax rate of every state.

bootlegging across state than federal boundaries. These results also have important implications for optimal tax policy, as they demonstrate that federal taxes are more successful at reducing beer consumption. This and the work of Barnett et al. (1995) indicate that excise taxes designed to mitigate the effect of negative externalities should focus on federal over individual state and local tax increases.

To further test the validity of these results, four alternative specifications are explored. The first specification includes advertising in the demand function. Next, because industry experts claimed that the wage and price controls imposed by the federal government from 1973-74 narrowed price-cost margins in brewing [*Fortune* (1975)], a dummy variable for this effect is included in the supply relation. A third specification includes both advertising in demand and the price-control dummy variable in supply. Finally, Tremblay (2002) argues that because of rising concentration in brewing during the 1980s, a trigger strategy may have successfully supported collusion during this period. As a result, the market power parameter is allowed to vary for different regimes (with various breaks in the 1980s). The empirical results reveal that advertising and the price-control dummy variable have insignificant effects and that the market power parameter is relatively constant over time. More importantly, the parameter estimates of the other variables (along with their levels of significance) and the conclusions from our original model are robust to these alternative specifications.

2.4 Concluding Remarks

In this paper, we investigate issues of market power and tax incidence in the U.S. brewing industry. Because the consumption of alcoholic beverages may be addictive, we derive a structural econometric model of addiction from a dynamic oligopoly game. Industry data are used to estimate a dynamic demand function and supply relation. This model is capable of identifying the degree of market power in a dynamic setting and allows us to compare the tax incidence of federal and state excise taxes.

Our estimation results for both the demand function and the supply relation are well- behaved and consistent with previous literature. We find empirical support for addiction, which justifies the dynamic specification of our model. In addition, our results confirm the presence of a modest degree of market power in brewing.

Finally, consistent with the results of Barnett et al. (1995) for cigarettes, we find that an increase in federal excise taxes causes a greater increase in price and a greater decrease in consumption than the same increase in average state excise taxes. This implies that an optimal tax policy that is designed to mitigate the impact of negative externalities should focus on raising federal rather than individual state and local tax rates.

2.5 Data Appendix

The data consist of 43 annual observations from 1953 through 1995. Measurement procedures and data sources for the demand variables are as follows. Beer consumption is measured in 31 gallon barrels and is obtained from *Brewers Almanac* (various issues). Consistent with marketing evidence [*Beer Industry Update* (1992)], the demographics variable is defined as the proportion of the total population in the 18-44 year old age group. This variable helps control for changes in demographics. Population figures come from the U.S. Bureau of the Census. The prices of beer, whiskey, and non-alcoholic drinks are measured by price indexes (equaling 100 in 1982) from the U.S. Bureau of Labor Statistics. Disposable income is obtained from the U.S. Bureau of the Census, *Current Population Reports*. Advertising expenditures are obtained from *Brewers Almanac* (various years).

On the supply side, the price of labor is defined as total production wages per barrel in the brewing industry, obtained from *Brewers Almanac* (various issues). The price of materials is defined as the cost per barrel of materials from *Brewers Almanac* (various issues). Capital is measured as the total brewing capacity, obtained from *Brewers Digest, Buyers Guide and Brewers Directory* (various issues). Federal and average state beer taxes per barrel are obtained from *Brewers Almanac* (various issues).

All money figures in our regression analysis are in 1982 dollars. Consumer goods are deflated by the Consumer Price Index, and producer goods are deflated by the Producer Price Index. Both indexes are obtained from the Bureau of Labor Statistics.

2.6 References

Barnett, Paul G., Theodore E. Keeler, and The-wei Hu, "Oligopoly Structure and the Incidence of Cigarette Excise Taxes," *Journal of Public Economics*, vol 57, no 3, July 1995, 457-470.

Beatty, Sally Goll and Yumiko Ono, "Liquor Industry Is Divided Over Use of TV Ads," *Wall Street Journal*, June 12, 1996, B1.

Beer Industry Update: A Review of Recent Developments, West Nyack, NY: Beer Marketer's Insights, Inc., 1992.

Brewers Almanac, U.S. Brewers Association Inc., Washington D.C., various issues.

Chaloupka, Frank J., "Rational Addictive Behavior and Cigarette Smoking," *Journal of Political Economy*, vol 99, no 4, August 1991, 722-742.

Cook, Philip J., "Editorial: Increasing the Federal Excise Taxes on Alcoholic Beverages," *Journal of Health Economics*, vol 7, no 1, March 1988, 89-91.

Corts, K. S., "Conduct Parameters and the Measurement of Market Power," *Journal of Econometrics*, vol 88, no 2, February 1999, 227-250.

Coulson, N. Edward, John R. Moran, and Jon P. Nelson, "The Long-run Demand for Alcoholic Beverages and the Advertising Debate: A Cointegration Analysis," in *Advances in Applied Microeconomics: Advertising and Differentiated Markets*, Michael R. Baye and Jon P. Nelson, editors, New York: JAI Press, 2001, 31-54.

Delipalla, Sophia, and Owen O'Donnell, "Estimating Tax Incidence, Market Power, and Market Conduct: The European Cigarette Industry," *International Journal of Industrial Organization*, vol 19, no 6, May 2001, 885-908.

Diewert, Erwin, "Applications of Duality Theory," in Michael Intriligator and D. Kendrick, editors, *Frontiers of Quantitative Economics*, Amsterdam: North-Holland, 1974.

Elyasiani, Elyas, and Seyed Mehdian, "Measuring Technical and Scale Inefficiencies in the Beer Industry: Nonparametric and Parametric Evidence," *Quarterly Review of Economics and Finance*, vol 33, no 4, Winter 1993, 383-408.

Elzinga, Kenneth G. "The Beer Industry," in *The Structure of American Industry*, Walter Adams, editor, New York: Macmillan, 1990, 128-60.

Elzinga, Kenneth G., "Beer," in Walter Adams and James W. Brock (editors), *The Structure of American Industry*, Upper Saddle River, NJ: Prentice Hall, 2001, 87-113.

Farr, Stephen J., Carol Horton Tremblay, and Victor J. Tremblay, "The Welfare Effect of Advertising Restrictions in the U.S. Cigarette Industry," *Review of Industrial Organization*, vol 18, no 2, March 2001, 147-160.

Fortune, "Why There's No Yeast in Brewers' Stocks," November 1975, 91.

Genesove, D. and W. P. Mullen, "Testing Static Oligopoly Models: Conduct and Cost in the Sugar Industry, 1890-1914," *Rand Journal of Economics*, vol 29, no 2, Summer 1998, 355-377.

Greene, William H., *Econometric Analysis*, New York: Macmillan, 1997.

Greer, Douglas F., "Causes of Structural Change," in Larry L. Duetsch (editor), *Industry Studies*, New York: M.E. Sharpe, 1998, 28-64.

Jarmin, Ronald S., "Learning by Doing and Competition in the Early Rayon Industry," *Rand Journal of Economics*, vol 25, no 3, Autumn 1994, 441-454.

Keeler, Theodore E., The-wei Hu, Willard G. Manning, and Hai-Yen Sung, "State Tobacco Taxation, Education, and Smoking: Controlling for the Effects of Omitted Variables," *National Tax Journal*, vol 54, no 1, January 2001, 83-102.

Kenkel, Donald S., "New Estimates of the Optimal Tax on Alcohol," *Economic Inquiry*, vol 34, no 2, April 1996, 296-319.

Kerkvliet, Joe R., William Nebesky, Carol Horton Tremblay, and Victor J. Tremblay, "Efficiency and Technological Change in the U.S. Brewing Industry," *Journal of Productivity Analysis*, vol 10, no 3, November 1998, 271-288.

Lee, Byunglak and Victor J. Tremblay, "Advertising and the US Market Demand for Beer," *Applied Economics*, vol 24, no 1, January 1992, 69-76.

Modern Brewery Age, October 11, 1993, 44 (41), 1-3.

Nelson, Jon P., "Broadcast Advertising and U.S. Demand for Alcoholic Beverages," *Southern Economic Journal*, vol 65, no 4, April 1999, 774-790.

Novshek, William, *Mathematics for Economists*, New York: Academic Press, 1993.

Phelps, Charles, "Death and Taxes: An Opportunity for Substitution," *Journal of Health Economics*, vol 7, no 1, March 1988, 1-24.

Pogue, T. F. and L. G. Sgontz, "Taxing to Control Social Costs: The Case of Alcohol." *American Economic Review*, vol 79, no 1, March 1989, 235-43.

Tremblay, Carol Horton, and Victor J. Tremblay, "The Impact of Cigarette Advertising on Consumer Surplus, Profit, and Social Welfare," *Contemporary Economic Policy*, vol 13, no 1, January 1995a, 113-124.

__________, "Advertising, Price, and Welfare: Evidence From the U.S. Brewing Industry," *Southern Economic Journal*, vol 62, no2, October 1995b, 367-381.

Tremblay, Victor J., "Strategic Groups and the Demand for Beer," *Journal of Industrial Economics*, vol 34, no 2, December 1985, 183-198.

__________, "Scale Economies, Technological Change, and Firm Cost Asymmetries in the U.S. Brewing Industry," *Quarterly Review of Economics and Business*, vol 27, no 2, Summer 1987, 71-86.

__________, *The U.S. Brewing Industry: Data and Economic Analysis*, mimeo, Oregon State University, 2002.

Tremblay, Victor J., and Carlos Martins-Filho, "A Model of Vertical Differentiation, Brand Loyalty, and Persuasive Advertising," in Michael Baye and Jon Nelson, editors, *Advances in Applied Microeconomics: Advertising and Differentiated Markets*, New York: JAI Press, 10, 2001.

Tremblay, Victor J., and Sephen Polasky, "Advertising with Subjective Horizontal and Vertical Product Differentiation," *Review of Industrial Organization*, vol 20, no 3, May 2002, 253-276

2.7 Tables of Estimation Result

Table 1

Description of the Variables and Data for the U.S. Brewing Industry (1953-1995)

Variable	Description(units)	Mean(std.Dev.)
Q	Quantity of beer consumed(thousands of 31-gallon barrels)	140,650 (41,965)
p	Index of the price of beer(equals 100 in 1982)	121.38 (20.39)
p^{cola}	Index of the price of cola(10 in 1982)	90.8 (10.73)
p^{whis}	Index of the price of whisky(100 in 1982)	151.63 (49.15)
Inc	Disposable income(billions of dollars)	1,973 (740)
Dem	Proportion of the population between 18 and 44 years old	0.387 (0.034)
w^{l}	Price of labor(wages per barrel in thousands of dollars)	30.15 (8.59)
w^{m}	Price of materials(costs per barrel in thousands of dollars)	0.036 (0.003)
K	Beer industry capacity(millions of barrels)	174.69 (41.47)
T	Time trend(1953=1)	22.0 (12.56)
τ_f	Federal excise tax rate(dollars per barrel)	20.1 (8.92)
τ_s	Average state excise tax rate(dollars per barrel)	9.31 (1.79)

All dollar values are measured in real terms (1982 dollars).

Table 2

U.S. Brewing Industry Demand Function and Supply Relation Parameter Estimates

Variable	Deman Function Parameter Estimate	t-statistic	Supply Relation Parameter Estimate	t-statistic
Intercept(x 10^{-3})	8.529	0.218		
p (x 10^{-2})	-3.871 [b]	2.68		
p^{cola} (x 10^{-2})	2.955 [a]	3.791		
p^{whis} (x 10^{-2})	0.141	0.129		
Inc	6.058 [b]	2.226		
Q_{t-1}	0.638 [a]	5.309		
Dem(x 10^{-4})	11.579 [c]	1.988		
Intercept(x 10^{-2})			1.040 [a]	16.186
w^{l}			3.537 [a]	4.295
w^{m} (x 10^{-2})			32.315 [a]	4.100
$w^{l} w^{m}$(x 10^{-2})			-2.213 [a]	4.240
K			-0.074 [b]	2.514
T			-1.193 [a]	8.230
τ_f			1.070 [a]	8.419
τ_s			0.306	0.722
Q(x 10^{3})			0.160 [b]	2.565
Adjusted R^2		0.998	0.994	
F		3223.9 [a]	908.9 [a]	

All dollar values are in 1982-84 dollars.
[a]Significant at the 0.01 level (two-tailed test).
[b]Significant at the 0.05 level (two-tailed test).
[c]Significant at the 0.10 level (two-tailed test).

Table 3

Own-Price, Cross-Price, and Income Elasticity Estimates

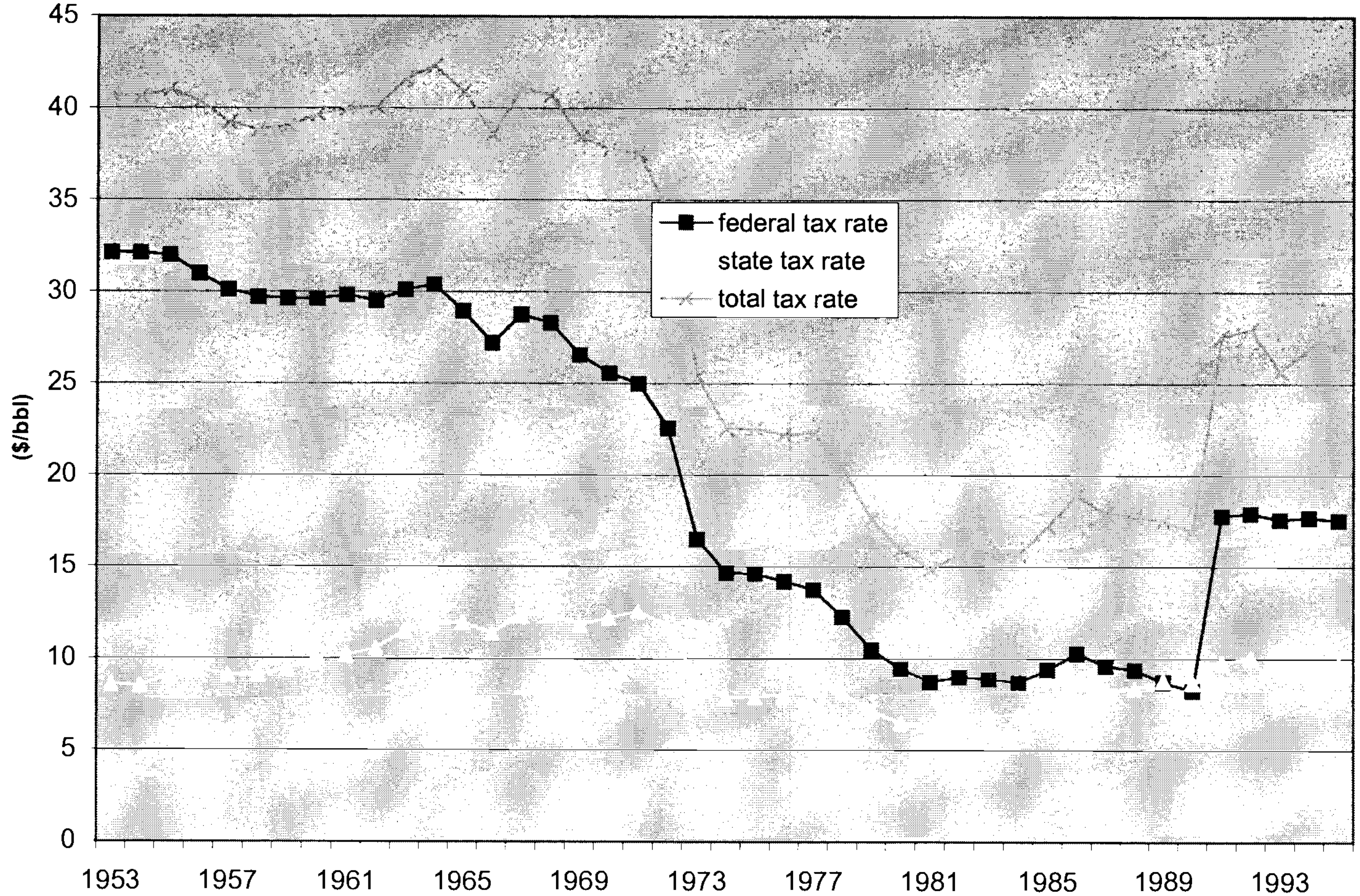
Variable	Elasticity Estimates Short Run	Long Run
Price of Beer	-0.298	-0.745
Price of Cola	0.191	0.478
Price of Whisky	0.015	0.038
Income	0.085	0.213

Table 4

Simulation Effects of a Dollar Increase in the Federal and State Tax Rates Per Barrel on Equilibrium Price and Consumption Levels

	Federal Tax Increase		State Tax Increase	
	Short Run	Long Run	Short Run	Long Run
Changes Due to a Dollar Tax Increase :				
Consumption(Thousand Barrels)	-390.2	-976.8	-111.4	-279.0
Price	0.8038	0.8039	0.2295	0.2296
Elasticity Estimates :				
Consumption	-0.0497	-0.1244	-0.0066	-0.0164
Price	0.1669	0.1670	0.0221	0.0221

Figure 2.1 Federal, State, and Total Excise Tax Rates($/bbl)



3. PRODUCTIVITY CHANGE AND THE SO_2 EMISSION REGULATION EFFECT OF PHASE I ELECTRIC UNITS

3.1 Introduction

The Clean Air Act Ammendment(CAAA) of 1990 required 261 generating units to reduce sulfur dioxide(SO_2) emissions to 2.5 pounds of SO_2 emission per million BTU of fuel input during the phase I period(1995-1999). In addition, the CAAA required most fossil fuel fired electricity generating units to reduce SO_2 emissions to the level of 1.2 pounds per million BTU of fuel input in the phase II period(starting in 2000). As a result, phase I units had to adopt SO_2 emission reduction compliance strategies to reduce SO_2 emissions during the phase I period.

In 1995, the first year of CAAA 1990, 52%(136 units) of the total 261 units reported switching their fuel from high-sulfur coal to low-sulfur coal(fuel-switch strategy) as their SO_2 emission reduction compliance method. Those units accounted for 59% of the total SO_2 emission's reduction from 1985 level. Thirty-two percentage(83 units) of the units used an allowances purchasing strategy and contributed to 9% of SO_2 emission reduction. Four units were retired, and eight units used other strategies(switch to natural gas, repowering, etc.). Only 10%(27 units) of the total units installed scrubbers, and they accounted for 28% of SO_2 emission reductions. The main reason for fuel switching from high-sulfur coal to low-sulfur coal was that the compliance cost of fuel switching was lowest (estimated to cost $113 per ton of SO_2 removal)(Ellerman et al,1997) since the comparative prices of low-sulfur coal, railroad transportation costs, and boiler-modifying costs were low. A small number of units installed scrubbers since the costs for scrubbers was highest($322 per ton of SO_2 removal).

One effect of the emission reduction compliance strategies was that it influenced the coal supply and demand pattern. Since many generating units switched their fuel to low-sulfur coal, the sales of low-sulfur coal from the Powder River basin(Wyoming and Montana) increased by 78 million tons between 1990 and 1995, while sales of high sulfur coal from the northern Appalachian region(Maryland, Pennsylvania, Ohio, west Virginia) decreased by 29 million tons during the same period(DOE/EIA, 1997).

The Department of Energy(DOE) reported that, because of the stronger environmental regulation, the 261 phase I generating units emitted 5.3 million tons of SO_2 in 1995, 45% less than 1990's emission level(9.7 million tons) and 50% less than 1985's emission(10.5 million tons)(this emission statistics includes the emission of total 435 units including 261 Table I units, 174 substitution and compensation units). In contrast, non-phase I units(those non-affected by CAAA) during the phase I period emitted 6.6 million tons in 1995, an amount 12% higher than 1990's emission level(5.9 million tons) (DOE/EIA, 1997). The Department of Energy(DOE) reported that the phase I generating units achieved the SO_2 emission goal of 5.7 million tons in the very first year of the phase I period. This report implies that the federal government's environmental policy was successful in achieving the reduction of emission in the first year of phase I period.

Meanwhile, the mean electricity generation in the phase I period was approximately 10% higher than the electricity generation prior to the phase I period(1990-1994), but SO_2 emission in the phase I period is around half of the SO_2 emission level before phase I period. In terms of input, generating capacity was almost constant during the whole period, and the amount of labor was actually reduced by 15% over the pre-pahse I period. The fuel consumption in the phase I period was around 10% higher than the fuel consumption before the phase I period. The general trend is that good output(electricity generation) increased, bad output(SO_2 emission) declined, labor input declined, and capital input remained constant, while fuel input increased. In other words, even under the stronger SO_2 emission regulations, good output increased and some input and bad output declined. In general, it seems like that electric units produced more good output and less bad output using less input under stronger environmental regulation.

The first question is, however, whether the SO_2 emission reduction regulations affected the productivity change of US electric power units, and if so, how did it affect the productivity. That is, did the introduction of stronger environmental regulation affect the productivity change of power units? And did the environmental regulation affect the productivity change by compliance strategy group asymmetrically? If the emission reduction induced a decline in productivity, then the U.S environmental policy achieved the emission goal sacrificing productivity growth. If not, the environmental policy was successful since it achieved the emission reduction without productivity decline.

The second question is about the sources of productivity change. That is, to what extent did the efficiency change affect the productivity change? What is the contribution of technological change to the productivity change? If we decompose the productivity change into scale efficiency change, pure technical efficiency change and the technological change, then we can identify the source of the productivity change.

The third question is about the opportunity cost of SO_2 emission regulation. In other words, what is the extent to which the phase I generating units could increase their productivity growth if there was no environmental regulation ? Since the generating units may have adjusted to the stronger environmental regualtion, we can decide whether this stronger environmental regualtion is binding on the productivity growth or not.

This paper estimates the Luenberger productivity indicator of 209 phase I generating units(we exclude 52 units) of fossil fuel powered electric power units in the pre-phase I period(1990-1994) and in the phase I period(1995-1999), and decompose the productivity change into scale efficiency change, "pure" technical efficiency and technological change. Then we can estimate the effect of environmental regulation on the productivity change and estimate the effect on the productivity change by SO_2 emission reduction compliance strategy group. Also, we can figure out the source of the inefficiency and the source of the productivity change. Non-parameteric technique for directional technology distance function was used to estimate the Luenberger productivity indicator. The generating unit level's data was used since the environmental regulation in phase I period was applied to individual generating unit. The time period of the data is from 1990 to 1999.

3.2 Literature Survey

3.2.1 Parametric Estimation of Productivity Growth

Dhrymes et al(1964) used constant-elasticity-of-substitution production model to identify the returns to scale and to estimate the effect of technological change on returns to scale of 362 steam electric generating plants constructed during the period between 1937-1959. They used electricity generation, 3 kinds of inputs(fuel, labor, capital), and found that the increasing returns to scale prevailed in the electricity generation industry.

Christensen et al(1976) used translog cost function for 124 privately owned fossil fuel fired electric utilities in 1955 and 114 utilities in 1970. They incorporated electricity output, prices of fuel, labor, and capital into a cost function to estimate the economies scale between 1955 and 1970. They found that the economies scale prevailed for most utilities in 1955, but was exhausted in 1970 since the per firm electricity output increase(around 3 times between two time periods) outweighed the firm size increase(around 60% increase) required to exhaust economies of scale.

Gollop et al(1981) estimated factor-augumented flexible translog cost function to estimtae the contribution of scale effect and technology change to the productivity growth. One good output(electricity generation), quantity and price of three inputs(capital, labor, fuel) of 11 electric utilities in 1958-1975 periods were used. The electric utility included the electricity generation, transmission, and distribution section. The productivity growth can be decomposed into scale economies, growth rate of output and technological change, and these three factors are a function of input prices, output, and time variable. The productivity growth rate was estimated to be 4% per year in the sample period, and the technological change(2.4%) contributed 3/4 of the productivity growth. The remaining contribution was from scale economies(1.6%). The productivity achieved a high growth rate during the 1958-73 period, but the productivity declined in 1973-75 period. The annual mean cost growth rate for the 11 utilities was 9.9%. The contribution of scale effect to the cost growth rate was 5.5%. The capital price had a positive effect on total cost growth, the fuel price had a negative effect, and the wage rate was not found to have a statistically significant effect. The mean effect of three input prices on the total cost growth was 5.9%(2.7% of capital price, 0.8% of wage, 2.4% of fuel price), and the contribution of output growth and technological change to the total cost growth was 5.5% and -2.4% respectively.

Cowing et al(1981) estimated and compared the productivity growth under different kinds of methodology. They studied 81 electrical utilities between 1964-75 by using one good output(electricity generation), quantity and input prices of three inputs(capital, labor, fuel). They decomposed the effect of returns to scale, capacity utilization, regulatory effect(rate-of-return constraint effect) into Laspeyres index, Divisia index, flexible translog cost function measurement. The mean total factor productivity(TFP) growth was from 1.35% to 2.0% under Divisia index method, was from 0.79% to 1.22% under Laspeyres index method. The industry mean productivity growth was statistically same across the various methodologies(Divisia index, Laspeyres index) and the adjustment of each variable(returns to scale, capacity utilization, regualtory constraint). The regulatory effect on the productivity growth was found to be relatively small.

Gollop et al(1983) estimated the effect of SO_2 emission regulation on the productivity growth of 56 privately owned electric utilities during the 1973-79 period. They incorporated the output(electricity generation), prices of capital, labor, high-sulfur fuel, low-sulfur fuel, regulatory intensity variable(combination of actual SO_2 emission, uncostrained SO_2 emission, state government's regulated SO_2 emission) and time variable into the translog cost function to estimate the productivity growth. They decomposed the productivity growth into the contribution of scale economies, environmental regulation, and technological change. The productivity growth of the utilities facing binding SO_2 emission constraints was lower than that of the utilities without regulation. The SO_2 emission regulation set by CAAA of 1970 reduced the productivity growth by 0.59% point annually because of the increased use of expensive low-sulfur fuel and capital. The effect of SO_2 emission regulation on the electricity production cost increased during the 1973-79 period, and the environmental regulation required more input except for high-sulfur fuel. SO_2 emission regulation affected the productivity change negatively in the sample period, and the degree of negative effect was highest in 1976 when the SO_2 emission regulation had to be met fully for the first time of CAAA of 1970. Economies of scale were present and contributed to the productivity growth in a small degree(0.3% annually) because of slow increase of output not because of exhaustion of scale economies. The smallest utilities faced substantial scale economies, but the largest utilities were producing in a range of scale diseconomies. Technological regression(1.05% for utilities facing binding regulation to 1.12% for utilities not facing binding regulation) was the main source of productivity decline.

Kleit et al(2001) estimated the efficiency, returns to scale, and price elasticities of 78 natural gas fired electricity generating plants using the Bayesian stochastic cost frontier model. They used total cost, output, prices of three inputs(capital, labor, fuel) for U.S plants in 1996. The wage was county level's data. The result showed that the plants could reduce production costs by 13% by eliminating inefficiency, and that most of the plants were operating at increasing returns to scale. So there is more potential to reduce cost by increasing the output. The finding that own-price elasticities(-1.45 for labor, -0.53 for fuel, -1.37 for capital) showed that capital and labor are more sensitive to price than fuel. This means that the deregulated plants can reduce costs by reducing labor costs.

3.2.2 Nonparametric Estimation of Productivity Growth

Fare et al(1986) estimated the effect of environmental regualtion on the efficiency of 100 electric plants in 1975 by using an output distance function. They imposed the strong(free) disposability and weak disposability of good and bad output separately. They then set up the ratio of output distance value with strong disposability to the distance value with weak disposability to calculate the effect of SO_2 regulation on the efficiency change. The opportunity cost measured in output loss due to disposability was from 0.1% to 48% of good output for each plant. On average, the total output loss of the 100 electric plants(1,622 million KWh) due to environmental regualtion was 1.3% of actual electricity output in 1975. One good output(net electricity generation) and four kinds of bad outputs(particulate matter, sulfur dioxide, nitrogen oxide, heat) and five inputs(generating capacity, labor, coal, oil, gas) were included. The efficiency of the plants regulated by the thermal pollution was higher than the efficiency of the regulated plants due to the adjustment in technology to avoid thermal pollution. The publicly owned plants and the non-based load plants(plants factor is less than 50%) were most affected by the environmental regulation.

Berstein et al(1990) estimated the impact of SO_2 regulation on the productivity of 76 coal-fired power plants in 1984. Good output(net electricity generation) and three inputs(generating capacity, fuel consumption and labor) were included in this input-based efficiency model. The efficiencies of the plants that had scrubbers was found to be 5-7% lower on average than those with no scrubbers.

The efficiency of the plants that had no regulation was the highest, and the efficiency of the plants that switched their fuel to low-sulfur coal was next highest. They regressed the efficiency score on several environmental variables to identify the impact of the variables on productivity. Since a 1% decrease in sulfur output related to a 0.01% decrease in efficiency, SO_2 emission regulation negatively affected the productivity. The size of the plants positively affected the productivity. The efficiency of the small size plants is higher than the large size plants, but the effect after imposition of SO_2 emission regulation was lower relative to the effect during the pre-regulation period.

Fare et al(1990) used an input based Malmquist productivity index to calculate the productivity change of 19 coal-fired plants in Illinois during the 1975-1981 period. They found that efficiency change was stable except for the period in 1975 and 1981 when efficiency improved. There was productivity decline only in the 1976-1977 period, while the productivity was stable in the other periods. Since there was a technological regress in the sample period, the productivity decline during the 1976-77 period. In this model, one good output(net generation) and three inputs(fuel, labor, load factor) were used.

Yaisawarng et al(1994) used 61 coal-fired electricity genarating plants' data to calculate the effect of sulfur dioxide regulation on the productivity change between 1985 and 1989. The input-based cumulative Malmquist productivity index was used, and the productivity change was decomposed into scale efficiency change, pure technical efficiency change, and changes in frontier technology. They used short-run technology and estimated sub-vector input efficiency. SO_2 emission was defined as bad output, net electricity generation as good output, sulfur content in the coal as bad input, generation capacity as fixed input, and fuel and labor as variable inputs. They imposed the strong disposability for bad input and imposed the constraint such that the sulfur content should be higher than the sulfur content of the frontier plants. That is, the sulfur content of the coal used by electric plants should not be below the minimum level that the frontier plants achieved. In order to avoid the zero bad input, they substituted a minimum sulfur content(0.3%) in the sample for the plants with zero sulfur content. The efficiency score measured the capability that the electric plant can use the variable inputs to produce given good output and bad output for a given technology and a fixed level of bad input. They found that the overall efficiency was 0.92-0.94, and the main source of inefficiency was pure technical inefficiency, rather than scale efficiency. Although the efficiency of the plants with scrubbers was slightly lower than the efficiency of plants without scrubbers, this difference was statistically insignificant. Around half(47.4%) of net electricity was produced by the plants that are in the increasing returns to scale range, 25.2% of the net generation was produced by the plants that was in the constant returns to scale, and 27.4% was produced by the plants showing decreasing returns to scale. They found that the productivity slowdown in the

1980's came from the exhaustion of the scale economies. One interesting finding was that both the scale efficiency and the pure technical efficiency of the plants that are in the constant returns to scale are very high(efficiency score is 1.0). The other plants that are in the range of decreasing or increasing returns to scale is scale inefficient. And the plants in the increasing returns to scale range are consistently more productively inefficient than the plants in the decreasing returns to scale range. The cumulative productivity change between the base year(1985) and the target years(1986-1989) was between -1.73% and 0.77%. The main source of productivity change was different each year. In 1986, the productivity decline came from the fact that the efficiency deteriation offset scale efficiency improvement and technological improvement.

One interesting finding between parametric estimation and the nonparametric estimation of productivity growth is that most of the parametric technique except for Gollop et al.'s method(1983) did not include the reduction of SO_2 emission in the functional form explicitely, while the nonparametric technique did. If we ignore the bad output reduction in the productivity measurement, then the efficiency or productivity will be biased. This will be discussed in the next section.

3.3 Directional Technology Distance Function

3.3.1 Compliance Strategy

In the Clean Air Act Amendment of 1990, the US federal government set electricity utilities' SO_2 emission target in terms of total annual SO_2 emission for phase I utilities. The annual target of 8.7 million tons(around half of emission level in 1980) that will be achieved through two phases(Curtis, et al., 2000). In the phase I period(from 1995 to 1999), the dirtiest 261 generating units(connected to 263 boilers that belong to 110 electric plants) had to reduce SO_2 emission rates to the level of 2.5 pounds per million BTU of fuel input. In the second phase(from 2000), most of the fossil fuel fired power units of which the generating capacity is 25 or more megawatts have to reduce SO_2 emissions to 1.2 pounds per million BTU of heat input. The federal government allocated the allowances to each generating unit in proportion to average heat input in the 1985-87 period(Carlson et al, 2001). That is, the federal government's allowance allocation will be limited to 2.5 pounds of SO_2 emission per million BTU of heat input in the phase I period and 1.2 pounds of SO_2 emission in the phase II period. One allowance is equivalent to the right to emit one ton of SO_2.

The electric power units can choose one or a combination of strategies to comply with the SO_2 emission standards. The electric power units can reduce the SO_2 emission by reducing the production of electricity since SO_2 emission is the byproduct of electricity generation. This compliance strategy includes Demand

Side Management(DSM), the purchase of electricity from Independent Power Producers(IPP) or other non-regulated power units, and retiring the unit. The other example of a fuel switch is to change the fuel from coal or oil to natural gas, or change from high-sulfur oil to low-sulfur oil. In this paper, these kinds of switches are referred to under the heading of "other" strategy. This strategy is labelled "other" strategy in this paper since the characteristics of these units is heterogeneous and the number of the generating units that used this strategy is relatively small(15 units).

The second strategy to comply with the environmental regulation is to install technology to reduce emissions from the coal burning process. The representative strategy of this method is to install scrubber(or FGD:Flue Gas Desulfurization equipment) to absorb the SO_2 emission. This strategy required a larger capital investment and operation and management costs compared to other strategies.

The third strategy is to decrease the use of dirty inputs that contain the pollutants, for example, high-sulfur coal in fossil fuel fired electric unit, and increase the use of clean inputs, for example, low-sulfur coal. This is called fuel switch strategy, that is, the electric units or generating units switch their fuel from cheap high-sulfur coal to expensive low-sulfur coal. In this paper, the fuel switch includes only the switch from high-sulfur coal to low-sulfur coal. The fuel switch from high-sulfur coal to low-sulfur coal needs a relatively small amount of capital compared to the capital costs of scrubber strategy or "other" strategy.

The fourth compliance strategy is to buy the right to emit the pollutants when the property right is well defined. This is called allowance purchasing strategy. In other words, electric units buy emission permits from other firms that reduced SO_2 emission below the emission standard or that they can buy permits in allowance auction market. The allowance strategy needs some transaction costs to deal with the strategic behavior in the allowance market.

The choice of strategy depends on several factors including the market situation of each input factors and the unit owners' expectation. If the capital cost is, or is expected to be, relatively cheap comparing to the cost of other strategies, then some units will choose the capital intensive strategy(for example, scrubbers). When the low-sulfur coal price is not expensive, then some units will switch their fuel from high-sulfur coal to low-sulfur coal. If some units' owners expect the allowance price to be low, then the owners will buy the allowances instead of choosing fuel switch or scrubber strategy.

Each strategy needs a different kind of input combination to produce electricity and to reduce SO_2 emission, and each generating unit uses different production technology. As a result, it is probable that the environmental regulation will affect the efficiency of the generating units based on their compliance strategy asymmetrically.

3.3.2 Bad Output and Productivity Measurement

If some of the outputs are bad outputs, the measurement of efficiency should include the reduction of bad output in the productivity measurement. The SO_2 emission is a byproduct of electricity generation procedure in the fossil fuel fired electric units. If one unit produces more electricity than another unit given inputs, then it's efficiency is higher than the efficiency of other units when we consider only good output in the efficiency measurement. Suppose another case in which one unit emits more SO_2 than another unit under the same level of electricity and inputs. The traditional efficiency measurement gives the same efficiency value to both of the units even though one unit produces more bad output. Giving both units same efficiency value is inappropriate especially considering that SO_2 emissions have a negative effect on the welfare of society. The appropriate method in measuring efficiency, then is to give credit for both having a higher level of good output and a lower level of bad output.

When we measure the productivity change or efficiency change of the electricity industry, the major problem is that there are some bad outputs as sulfur dioxide(SO_2), nitrogen oxide(NO_x), and carbon dioxide(CO_2) and particulates. These bad outputs are usually jointly produced as a by-product of good output. When the government regulates the emission of bad output, then the electric units or utility will use more resources to decrease the bad output. Since all the compliance strategies need more resources to reduce bad output when there is a environmental regualtion, the amount of bad output must be considered. For example, say an electric utility has to install scrubber to reduce SO_2 emissions from coal burning. The scrubber needs more capital expenditure for it's installation, operation, and maintenance. The fuel switch strategy needs capital expenditure to retrofit the boiler to burn low-sulfur coal and spend more capital expenditure to buy expensive low-sulfur coal. If we exclude the reduction of bad output, then the productivity measurement will be downwardly biased since the effort to reduce the bad outputs are not included in the productivity measurement, even though the electric unit decreased the socially undesirable outputs.

The directional distance function(output and input distance function) can can take any positive or negative values as the efficiency score(Chung et al, 1997). The directional output distance function, however, does not consider the simultaneous decrease of input even though this function gives credit for the simultaneous decrease of bad output and the increase of good output. The directional input distance function does not consider the simultaneous adjustment of good output and bad output. Since the directional technology distance function can account for the simultaneous decrease of bad output, inputs, and the increase of good output, this distance function can encompass all kind of distance functions(Fare at el, 2000).

3.3.3 Directional Technology Distance Function

The directional technology distance function is an appropriate model to estimate the productivity change when there is bad output. Also, the directional technology distance function can generalize all the known distance functions(Fare et al, 1996).

First, technology is defined by

$$T = \{(x,y,b) : x \text{ can produce } y \text{ and } b\} \tag{3.1}$$

where $x = (x_1, x_2, \ldots\ldots x_N) \in R^N$ are input vector, good output vectors are $y = (y_1, y_2, \ldots\ldots y_M) \in R^M$, and bad output vectors are $b = (b_1, b_2, \ldots\ldots b_J) \in R^J$. This technology represents the mapping of input vector into good output and bad output vectors.

Good outputs are assumed to be costlessly disposable. That is,

$$(x, y, b) \in T \text{ and } y' \leq y \text{ then } (x, y', b) \in T. \tag{3.2}$$

In other words, less or equal amount of good outputs are feasible given technology, inputs, and bad outputs. Since the reduction of bad output is costly, and the bad output is jointly produced with good output, the reduction of bad output is feasible when the good output is reduced. So we assume the weak disposability of good output and bad output as :

$$(x, y, b) \in T \text{ and } 0 \leq \theta \leq 1 \text{ imply } (x, \theta y, \theta b) \in T \tag{3.3}$$

We also assume that the strong disposability of inputs as:

$$(x, y, b) \in T \text{ and } x \leq x' \text{ then } (x', y, b) \in T \tag{3.4}$$

That is, more or equal amount of inputs are feasible given technology and good output and bad outputs.

Also, we have to impose the null jointness of good output and bad output since the bad output is jointly produced with the good output. So the zero good output is feasible only when zero bad output is produced. The imposition of null jointness as follows :

$$\text{if } (x, y, b) \in T \text{ and } b = 0 \text{ then } y = 0 \tag{3.5}$$

In other words, this null jointness means that there should be a positive amount of bad output when there is a positive amount of good output. This restriction means that we have to exclude zero SO_2 emissions when the unit produced some positive electricity in the empirical model. It is impossible to produce positive output when there is no input, but it is possible that positive amount of inputs can produce no outputs(Fare et al, 1996). That is, we can produce outputs whenever we use inputs, but it is possible not to produce outputs even though we use some positive inputs.

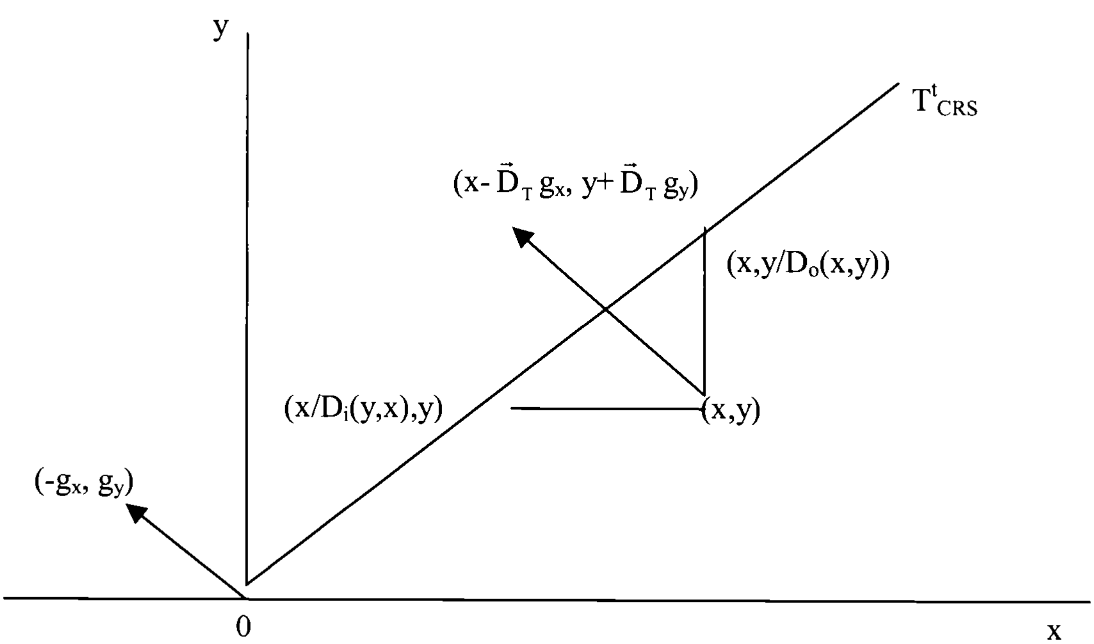
The Directional technology distance function is defined on the technology as follows :

$$\vec{D}_T(x,y,b;-g_x, g_y, -g_b) = \sup\{\beta : (x-\beta g_x, y+\beta g_y, b-\beta g_b) \in T\} \tag{3.6}$$

where $(-g_x, g_y, -g_b)$ is a non-zero directional vector. The directional technology distance function represents the maximum distance value compared to the reference technology.

For convenience, suppose that there is one good output and one input, and the technology is constant returns to scale(CRS). Then the directional technology can be visualized as all input-output vectors, and the point(x,y) is the observed input-output vector(Fare, et al, 1996). The direction in which the input-output vector(x,y) is expanded is given by ($-g_x$, g_y). The direction of g_y means that the observation or decision making unit(DMU) can add the output as much as β times g_y to the observed output(y), and the direction of $-g_x$ means that the firm can subtract the input as much as β times g_x from observed input(x). The maximal expansion value, that is the maximum increase of output and the maximal decrease of input, is defined by $\vec{D}_T(x,y;-g_x, g_y)$.

Figure 3.1 Directional Technology Distance Function



The directional distance function has translation property. That is, the directional distance function satisfies the translation property if for $\alpha \in R$

$$\vec{D}_T(x-\alpha g_x, y+\alpha g_y ; -g_x, g_y) = \vec{D}_T(x, y ; -g_x, g_y) - \alpha \qquad (3.8)$$

The translation property means that if we increase or decrease the observations being evaluated as much as α times directional vector, then the new directional distance value is equal to the original distance value minus α under the same reference technology(Fare et al, 2000). This property corresponds to the homogeneity of degree one of outputs in the output distance function.

The Shephard output distance function is defined on the technology as follows :

$$D_o(x,y) = \inf\{\theta : (x, y/\theta) \in T\} \qquad (3.9)$$

The output distance function measure the maximum expansion of output given inputs under the current technology relative to the frontier technology.

And the output distance function is homogeneous of degree one in outputs(Fare et al, 1995) :

$$D_o(x, \theta y) = \theta D_o(x, y) \qquad (3.10)$$

Homegeneity of degree one means that if all of the output increases by θ times given inputs, then the maximal distance of output will increase by θ times.

The directional distance function is related to the Shephard output distance function when the directional vector of input is zero, that is, when $g_x = 0$, $g_y = y$, as follows :

$$\vec{D}_T(x,y ; 0, y) = 1/D_o(x,y) - 1 \qquad (3.11)$$

Also, when we take the zero directional vector of output, that is, when g_x =x, g_y =0, then the directional technology distance function is related with the Shephard input distance function as follows :

$$\vec{D}_T(x,y\,;\,x,0) = 1 - 1/D_i(y,x) \qquad (3.12)$$

The traditional input distance function and the output distance function are thus a special case of directional technology distance function. There are also other relationships between the traditional distance function and the directional distance function(Fare et al,2000).

3.4 Luenberger Productivity Indicator

3.4.1 Efficiency Measurement

The directional technology distance function evaluates the efficiency of each observation in specified time period compared to the frontier technology in a specified time period, and based on a specified directional vector. That is, the directional technology distance function measures the efficiency of each observation based on the combination of observed input-output vectors, reference technology, directional vectors and time period. For example, $\vec{D}_T{}^t(x^t, y^t, b^t;-g_x, g_y, -g_b)$ evaluates the efficiency of observed good output, bad output, and inputs of (y^t, b^t, x^t) of each observation in time period t compared to the reference technology of T^t in time period t based on the directional vector of $(-g_x, g_y, -g_b)$ as follows :

$$\vec{D}_T{}^t(x^t, y^t, b^t;-g_x, g_y, -g_b) = \sup\{\beta : (x^t- \beta g_x, y^t+\beta g_y, b^t-\beta g_b)\in T^t \} \tag{3.13}$$

Also, we can change the time period of the input-output vectors being evaluated, and we can change the time period of the reference technology to which it is being comapred. So $\vec{D}_T{}^{t+1}$ $(x^t, y^t, b^t;-g_x, g_y, -g_b)$ evaluates the efficiency of observed good output, bad output, and inputs of (y^t, b^t, x^t) of each observation in time period t compared to the reference technology of T^{t+1} in time period t+1 based on the directional vector of $(-g_x, g_y, -g_b)$ as follows :

$$\vec{D}_T{}^{t+1}(x^t, y^t, b^t;-g_x, g_y, -g_b) = \sup\{\beta : (x^t- \beta g_x, y^t+\beta g_y, b^t-\beta g_b)\in T^{t+1} \} \tag{3.14}$$

$\vec{D}_T^{\,t}(x^{t+1}, y^{t+1}, b^{t+1}; -g_x, g_y, -g_b)$ evaluates input-output vector in time period t+1 compared to the reference technology in time period t based on the same directional vector as:

$$\vec{D}_T^{\,t}(x^{t+1}, y^{t+1}, b^{t+1}; -g_x, g_y, -g_b) = \sup\{\beta : (x^{t+1} - \beta g_x, y^{t+1} + \beta g_y, b^{t+1} - \beta g_b) \in T^t\} \quad (3.15)$$

$\vec{D}_T^{\,t+1}(x^{t+1}, y^{t+1}, b^{t+1}; -g_x, g_y, -g_b)$ evaluates output-input in time period t+1 compared to the reference technology in time period t+1 based on the same directional vector as above :

$$\vec{D}_T^{\,t+1}(x^{t+1}, y^{t+1}, b^{t+1}; -g_x, g_y, -g_b) = \sup\{\beta : (x^{t+1} - \beta g_x, y^{t+1} + \beta g_y, b^{t+1} - \beta g_b) \in T^{t+1}\} \quad (3.16)$$

In the diretional distance function, the distance value measures the efficiency of each observation relative to the refernence technology. That is, the efficiency score measures the extent to which each observation can increase the good output and decrease the input and bad output simultaneously compared to the frontier technology in the directional technology distance function. Suppose the distance value of one observation is 0.6 based on its own directional vector($-g_x=x$, $g_y=y$, $-g_x=b$). This observation can increase it's own output and can decrease its own bad output and inputs by 60% to get to the frontier technology.

The distance value in the directional distance function can take positive, negative or zero value depending on the observations being evaluated and the reference technology, it is being compared to. The most efficienct observation's efficiency score is zero when the time period for observations being evaluated is the same as the time period for which the reference technology is being compared to-- that is, when the reference technology envelopes all observations. In this case, the positive distance value means the inefficiency.

A negative efficiency value is possible only when observations are placed outside the reference technology. In other words, this case is possible only when the time period of the observations being evaluated is different from the time period of the reference technology it is being compared to. The negative distance value means a higher efficiency score than the most efficient observation's score when some observations are placed outside the reference technology.

So the efficiency is defined as the directional technology distance value in the corresponding time period. That is, the efficiency in time period t[EF(t,t)] is defined as the directional technology distance value in time period t such that distance value measures the maximal distance of input-output vector in time period t relative to the reference technology in time period t. The efficiency in time period t+1[EF(t+1, t+1)] is also defined as the directional technology distance value in time period t+1. The efficiency[EF(t, t+1)] is defined as the distance value when we evaluate the input-output vector in time period t relative to the reference technology in time period t+1.

$$EF(t, t) = \vec{D}_T^{\,t}(x^t, y^t, b^t; -g_x, g_y, -g_b)$$

$$EF(t, t+1) = \vec{D}_T^{\,t+1}(x^t, y^t, b^t; -g_x, g_y, -g_b)$$

$$EF(t+1, t) = \vec{D}_T^{\,t}(x^{t+1}, y^{t+1}, b^{t+1}; -g_x, g_y, -g_b)$$

$$EF(t+1, t+1) = \vec{D}_T^{\,t+1}(x^{t+1}, y^{t+1}, b^{t+1}; -g_x, g_y, -g_b) \tag{3.17}$$

The efficiency measure can be decomposed into scale efficiency and pure technical efficiency. Suppose that the production technology is constant returns to scale, then the efficiency of each observation will be lower than the efficiency under another kind of production technology, for example, variable returns to scale technology(increasing, constant and decreasing returns to scale technology). If one observation is in the increasing or decreasing returns to scale range, then the efficiency under the variable returns to scale technology will be different from the efficiency under the constant returns to scale technology. Since the variable returns to scale technology envelopes the input-output vectors more closely than the constant returns to scale, the efficiency under variable returns to scale(VRS) is higher than the efficiency under CRS.

The difference between the efficiency score under the constant returns to scale technology and the efficiency score under the variable returns to scale technology is defined as the scale efficiency since this difference comes from a different kind of returns to scale technology. That is,

$$SCEF(t, t) = EF(t, t)_{CRS} - EF(t, t)_{VRS} \tag{3.18}$$

where $EF(t, t)_{CRS}$ is efficiency under CRS technology

$EF(t, t)_{VRS}$ is efficiency under VRS technology

Pure technical efficiency is defined as the efficiency when we exclude any specific assumptions for the reference technology. That is, the pure technical efficiency is the efficiency under VRS technology as :

$$PUTE(t, t) = EF(t, t)_{VRS} \qquad (3.19)$$

In other words, pure technical efficiency is the difference between the efficiency score and the scale efficiency.

If the observation is in the range of constant returns to scale, then the efficiency of the observation will not alter when we change the returns to scale technology. However, if the observation is in the increasing returns to scale range, then the efficiency under the constant returns to scale technology should be lower than the efficiency under the variable returns to scale technology and should be the same as the efficiency under non-increasing returns to scale(NIRS). Also, when the efficiency of the observation under the non-increasing returns to scale technology is higher than the efficiency under the constant returns to scale technology, then the observation is in the range of decreasing returns to scale.

Since the directional distance function takes the additive form, the efficiency is the sum of scale efficiency and the pure technical efficiency. That is,

$$EF(t, t) = SCEF(t, t) + PUTE(t, t)$$

$$= [EF(t, t)_{CRS} - EF(t, t)_{VRS}] + EF(t, t)_{VRS}$$

$$= [\vec{D}_T{}^t(x^t,y^t,b^t;-g_x,g_y,-g_b)_{CRS} - \vec{D}_T{}^t(x^t,y^t,b^t;-g_x,g_y,-g_b)_{VRS}] + \vec{D}_T{}^t(x^t,y^t,b^t;-g_x,g_y,-g_b)_{VRS}$$

$$= \vec{D}_T{}^t(x^t, y^t, b^t;-g_x, g_y, -g_b)_{CRS} \qquad (3.20)$$

3.4.2 Productivity Change Measurement

The difference in the efficiency between two time periods measures the change of efficiency. Suppose that the efficiency of one observation in time period t is 0.6, and the efficiency in time period t+1 is 0.4 when we assume there is no technological change, that is, the frontier technology is same. Then the difference of the efficiency measure is 0.2. This positive efficiency change means an improvement of efficiency between time period t and t+1 since the smaller distance value means a higher efficiency score. In other words, the observation is placed closer to the frontier technology in time period t+1 than time period t. So the efficiency of the observation improved.

However, there should be a technological change between the two time periods. Suppose that there is a technological development in time t+1 such that the most efficient observations in t period introduced advanced technology into the production procedure. Then the frontier production technology in t+1 will be shifted outward. As a result, the efficiency of one observation may be deteriorated even though the observation produced more output given input in time period t+1 because of the technological change in the frontier production technology. So we have to consider the technological change when we measure the productivity change. The productivity change includes the efficiency change and the technological change simultaneously.

If we use the directional technology distance function, the Luenberger productivity indicator is defined as the difference of the directional distance function since the directional distance function takes the additive distance value(Chamber et al,1996, Fare et al,2001). The Luenberger productivity indicator for period t and t+1 based on the directional technology distance function is defined as the combination of efficiency change and the technological change when there is good output, bad output and inputs as follows :

$$\text{PRODCH}(t, t+1) = L(x^t, y^t, b^t, x^{t+1}, y^{t+1}, b^{t+1}) \qquad (3.21)$$

or

$$\text{PRODCH}(t, t+1) = 1/2[(\vec{D}_T{}^{t+1}(x^t,y^t,b^t;-g_x, g_y, -g_b) - \vec{D}_T{}^{t+1}(x^{t+1}, y^{t+1},b^{t+1};-g_x, g_y, -g_b) + \vec{D}_T{}^{t}(x^t,y^t,b^t;-g_x,g_y,-g_b) - \vec{D}_T{}^{t}(x^{t+1},y^{t+1},b^{t+1};-g_x,g_y,-g_b)] \qquad (2.22)$$

We can decompose the Luenberger productivity indicator into efficiency change and technological change. Efficiency change comes from the technical combination of input vectors and the output vectors of each observation. That is, the efficiency change is the result of the observation's owner's capability to map the inputs into outputs. However, the technological change comes from outside the observation's decision making, that is, technological change is exogeneous to the owner's decision making.

$$\text{PRODCH}(t, t+1) = \text{EFCH}(t, t+1) + \text{TECH}(t, t+1) \qquad (3.23)$$

Efficiency change between time period t and t+1 is defined as the difference in the directional technology distance value between two time periods. We can get the following equation using efficiency defined in the directional technology distance function(3.17) as:

EFCH(t, t+1) = EF(t, t) - EF(t+1, t+1)

$$= \vec{D}_T{}^{t}(x^t, y^t, b^t; -g_x, g_y, -g_b) - \vec{D}_T{}^{t+1}(x^{t+1}, y^{t+1}, b^{t+1}; -g_x, g_y, -g_b) \tag{3.24}$$

That is, the efficiency change is the difference between the efficiency of each observation in time period t when each observed input-output vector is evaluated to the reference technology in time period t and the efficiency in time period t+1 when each observed input-output vectors is evaluated to the reference technology in time period t+1.

We can also decompose the efficiency change into scale efficiency change and pure technical efficiency change. Scale efficiency in period t is defined as the difference between the distance value under the constant returns to scale(CRS) technology and the distance value under the variable returns to scale(VRS) technology. The scale efficiency change is also defined as the difference between the scale efficiency in period t and the scale efficiency in period t+1. Since the pure technical efficiency in period t is defined as the distance value under VRS technology, pure technical efficiency change is defined as the difference between the pure technical efficiency in period t and the pure technical efficiency in period t+1.

That is,

EFCH(t, t+1)

$= SCEFCH(t, t+1) + PUTECH(t, t+1)$

$= [SCEF(t, t) - SCEF(t+1, t+1)] + [PUTE(t, t) - PUTE(t+1, t+1)]$

$$=[\{ \vec{D}_T{}^{t}{}_{CRS}(x^t, y^t, b^t; -g_x, g_y, -g_b) - \vec{D}_T{}^{t}{}_{VRS}(x^t, y^t, b^t; -g_x, g_y, -g_b)\} -$$

$$\{ \vec{D}_T{}^{t+1}{}_{CRS}(x^{t+1}, y^{t+1}, b^{t+1}; -g_x, g_y, -g_b) - \vec{D}_T{}^{t+1}{}_{VRS}(x^{t+1}, y^{t+1}, b^{t+1}; -g_x, g_y, -g_b)\}] +$$

$$[\{ \vec{D}_T{}^{t}{}_{VRS}(x^t, y^t, b^t; -g_x, g_y, -g_b) - \vec{D}_T{}^{t+1}{}_{VRS}(x^{t+1}, y^{t+1}, b^{t+1}; -g_x, g_y, -g_b)\}] \quad (3.25)$$

The technological change measures the average distance in technologies between the two time periods. In other words, technological change measures the effect of the technological change between two time periods when we evaluate each observation under different reference technology.

$TECH(t, t+1)$

$= 1/2[\{EF(t+1, t) - EF(t, t)\} + \{EF(t+1, t+1) - EF(t, t+1)\}]$

$$= 1/2[\{ \vec{D}_T{}^{t+1}(x^t, y^t, b^t; -g_x, g_y, -g_b) - \vec{D}_T{}^{t}(x^t, y^t, b^t; -g_x, g_y, -g_b) \} +$$

$$\{ \vec{D}_T{}^{t+1}(x^{t+1}, y^{t+1}, b^{t+1}; -g_x, g_y, -g_b) - \vec{D}_T{}^{t}(x^{t+1}, y^{t+1}, b^{t+1}; -g_x, g_y, -g_b) \}] \quad (3.26)$$

And, since the directional distance function takes the additive distance value, the Luenberger productivity indicator is the sum of the efficiency change and the technological change. The positive indicator means an improvement in productivity, and the negative indicator means a decline in productivity between the two adjacent periods. We can get the following equation for the Luenberger productivity indicator using previous equations as :

$PRODCH(t, t+1)$

= EFCH(t, t+1) + TECH(t, t+1)

= SCEFCH(T, T+1) + PUTECH(T, T+1) + TECH(T, T+1)

= [EF(t, t) - EF(t+1, t+1)] + 1/2[{EF(t+1, t) - EF(t, t)} + {EF(t+1, t+1) - EF(t, t+1)}]

or,

PRODCH(t, t+1)

$= L(x^t, y^t, b^t, x^{t+1}, y^{t+1}, b^{t+1})$

$= [\vec{D}_T{}^t(x^t, y^t, b^t; -g_x, g_y, -g_b) - \vec{D}_T{}^{t+1}(x^{t+1}, y^{t+1}, b^{t+1}; -g_x, g_y, -g_b)]$

$+ 1/2[\{(\vec{D}_T{}^t(x^{t+1}, y^{t+1}, b^{t+1}; -g_x, g_y, -g_b) - \vec{D}_T{}^t(x^t, y^t, b^t; -g_x, g_y, -g_b)\} + \{\vec{D}_T{}^{t+1}(x^{t+1}, y^{t+1}, b^{t+1}; -g_x, g_y, -g_b) - \vec{D}_T{}^{t+1}(x^t, y^t, b^t; -g_x, g_y, -g_b)\}]$

$= 1/2[\{(\vec{D}_T{}^{t+1}(x^t, y^t, b^t; -g_x, g_y, -g_b) - \vec{D}_T{}^{t+1}(x^{t+1}, y^{t+1}, b^{t+1}; -g_x, g_y, -g_b) + \vec{D}_T{}^t(x^t, y^t, b^t; -g_x, g_y, -g_b) - \vec{D}_T{}^t(x^{t+1}, y^{t+1}, b^{t+1}; -g_x, g_y, -g_b)]$ (3.27)

Suppose the variable returns to scale technologies are represented by $T^t{}_{VRS}$ and $T^{t+1}{}_{VRS}$ in period t and t+1 respectively, and the constant returns to scale technology is represented by $T^t{}_{CRS}$ and $T^{t+1}{}_{CRS}$ respectively in the following figure. The directional vector is denoted by $g(-g_x, g_y)$ when there is only one good output and one input for convenience. The observed input-output vector(x^t, y^t) being evaluated in period t is a, and the observed input-output vector(x^{t+1}, y^{t+1}) being evaluated in period t+1 is d. Then the most efficient observations based on constant returns to scale technology(b, c, e, f) and variable returns to scale technology(g, i) can be defined in terms of the observed input-output vectors(a, d), technology(T_{CRS}, T_{VRS}) and directional vector(g) in two time period(t, t+1) as follows :

$$b = a + \vec{D}_T{}^{t}{}_{CRS}\,(a : g)\, g$$

$$c = a + \vec{D}_T{}^{t+1}{}_{CRS}\,(a : g)\, g$$

$$e = d + \vec{D}_T{}^{t+1}{}_{CRS}\,(d : g)\, g$$

$$f = d + \vec{D}_T{}^{t+1}{}_{CRS}\,(d : g)\, g$$

$$g = a + \vec{D}_T{}^{t}{}_{VRS}\,(a : g)\, g$$

$$i = d + \vec{D}_T{}^{t+1}{}_{VRS}\,(d : g)\, g \qquad (3.28)$$

And efficiency change is defined as;

$$\begin{aligned} EFCH &= EF^{t} - EF^{t+1} \\ &= (b-a) - (f - d) \\ &= \vec{D}_T{}^{t}{}_{CRS}\,(a : g)\, g - \vec{D}_T{}^{t+1}{}_{CRS}\,(d : g)\, g \\ &= [\,\vec{D}_T{}^{t}{}_{CRS}\,(a : g) - \vec{D}_T{}^{t+1}{}_{CRS}\,(d : g)\,]g \end{aligned} \qquad (3.29)$$

Also efficiency change can be decomposed into scale efficiency change and pure technical change as;

$$\begin{aligned} EFCH &= SCEFCH + PUTECH \\ &= [(SCEF(t, t)- SCEF(t+1, t+1) + (PUTE(t, t) - PUTE(t+1, t+1))] \\ &= [(b-g) - (f-i)] + [(g-a) - (i-d)] \\ &= [\{(\vec{D}_T{}^{t}{}_{CRS}\,(a{:}g)g - \vec{D}_T{}^{t}{}_{VRS}\,(a{:}g)g) - (\vec{D}_T{}^{t+1}{}_{CRS}(d{:}g)g - \vec{D}_T{}^{t+1}{}_{VRS}(d : g)g)\} \end{aligned}$$

$$+ \{ \vec{D}_T{}^{t}{}_{VRS} (a : g)\, g - \vec{D}_T{}^{t+1}{}_{VRS} (d : g)\, g\}]$$

$$= [\vec{D}_T{}^{t}{}_{CRS} (a : g)\, g - \vec{D}_T{}^{t+1}{}_{CRS} (d : g)\, g]$$

$$= [\vec{D}_T{}^{t}{}_{CRS} (a : g) - \vec{D}_T{}^{t+1}{}_{CRS} (d : g)]\, g \qquad (3.30)$$

And technological change is defined as:

$$TECH = 1/2\ [(EF^{t}{}_{Tt+1} - EF^{t}{}_{Tt}) + (EF^{t+1}{}_{Tt+1} - EF^{t+1}{}_{Tt})]$$

$$= 1/2\ [\{(c-a) - (b-a) \} + \{ (f-d) -(e-d)\}]$$

$$= 1/2\ [(f-e) + (c-b)]$$

$$= 1/2\ [\vec{D}_T{}^{t+1}{}_{CRS} (d{:}g)g - \vec{D}_T{}^{t}{}_{CRS}(d{:}g)g + \vec{D}_T{}^{t+1}{}_{CRS}(a{:}g)g - \vec{D}_T{}^{t+1}{}_{CRS} (a{:}g)g]$$

$$= 1/2\ [\vec{D}_T{}^{t+1}{}_{CRS}(d{:}g) - \vec{D}_T{}^{t}{}_{CRS}(d{:}g) + \vec{D}_T{}^{t+1}{}_{CRS}(a{:}g) - \vec{D}_T{}^{t+1}{}_{CRS} (a{:}g)]g \qquad (3.31)$$

That is, the efficiency change measures how close the input-output vector(a,d) is to the constant returns to scale technologies in each time period. The technological change is the average distance between the two constant returns to scale technologies. Also, the efficiency change can be decomposed into scale efficiency change and pure technical change. That is, scale efficiency change between time period t and t+1 is (b-g) -(f-i), and the pure technical change is (g-a) -(i-d). So the efficiency change is the sum of scale efficiency and the pure technical change. The Luenberger productivity indicator is defined in the figure as;

PRODCH(T, T+1)

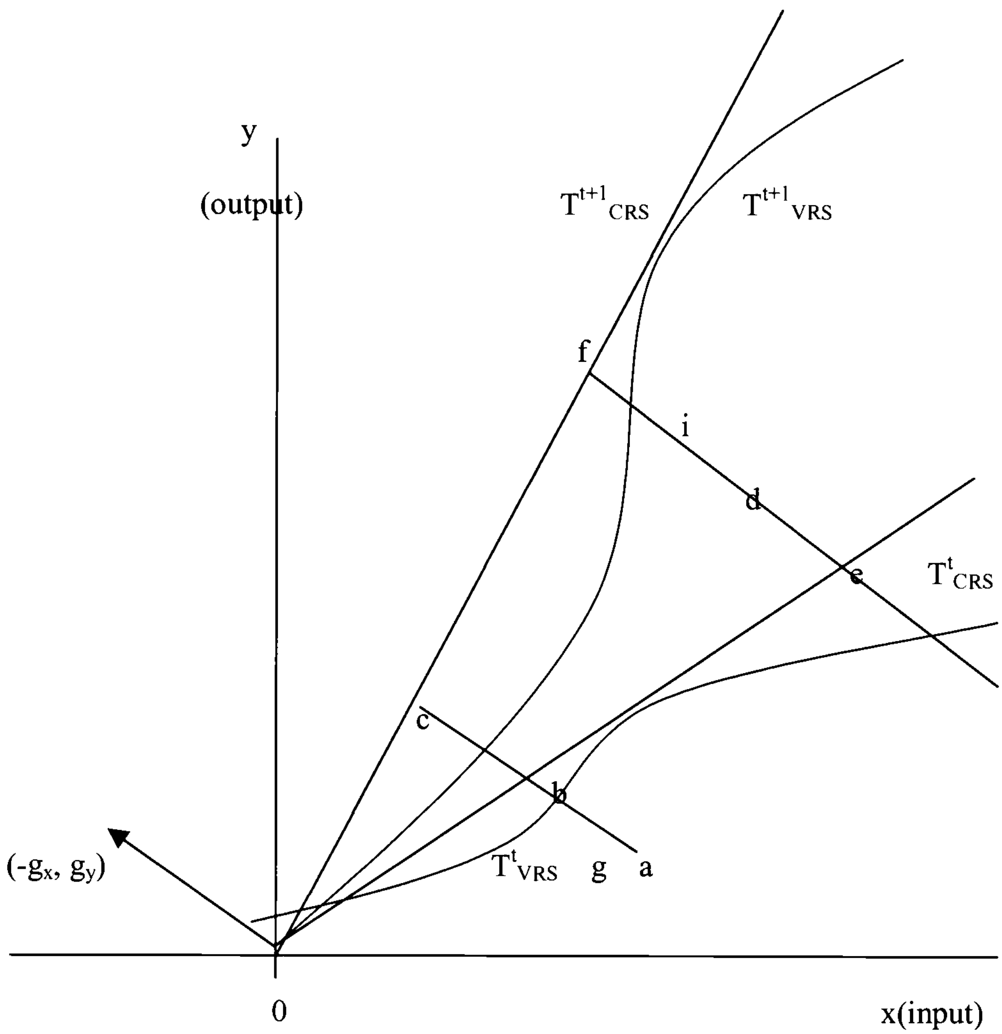
$= EFCH(T, T+1) + TECH(T, T+1)$

$= [(b-a) - (f-d)] + 1/2\ [(f-e) + (c-b)] = 1/2[(f-e) + (c+b)] + (d-a)$

$$= [\{\vec{D}_T{}^{t}{}_{CRS}(a:g) - \vec{D}_T{}^{t+1}{}_{CRS}(d:g)\} + 1/2\{\vec{D}_T{}^{t+1}{}_{CRS}(d:g) - \vec{D}_T{}^{t}{}_{CRS}(d:g)$$

$$+ \vec{D}_T{}^{t+1}{}_{CRS}(a:g) - \vec{D}_T{}^{t+1}{}_{CRS}(a:g)\}]g \qquad (3.32)$$

Figure 3.2 Productivity Change Measurement



3.5 Effect of SO_2 Emission Regulation on Productivity Growth Potential

3.5.1 Opportunity Cost of SO_2 Emission Regulation

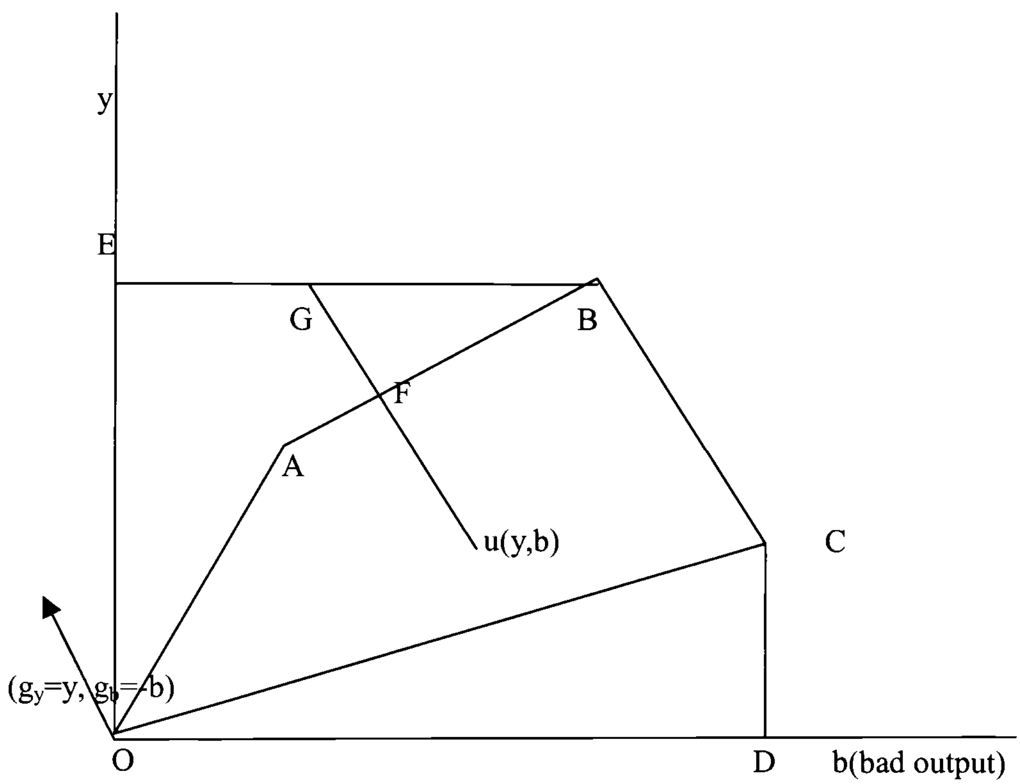
In the previous section, we assumed weak disposability of outputs. Since the reduction of bad output is not necessarily costless under the SO_2 emission regulation, good output should be reduced with the reduction of bad output, or more inputs should be required to reduce bad output. The reduction of bad output can be costlessly disposed if there is no SO_2 emission regulation, however. Then the generating units can produce more good output without any restriction of disposability of bad output when there is no restriction in the disposability of bad output.

For convenience, suppose the output sets have one good output(y) and one bad output(b)(Fare et al, 1986, 1989). The output set with weak disposability is bounded by OABCD, and the output set with strong disposability is bounded by OEBCD. If the bad output can be disposed costlessly, then the OEBA is the feasible part of the technology. If the disposal of bad output is not costlessly, then OEBA is not feasible.

Suppose that we measure the efficiency of the generating unit of u(y,b) based on the directional vector of (g_y=y, g_b=-b) and that $\vec{D}os$ and $\vec{D}ow$ are the distance values of the directional output distance function under strong disposability and weak disposability respectively. The maximal good output under the strong disposability is y + g_y* $\vec{D}os$ when the generating unit is most efficient(point G).

And the minimized bad output at point G is b - $g_b * \vec{D}os$. Also, maximal good output under the weak disposability when the generating unit is most efficienct(point F) is y + $g_y * \vec{D}ow$ since the maximal expansion of good output is restricted to the point F because of the disposability restriction of bad output, and the minimized bad output at point F is b - $g_b * \vec{D}ow$.

Figure 3.3 Opportunity Cost of Bad Output Regulation



As a result, the difference between the distance value under strong disposability and the distance value under weak disposability is defined as efficiency loss due to the environmental regulation of bad output in the same time period. That is,

EFLOSS(t, t)

$= EF(t, t)_S - EF(t, t)_W$

$$= (\vec{D}os - \vec{D}ow) \tag{3.33}$$

where $EF(t, t)_S$ is efficiency under strong disposability

$EF(t, t)_W$ is efficiency under weak disposability

If we multiply the efficiency loss by the good output, then we can get the opportunity cost of bad output regulation in a specific time period. More specifically, the opportunity cost of the restricted disposability of bad output is the directional vector of good output times the difference between the distance value under strong disposability and the distance value under weak disposability. That is, the opportunity cost of the restricted disposability of bad output in terms of good output is defined as the efficiency loss times the directional vector of good output in the same time period as:

$OPPCOST = EFLOSS*g_y$

$= (g_y* \vec{D}os) - (g_y* \vec{D}ow)$

$$= g_y*(\vec{D}os - \vec{D}ow) \tag{3.34}$$

where EFLOSS is the efficiency loss defined as the difference between the distance value under strong disposability and the distance value under weak disposability

$\vec{D}os$, $\vec{D}ow$ are distance values in the output directional distance function under strong disposability and weak disposability respectively

The same logic can be applied to the directional technology distance function. That is, the opportunity cost of the regulation of bad output disposability is defined as the directional vector of good output times the differential in the distance value between under strong disposability and under weak disposability in the directional technology distance function :

OPPCOST

$= [g_y * \vec{D}_{T.S}] - [g_y * \vec{D}_{T.W}]$

$$= g_y * (\vec{D}_{T.S} - \vec{D}_{T.W}) \qquad (3.35)$$

where $\vec{D}_{T.S}$ and $\vec{D}_{T.W}$ are the distance values in the directional technology distance function under strong disposability and the distance value under weak disposability respectively.

Opportunity cost can be defined only in terms of potential loss of good output in the directional technology distance function since both the distance value under strong disposability and weak disposability include the adjustment of inputs.

Opportunity cost can be decomposed into opportunity cost derived from scale efficiency and the opportunity cost derived from pure technical efficiency. That is,

$$
\begin{aligned}
&OPPCOST \\
&= OPPCOST_{SCEF} + OPPCOST_{PUTE} \\
&= (g_y{*}SCEFLOSS) + (g_y{*}PUTELOSS) \\
&= g_y{*}\{SCEF(t, t)_S - SCEF(t, t)_W\} + g_y{*}\{PUTE(t, t)_S - PUTE(t, t)_W\} \\
&= g_y{*}[\{(EF(t, t)_{CRS, S} - EF(t, t)_{VRS, S})\} - \{(EF(t, t)_{CRS, W} - EF(t, t)_{VRS, W})\}] + \\
&\quad [\{EF(t, t)_{VRS, S} - EF(t, t)_{VRS, S}\} - \{EF(t, t)_{VRS, W} - EF(t, t)_{VRS, W}\}] \qquad (3.36)
\end{aligned}
$$

where $OPPCOST_{SCEF}$ is opportunity cost derived from scale efficiency

$OPPCOST_{PUTE}$ is opportunity cost derived from pure technical efficiency

SCEFLOSS is efficiency loss derived from scale efficiency

PUTELOSS is efficiency loss derived from pure technical efficiency

3.5.2 Effect of SO_2 emission regulation on productivity growth potential

Let us take an example in which the productivity of one generating unit under strong disposability improved by 0.5 between two time periods, and the productivity under weak disposability improved by 0.3 in the same time period. If there is no environmental regulation, the productivity growth of this unit should be 0.5 which is the same as the productivity growth under strong disposability. The productivity growth of this unit, however, improved only by 0.3 because of the restriction of the bad output disposability. So the difference in productivity between under strong disposability(0.5) and under weak disposability(0.3) is 0.2 which is thus the effect of SO_2 emissions regulation on the productivity growth potential.

The productivity change under strong disposability generally shows a more stable trend compared with the productivity changes under weak disposability. This fact comes from the characteristic that the technology of weak disposability more closely envelopes the data set than does the technology of strong disposability. Suppose that the productivity of one generating unit under strong disposability improved by 0.5, but the productivity under weak disposability declined by 1.3 because of the introduction of stronger SO_2 emission regulation. The effect of environmental regualtion on the productivity change is thus 1.8. That is, this unit can increase the directional vector of good output 1.8 times if there is no environmental regulation. So the positive value of opportunity cost change means an increase of productivity growth potential because of the environmental regulation. If the environmental regulation affects the productivity change negatively, then the productivity growth potential should be positive. However, if the extent to which the regulation binds on the productivity change is neglegible, then the productivity growth potential will be positive or zero. We expect a positive value of productivity growth potential in the phase I period compared with the pre-phase I period since stronger regulation was introduced in the phase I period.

So, the effect of SO_2 emission regulation on the productivity growth potential, can be defined as the difference between productivity growth under strong disposability and productivity growth under weak disposability. That is,

OPPCOSTCH

$$= PRODCH(t, t+1)_S - PRODCH(t, t+1)_W \quad (3.37)$$

where $PRODCH_S$ is productivity change under strong disposability of output

$PRODCH_W$ is productivity change under weak disposability of output

We can decompose the productivity growth potential into the productivity growth potential derived from the efficiency loss change and the productivity growth potential derived from technological loss change. The logic is the same as the decomposition for the productivity change. The only difference is that we impose strong disposability and weak disposability separately.

The change of the efficiency loss between two time periods(t and t+1) is defined as the difference in the efficiency loss in time period t and the efficiency loss in time period t+1 under the same directional vector(g). That is,

EFLOSSCH(t, t+1)

$$= EFLOSS(t, t) - EFLOSS(t+1, t+1)$$

$$= [EF(t, t)_S - EF(t, t)_W] - [EF(t+1, t+1)_S - EF(t+1, t+1)_W]$$

$$= [\{\vec{D}_{T,S}{}^{t}(x^t, y^t, b^t; -g_x, g_y, -g_b) - \vec{D}_{T,W}{}^{t}(x^t, y^t, b^t; -g_x, g_y, -g_b)\} -$$

$$\{\vec{D}_{T,S}{}^{t+1}(x^{t+1}, y^{t+1}, b^{t+1}; -g_x, g_y, -g_b) - \vec{D}_{T,W}{}^{t+1}(x^{t+1}, y^{t+1}, b^{t+1}; -g_x, g_y, -g_b)\}] \quad (3.38)$$

where

EFLOSSCH(t, t+1) is the efficiency loss change between time period t and t+1

EFLOSS(t, t) and EFLOSS(t+1, t+1) are efficiency loss in t and t+1 period respectively.

The change of efficiency loss between two time periods is defined as the effect of SO_2 emission regulation on the efficiency change. For example, the efficiency score of one generating unit under strong disposability is 0.8, and the efficiency score under weak disposability is 0.5. Then the efficiency loss due to the lack of disposability of bad output in time period t is 0.3. In the next time period(t+1), the efficiency score under strong disposability is 0.6, and the efficiency score under weak disposability is 0.4 because of the strong environmental regulation. Then the efficiency loss in time period t+1 is 0.2. So the efficiency loss change is positive(0.1) because of the stronger environmental regualtion. If the efficiency loss change is positive, then the productivity growth potential increased. Also if the efficiency loss change is negative, then the productivity growth potential from efficiency change declined.

So, productivity growth potential derived from efficiency loss change, that is, the effect of SO_2 emission regulation on the productivity growth potential derived from the efficiency loss change, is defined as the efficiency loss change weighted by the directional vector of good output. In other words, productivity growth potential derived from efficiency loss change is defined as the good output directional vector times the efficiency loss change :

$OPPCOSTCH_{EFCH}$

$= g_y$*EFLOSSCH(t, t+1)

$= g_y$*[EFLOSS(t, t) - EFLOSS(t+1, t+1)] (3.39)

The effect of SO2 emission regulation on the productivity growth potential derived from the efficiency loss change also can be decomposed into productivity growth potential derived from scale efficiency loss change and productivity growth potential derived from pure technical efficiency loss change :

$OPPCOSTCH_{EFCH}$

$= g_y$*[SCEFLOSSCH(t, t+1) + PUTELOSSCH(t, t+1)] (3.40)

The effect of SO_2 emission on the technological growth potential is also defined as the average distance between technologies in two time periods when we evaluate the technology under strong disposability and weak disposability for each time period. As we noted previously, each generating unit can generally produce more good output under no environmental regulations. So the frontier production technology under no environmental regulation will shift outwardly more than the frontier production technology under the environmental regualtion. The loss in the technological change because of the environmental regulation is defined as the average distance value between technology under strong disposability and the technology under weak disposability :

TELOSSCH

$= 1/2[\{\vec{D}_{T,S}^{\,t+1}(x^t,y^t,b^t;-g_x,g_y,-g_b) - \vec{D}_{T,S}^{\,t}(x^t,y^t,b^t;-g_x,g_y,-g_b)\} + \{\vec{D}_{T,S}^{\,t+1}(x^{t+1},y^{t+1},b^{t+1};$

$-g_x,g_y,-g_b) - \vec{D}_{T,S}{}^{t}(x^{t+1},y^{t+1},b^{t+1};-g_x,g_y,-g_b)\} - \{\vec{D}_{T,W}{}^{t+1}(x^t,y^t,b^t;-g_x,g_y,-g_b) - \vec{D}_{T,W}{}^{t}(x^t,y^t,b^t;$

$-g_x,g_y,-g_b)\} + \vec{D}_{T,W}{}^{t+1}(x^{t+1},y^{t+1},b^{t+1};-g_x,g_y,-g_b) - \vec{D}_{T,W}{}^{t}(x^{t+1},y^{t+1},b^{t+1};-g_x,g_y,-g_b)\ \}$ (3.41)

The productivity growth potential derived from technological change is defined as the directional vector of good output times technological change loss :

$$OPPCOSTCH_{TECH} = g_y * TELOSSCH \quad (3.42)$$

So the effect of SO_2 emission regulation on the productivity growth potential is the sum of the effect on the efficiency change and the effect on the technological change. That is, the effect of SO_2 emission regulation on the productivity growth potential is the sum of efficiency loss change and the technological loss change follows;

$$OPPCOSTCH = OPPCOSTCH_{EFCH} + OPPCOSTCH_{TECH} \quad (3.43)$$

3.6 Empirical Model

3.6.1 Returns to Scale Technology

The first step for empirical model specification is to set the linear programming for the technology based on the assumption as noted in the previous section. Assume that there are k generating units and good output(y), bad output(b) and inputs(x) in period t. The analysis model for the constant returns to scale technology(CRS) with the observation of input and output ($x^{k,t}$, $y^{k,t}$, $b^{k,t}$) in time period t is

$T^{t}_{CRS} = \{(x^{t}, y^{t}, b^{t}) :$

$$\sum_{k=1}^{K} z_k \, y^{t}_{km} \geq y^{t}_{m} \ , m = 1, \ldots, M$$

$$\sum_{k=1}^{K} z_k \, b^{t}_{Kj} = b^{t}_{j} \ , j = 1, \ldots, J$$

$$\sum_{k=1}^{K} z_k \, x^{t}_{kn} \leq x^{t}_{n} \ , n = 1, \ldots, N$$

$$z_k \geq 0, k = 1, \ldots, K \}$$

(3.44)

The inequality of good output(y_m) and input(x_n) means the free disposability(strong disposability) of good output and inputs, and the equality of bad output(b_j) means the weak disposability of good output and bad output. The inequality of activity intensity(z_k), that is, the positive activity intensity for each firm means that the technology is represented by a constant returns to scale. We have to impose different technology constraints in the linear programming. The technological constraint of variable returns to scale technology(VRS) is that the sum of each activity intensity is equal to one. That is, the additional constraint to positive activity intensity of CRS is

$$\sum_{k=1}^{K} z_k = 1 \tag{3.45}$$

So the linear programming for the variable returns to scale technology(VRS) is follows :

$T^t{}_{VRS} = \{(x^t, y^t, b^t)$:

$$\sum_{k=1}^{K} z_k \, y^t_{km} \geq y^t_m \;, m = 1,\ldots,M$$

$$\sum_{k=1}^{K} z_k \, b^t_{Kj} = \delta b^t_j \;, j = 1,\ldots,J$$

$$\sum_{k=1}^{K} z_k \, x^t_{kn} \leq x^t_n \;, n = 1,\ldots,N$$

$$\delta \geq 1$$

$$z_k \geq 0, k = 1,\ldots,K \tag{3.46}$$

And the constraint of non-increasing returns to scale technology(NIRS) is that the sum of the activity intensity is equal or less that one, that is, the additional constraint to positive activity intensity of CRS is

$$\sum_{k=1}^{K} z_k \leq 1$$

(3.47)

We have three kinds of returns to scale technology. When we change the technology, we have to add the technological constraint to the CRS constraint. Let ($-g_x$, g_y, $-g_b$) be the directional vector of input, good output and bad output. Then the representative linear programming for the Luenberger productivity indicator under the constant returns to scale technology(CRS) is

$$\vec{D}_T{}^{t}{}_{CRS}\,(x^{k',t}, y^{k',t}, b^{k',t}; -g_x, g_y, -g_b) = \max \beta$$

s.t

$$\sum_{k=1}^{K} z_k\, y^t_{km} \geq y^t_{k'm} + \beta g_{ym}, m = 1,\ldots,M$$

$$\sum_{k=1}^{K} z_k\, x^t_{kn} \leq x^t_{k'n} - \beta g_{xn}, n = 1,\ldots,N$$

$$\sum_{k=1}^{K} z_k\, b^t_{jk} = b^t_{k'j} - \beta g_{bj}, j = 1,\ldots,J$$

$$z_k \geq 0, k = 1,\ldots,K\}$$

(3.48)

3.6.2 Time Period

The second step is to change the time period of the observation being evaluated and the reference technology. The above linear programming evaluates observation k' in t period relative to the reference technology T^t in t period under the constant returns to scale technology in the direction of ($-g_x$, g_y, $-g_b$). This directional distance value measures the maximum expansion of good output and the maximum contraction of bad output and input in time period t under the constant returns to scale technology as compared to the reference technology in time period t. Similar programming can be formed for the different time period's combination of the observation being evaluated and the technology being compared. For example, the linear programming to evaluate the observations k' in t period relative to the reference technology T^{t+1} in t+1 period under the constant returns to scale technology in the direction of ($-g_x$, g_y, $-g_b$) as follows :

$$\vec{D}_T{}^{t+1}{}_{CRS}(x^{k',t}, y^{k',t}, b^{k',t}; -g_x, g_y, -g_b) = \max \beta$$

s.t

$$\sum_{k=1}^{K} z_k\, y_{km}^{t+1} \geq y_{k'm}^{t} + \beta g_{ym}, m = 1,\ldots,M$$

$$\sum_{k=1}^{K} z_k\, b_{jk}^{t+1} = b_{k'j}^{t} - \beta g_{bj}, j = 1,\ldots,J$$

$$\sum_{k=1}^{K} z_k\, x_{kn}^{t+1} \leq x_{k'n}^{t} - \beta g_{xn}, n = 1,\ldots,N$$

$$z_k \geq 0, k = 1,\ldots,K$$

(3.49)

The remaining combination of observation and reference technology are to evaluate k' in time period t+1 relative to reference technology in t, and to evaluate k' in t+1 period relative to reference technology in t+1. As a result, we have four kinds of combination of observation and reference technology under the same returns to scale technology and directional vector. That is, the first combination of observation and reference technology is observations being evaluated in t time period($x^{k',t}$, $y^{k',t}$, $b^{k',t}$) and the reference technology to being compared in t time period(T^t). The second combination of observation and the reference technology is observations being evaluated in t time period($x^{k',t}$, $y^{k',t}$, $b^{k',t}$) and the reference technology to being compared in t+1 time period(T^{t+1}). The third combination of observation and the reference technology is observations being evaluated in t+1 time period($x^{k',t+1}$, $y^{k',t+1}$, $b^{k',t+1}$) and the reference technology to being compared in t time period(T^t), and the last combination of observation and the reference technology is observations being evaluated in t+1 time period($x^{k',t+1}$, $y^{k',t+1}$, $b^{k',t+1}$) and the reference technology to being compared in t+1 time period(T^{t+1}). Through 4 kinds of combinations, we get four different efficiencies of each observation.

3.6.3 Directional Vector

The third step is to choose the directional vector. There are many choices of the directional vectors. In this paper, we are using the symmetric directional vector(g_y=y, g_b=-b, g_x=x) since this directional vector has a good property for aggregation. This directional vector evaluates each observation based on the symmetric direction such that the maximal expansion of good output and the maximal contraction of bad output and inputs are treated symmetrically. Suppose that the measurement unit of good output(electricity generation) is KWh, bad output(SO_2 emission) is ton, input(fuel consumption) is million BTU, and the distance value of one generating unit is 12. Then the distance value means that the generating unit can increase good output by 12 KWh, and can contract bad output and input by 12 ton and 12 million BTU respectively relative to the frontier technology. If the measurement unit of good output is changed from KWh to MWh, and if we multiply the directional vector by 1,000, then we can get the same distance value. This directional vector can get an unbiased aggregate efficiency or aggregate productivity indicator.

$$\vec{D}_T{}^t{}_{CRS}(x^{k',t}, y^{k',t}, b^{k',t}; -1,1,-1) = \max \beta$$

s.t

$$\sum_{k=1}^{K} z_k \, y^t_{km} \geq y^t_{k'm} + \beta, m = 1,\ldots,M$$

$$\sum_{k=1}^{K} z_{kj} \, b^t_{kj} = b^t_{k'j} - \beta, j = 1,\ldots,J$$

$$\sum_{k=1}^{K} z_k \, x^t_{kn} \leq x^t_{k'n} - \beta, n = 1,\ldots,N$$

$$z_k \geq 0, k = 1,\ldots,K$$

(3.50)

3.6.4 Productivity Change

The next step is to calculate the efficiency change and productivity change using the previous linear programming. This step follows the definition of efficiency change measurement and productivity change measurement from the previous section. The only difference is that we measure the efficiency and productivity change of each generating unit as follows :

$$EFCH_{k,CRS} = \vec{D}_T{}^{t}{}_{CRS}(x^{k',t}, y^{k',t}, b^{k',t}; g) - \vec{D}_T{}^{t+1}{}_{CRS}(x^{k',t+1}, y^{k',t+1}, b^{k',t+1}; g) \quad (3.51)$$

The efficiency change of unit k under CRS is the difference in the distance value in period t and period t+1 under CRS based on directional vector(g). The scale efficiency is calculated as the difference in the distance value between CRS and VRS;

$$SCEFCH_k = [\vec{D}_T{}^{t}{}_{CRS}(x^{k',t}, y^{k',t}, b^{k',t}; g) - \vec{D}_T{}^{t}{}_{VRS}(x^{k',t}, y^{k',t}, b^{k',t}; g)] -$$

$$[\vec{D}_T{}^{t+1}{}_{CRS}(x^{k',t+1}, y^{k',t+1}, b^{k',t+1}; g) - \vec{D}_T{}^{t+1}{}_{VRS}(x^{k',t+1}, y^{k',t+1}, b^{k',t+1}; g)] \quad (3.52)$$

Also, the pure technical efficiency change is the difference between overall efficiency change and the scale efficiency change. That is,

$$PUTECH_k = [\vec{D}_T{}^{t}{}_{VRS}(x^{k',t}, y^{k',t}, b^{k',t}; g) - \vec{D}_T{}^{t+1}{}_{VRS}(x^{k',t+1}, y^{k',t+1}, b^{k',t+1}\ g)] \quad (3.53)$$

As noted in the previous section, the efficiency change is decomposed into scale efficiency change and the pure technical efficiency change. That is,

$$EFCH_k = SCEFCH_k + PUTECH_k \quad (3.54)$$

The technological change is calculated under the CRS technology as follows :

$$TECH_k = 1/2\{[\vec{D}_T{}^{t+1}{}_{CRS}(x^{k',t+1}, y^{k',t+1}, b^{k',t+1}; g) - \vec{D}_T{}^{t}{}_{CRS}(x^{k',t+1}, y^{k',t+1}, b^{k',t+1}; g)]$$

$$+[\vec{D}_T{}^{t+1}{}_{CRS}(x^{k',t}, y^{k',t}, b^{k',t}; g) - \vec{D}_T{}^{t+1}{}_{CRS}(x^{k',t}, y^{k',t}, b^{k',t}; g)]\} \quad (3.55)$$

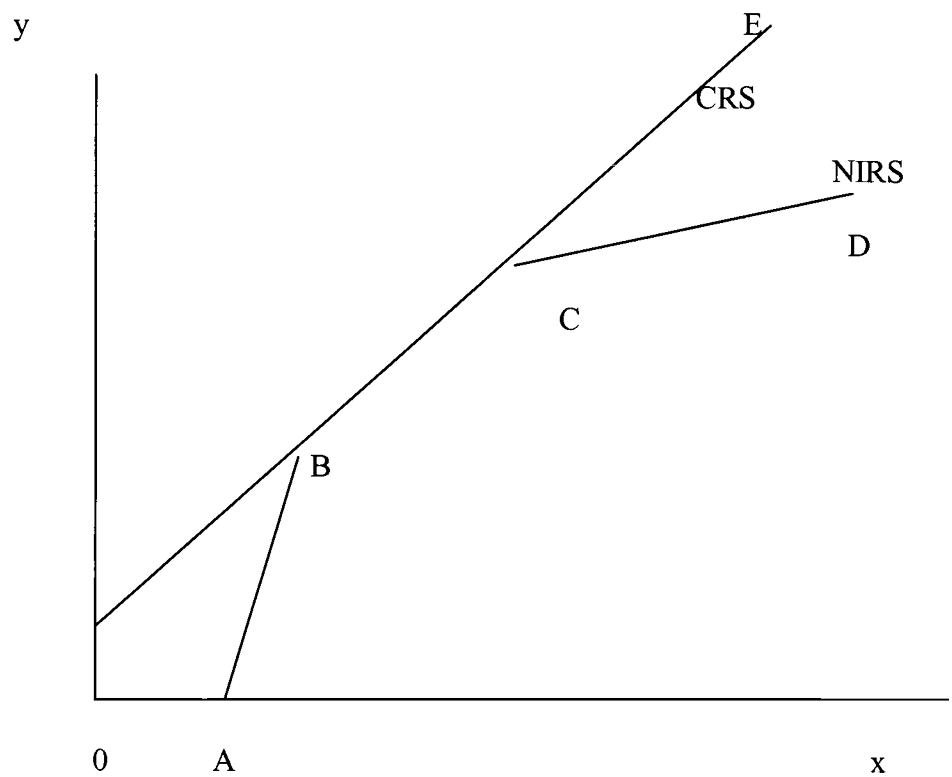
The Luenberger productivity change is the sum of efficiency change and technological change. That is,

$$PRODCH_k = EFCH_k + TECH_k \quad (3.56)$$

3.6.5 Identification of Returns to Scale

When the distance value under CRS is the same as the distance value under VRS, then the unit is in the constant returns to scale range like OBCE in the following figure. When the distance value under CRS is different from the distance value under VRS, but the distance value under VRS is same as the distance value under non-increasing returns to scale(NIRS), then the unit is in the decreasing returns to scale range like CD in the figure. If the CRS distance value is different from the VRS distance value, and the VRS distance value is not same(or greater) as the NIRS distance value, then the unit is in the increasing returns to scale range like AB in the figure.

Figure 3.4 Identification of Returns to Scale



3.7 Data

3.7.1 Definition and Source

The Acid Rain Program of CAAA 1990 started in 1995 to reduce the sulfur dioxide(SO_2) emissions of the electricity industry. This program achieved the target level of SO_2 emission through two Phases. The first Phase started in 1995 and ended in 1999, and the second Phase was implemented from 2000. In Phase I, the emission rate standard for sulfur dioxide(SO_2) was set to 2.5 pounds per million BTU of heat input for the dirtiest 261 generating units. The emission rate standard in Phase II was strengthened to 1.2 pounds of SO_2 emission per million BTU of heat input for most of the fossil fuel fired electric generating units of which generating capacity is 25 MW or more including Phase I units. The federal government gave each generating unit allowances that are equivalent to the SO_2 emission rate standard calculated based on the average heat input during the 1985-87 period.

The 261 Phase I generating units were the objective of the Phase I environmental regulation from 1995 to 1999 since these units' SO_2 emission rate was the highest. In Phase II, over 3000 units including Phase I units are affected by the Phase II SO_2 emission regulation. Since the environmental regulation of Acid Rain Program is applied to the individual unit instead of electric plant or utility, we use the electric generating unit level's data.

Boilers produce heat, and the generating unit use that heat to produce electricity. So there is a basic physical relationship between boilers and the generating unit. In most cases, there is a one-to-one relationship between boilers and the generating unit such that one boiler supplies the heat to one generating unit. But, there is a multiple relationship among boilers and generating units too. In those cases, one boiler supplies heat to multiple generating units, several boilers supply heat to one generating unit, or several boilers supply heat to several generating units. There are 263 boilers that supply the heat to the 261 Phase I generating units. Among the 263 boilers, 261 boilers have a one-to-one relationship with generating units, and only 2 boilers have a multiple relationship. Electricity is produced from generating unit using the heat supplied from boilers, but the SO_2 is emitted from boilers. So we assume that the basic observation unit is the generating unit.

The EIA767(Annual Steam Electric Unit Operation and Design Report) of the Energy Information Administration(EIA) of the Department of Energy(DOE) contains the unit and boiler level's data. The EIA-767 data file is a steam-electric unit data file that includes annual data from organic- or nuclear-fueled steam-electric units with a generator nameplate rating of 10 or more megawatts. The data are derived from the Form EIA-767 "Steam-Electric Unit Operation and Design Report".

We get the annual electricity production(MWh) and generating capacity(MW) of each generating unit from EIA767. Some of the generating units do not produce electricity, and instead receive electricity from other generating units(this electricity production is listed as minus electricity production in the EIA767 database). We exclude these units from the sample.

Except for electricity generation and generating capacity data, we can not get the data of the generating unit. Since most of the 261 Phase I generating units(except for 2 units) have a one-to-one relationship with the boiler, we assume that the boiler's data is the same as the generating unit's data. That is, the fuel consumption and SO_2 emission of each boiler are assumed to be the fuel consumption and SO_2 emission of each corresponding generating unit. However, in the case of a multiple relationship between boiler and unit, we assume that the fuel consumption and the SO_2 emission of generating units are proportional to the ratio that each boiler contributed to the total electricity generation of each unit. We can get the fuel consumption(million BTU) of each generating unit by multiplying the boiler's fuel consumption by the electricity production ratio of each generating unit since the electricity production is assumed to be proportional to the heat input. There are four kinds of fuel : coal, oil, gas and other fuel. We multiply the monthly quantity of fuel consumption by the heat content of each fuel. Then we sum it to get the annual fuel consumption using the data from the

EIA767 data set since the EIA767 data base offers monthly fuel quantity and heat content for each boiler.

We get the SO_2 emission(ton) data of each boiler from the Environmental Protection Agency(EPA)'s Acid Rain Program data base. This emission data is measured from Continuous Emissions Monitoring System(CEMS). CEMS was installed with the implementation of the Acid Rain Program in 1994. We transformed the boiler's SO_2 emissions multiplying the emission by the electricity production ratio to get the SO_2 emissions of each generating unit. In the period between 1995-1997, we could not get separate SO_2 emissions for some boilers that shared a stack. In this case, we also divided the SO_2 emissions of the stack by the electricity generation ratio of each unit. Since 1998, we were able to get separate CEMS SO_2 emission data for each boiler.

Table 3.1 Variable Definition and Source

Variable	data file name	institute
Quantity		
- good output : electricity generation(MWh)	EIA767	DOE/EIA
- bad output : SO2 emission(ton)	Acid Rain Program Database	EPA
- input1 : fuel consumption(mmBTU)	EIA767	DOE/EIA
- input2 : electricity capacity(MW)	EIA767	DOE/EIA
- input3 : labor(person)	FERC-1	FERC

We could not get the generating unit's labor data since the labor data was available only in the level of electric utility. Instead we got the utility's labor data from the Federal Energy Regulatory Commission's FERC-1(Electric Utility Annual Report). The FERC-1 is a comprehensive and operating Report for Electric Rate regulation and financial audits. Major defined as (1) one million Megawatt hours or more; (2) 100 megawatt hours of annual sales for resale; (3) 500 megawatt hours of annual power exchange delivered or (4) 500 megawatt hours of annual wheeling for others (deliveries plus losses). So we assume that the generating unit's labor is proportional to the electricity production ratio of each unit to the electric utility' electricity production. We multiply the number of the utility's employees by the electricity generation ratio of each generating unit to get the labor of each generating unit. The labor of the half-time employee is assumed to be the half of the full-time employee.

We excluded 52 units from the sample data since we could not get their labor data. So the final data set is composed of 209 generating units during the 1990-1999 period.

3.7.2 Identification of Compliance Strategy Change

All of the phase I generating units reported their SO_2 emission reduction compliance strategy to the Department of Energy(DOE) before 1995. This information is the only available data to identify the compliance strategy of each generating unit. Among the 261 phase I generating units, 136 units reported switching their fuel to low-sulfur coal, 27 units were to install scrubbers, 83 units were planning to purchase allowance, 7 units were scheduled to retire, and 8 units were to use "other" strategies according to the report. However, many plants changed their compliance strategy in the phase I period because of changes in the market and the time lag between the reports and the implementation of the strategies.

For information about utilities applying the scrubber compliance strategy, we checked the scrubber(FGD) data for each generating unit. We identified whether the unit installed the scrubber or not, and the year when the unit installed and operated scrubber even before the phase I period. All 27 units which reported their compliance strategy as scrubbers had installed and operated scrubber from 1995. One unit(utcode-ptcode-unit-blid:13998-2861-1-1) used scrubber strategy from 1996, and another unit(utcode-ptcode-unit-blid:18454-645-ST3-BB03) operated scrubber from 1997. Even though two other units(18454-645-1,ST2-BB01,BB02) installed scrubber in 1999, these units are applied to the phase II period(from 2000) since they did not operate scrubber in 1999. So two units additionally adopted scrubber strategy. Both of these units had previously reported their compliance strategy to be a fuel switch. As a result, the realized number of generating units that installed and used scrubber strategy in the phase I period was 29 units.

If the SO_2 emission of the generating units in phase I period that reported allowance strategy as a compliance strategy is continuously below the emission standard(2.5 pound of SO_2/mmBTU of heat input), and these units did not buy allowance, then we identified these units changed strategy from reported allowance purchasing to actual fuel switch strategy. Four generating units(ptcode-unit:2872-5,2049-4,5, 2527-4) changed their strategy to fuel switch from the allowance strategy they reported to the Department of Energy(DOE). Of these, one unit changed its strategy in 1995, while the remaining three units changed their strategies in 1997.

If the SO_2 emissions of the generating units that switched their fuel to low-sulfur coal was continuously over the emission standard(2.5 pound of SO_2/mmBTU of fuel consumption) and bought the allowance, then we identified their strategy changed from reported fuel switch to actual allowance strategy. Twenty-three generating units changed their compliance strategy to allowance strategy from fuel switch. Only one unit changed its strategy in 1996, while the remaining 22 units changed their strategies in 1995.

Instead of 7 units, only 4 generating units retired. Seven units used "other" strategies including switching to natural gas or oil. The final total of compliance strategies for the 261 phase I generating units, then, is as follows : 29 generating units used scrubber strategy as SO_2 emission reduction compliance strategy, 102 units used allowance strategy, 116 units used fuel switch strategy, 11 units used "other" strategy.

One interesting point to note is that 23 units changed their strategies from fuel switch to allowance, while only 4 units changed their strategies from allowance to fuel switch. The reason for this is that the initial forecasted price of allowance before 1993 was much higher than the actual price when the allowance market opened in 1993. The allowance price was between $100 and $150, while the forecasted price was over $200. Since the reported compliance strategy was made before the opening of allowance market, the electric utility may have based their compliance strategy on the forecasted price of allowance.

Table 3.2 Number of Generating Units by Compliance Strategy

allowance strategy	1995	1996	1997
- reported	83	104	105
- change from fuel switch	22	1	0
- change to fuel switch	1	0	3
- estimated	104	105	102
"other" strategy			
- reported	11	11	11
scrubber strategy			
- reported	27	28	28
- change from fuel switch	1	0	1
- estimated	28	28	29
fuel switch strategy			
- reported	136	114	113
- changed from allowance	1	0	3
- change to allowance	22	1	0
- estimated	114	113	116

3.7.3 Data Statistics

The mean electricity generation(MWh) of the 209 phase I generating units declined continuously before 1995, but rapidly increased in the phase I period(1995-1999). SO_2 emission(ton) declined sharply in the pre-phase I period, but stabilized in the phase I period. Fuel consumption(mmBTU) which generally declined before 1995, increased in the phase I period. Generating capacity(MW) was constant from 1990 to 1998, increased a little in 1999. Labor(person) declined continuously in the sample period. One interesting point is that electricity generation and fuel consumption increased from 1996.

The mean electricity generation of the units with scrubber was the biggest, the next was fuel switch, then allowance and "other" strategies. In terms of electricity generation level, the units with scrubber generated about twice as much as units with fuel switch and allowance and three times as much as units with "other" strategies. In particular, the mean electricity generation of the units with "other" strategies in 1995 declined to half level of 1990's level and finally returned to 1990's level in 1999.

In the pre-phase I period, units with "other" strategies emitted the highest level of SO_2. units using a scrubber strategy emitted half of what those units did, while units applying a fuel switch strategy reported emitting only 1/4 as much. However, the units applying "other" strategies emitted the lowest SO_2 emission in phase I period, the emission level of the units with scrubber is the next lowest, followed by fuel switch and allowance. As a result, the units with "other" and scrubber strategy decreased SO_2 emission rapidly, but the units with allowance decreased SO_2 emission only a little. The mean SO_2 emission of the units with allowance in the phase I period was around three times the SO_2 emission of the units with "other" and scrubber strategy.

Table 3.3 Data Statistics of 209 Phase I Generating Units in 1990-1999

Variable	unit	Mean	Std Dev	Minimum	Maximum
1990					
gen	(MWh)	1775873.06	1370720.12	19467.00	7518927.00
so2	(ton)	37882.95	37532.52	940.8080000	232218.70
cap	(MW)	348.4261579	248.9971032	18.7500000	1300.00
fuel	(mmBTU)	17634256.65	13139777.26	412831.04	71469772.74
labor	(person)	335.6736427	270.6323179	4.2931790	1137.51
1991					
gen	(MWh)	1733597.59	1431387.56	13226.70	7696922.00
so2	(ton)	37028.33	39344.56	506.4652600	252220.50
cap	(MW)	348.4261579	248.9971032	18.7500000	1300.00
fuel	(mmBTU)	17192218.11	13700742.69	263628.02	75603347.39
labor	(person)	315.0047325	272.8067020	3.2364950	1374.89
1992					
gen	(MWh)	1731247.56	1430171.82	94.0000000	7565484.00
so2	(ton)	34332.05	34443.23	113.0300000	204588.96
cap	(MW)	348.4261579	248.9971032	18.7500000	1300.00
fuel	(mmBTU)	17201869.26	13818019.58	43792.86	72649029.91
labor	(person)	318.3897140	268.2475773	0.0238202	1285.78
1993					
gen	(MWh)	1719881.40	1354831.97	43679.00	7635631.00
so2	(ton)	32188.18	32550.35	513.7107348	201666.50
cap	(MW)	348.4261579	248.9971032	18.7500000	1300.00
fuel	(mmBTU)	17083906.73	12932880.82	705786.28	73148144.10
labor	(person)	306.0908743	250.2589442	6.4797670	1281.81
1994					
gen	(MWh)	1674907.63	1378213.01	16218.50	6492163.00
so2	(ton)	27210.50	26493.05	461.1526500	169776.03
cap	(MW)	348.4261579	248.9971032	18.7500000	1300.00
fuel	(mmBTU)	16699725.60	13283718.10	265943.58	62866288.46
labor	(person)	279.3140586	233.8854289	3.4525605	1196.70
1995					
gen	(MWh)	1682788.04	1431325.41	2679.00	7437300.00
so2	(ton)	17134.16	17398.48	10.0000000	104172.00
cap	(MW)	348.4261579	248.9971032	18.7500000	1300.00
fuel	(mmBTU)	16435212.26	13550926.99	132144.00	73277883.79
labor	(person)	255.8648205	223.5761547	0.2392648	973.3960567
1996					
gen	(MWh)	1793539.78	1472783.89	11364.00	9163854.00
so2	(ton)	18575.13	17218.37	4.0000000	105553.00
cap	(MW)	348.4261579	248.9971032	18.7500000	1300.00
fuel	(mmBTU)	17576554.31	13932728.89	139939.65	88418383.67
labor	(person)	254.6653751	222.8778100	2.1338257	997.3714125

Variable	Label	Mean	Std Dev	Minimum	Maximum
1997					
gen	(MWh)	1829141.87	1448321.66	4352.00	7933261.00
so2	(ton)	18649.98	17300.75	3.0000000	95312.00
cap	(MW)	348.4261579	248.9971032	18.7500000	1300.00
fuel	(mmBTU)	18325846.02	14014520.39	47658.69	77800003.42
labor	(person)	250.1796626	212.8769525	2.1463232	950.0194826
1998					
gen	(MWh)	1872398.98	1491141.73	14804.00	9051140.00
so2	(ton)	18727.94	17270.01	7.0000000	120253.00
cap	(MW)	348.4261579	248.9971032	18.7500000	1300.00
fuel	(mmBTU)	18756872.22	14390526.05	164675.14	88499674.27
labor	(person)	236.8375799	207.1038679	8.1806157	1051.31
1999					
gen	(MWh)	1880184.35	1494072.99	3661.00	8297011.00
so2	(ton)	17314.60	16342.79	22.5423858	91310.00
cap	(MW)	348.4936220	248.9245636	18.7500000	1300.00
fuel	(mmBTU)	18846785.94	14393586.46	40792.19	81169346.19
labor	(person)	238.5745910	221.1468727	1.8238992	1357.45

Figure 3.5 Mean Electricity Generation(MWh)

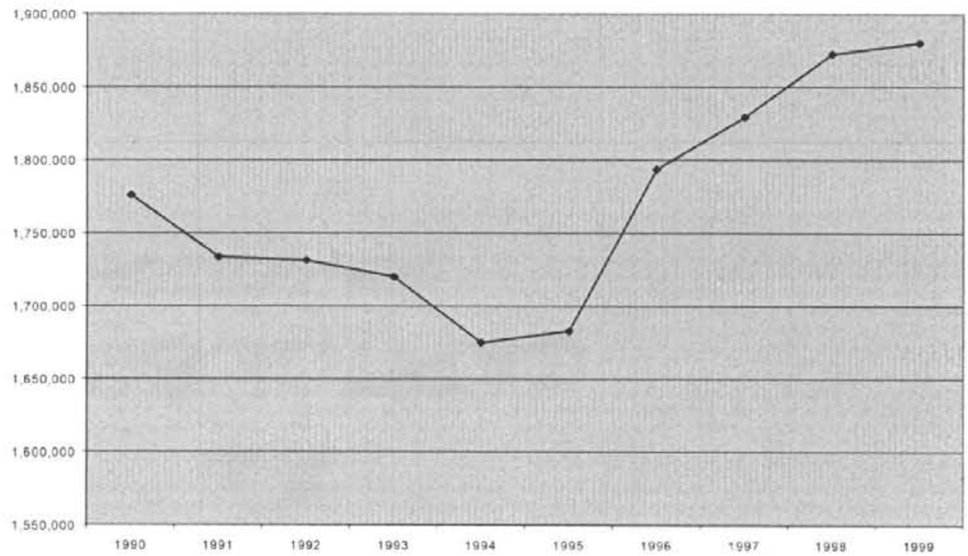


Figure 3.6 Mean Electricity Generation(MWh) by Strategy

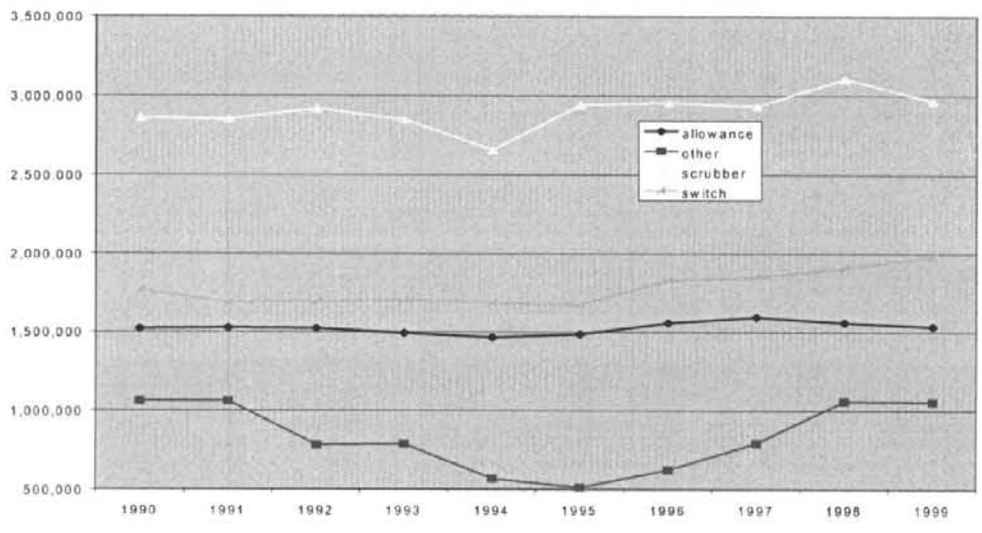


Figure 3.7 Mean SO_2 emission(ton)

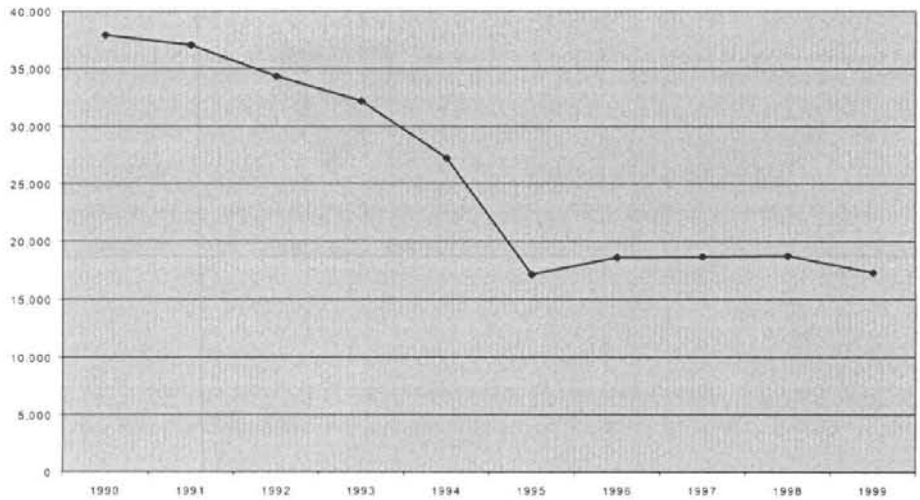


Figure 3.8 Mean SO_2 emission(ton) by Strategy

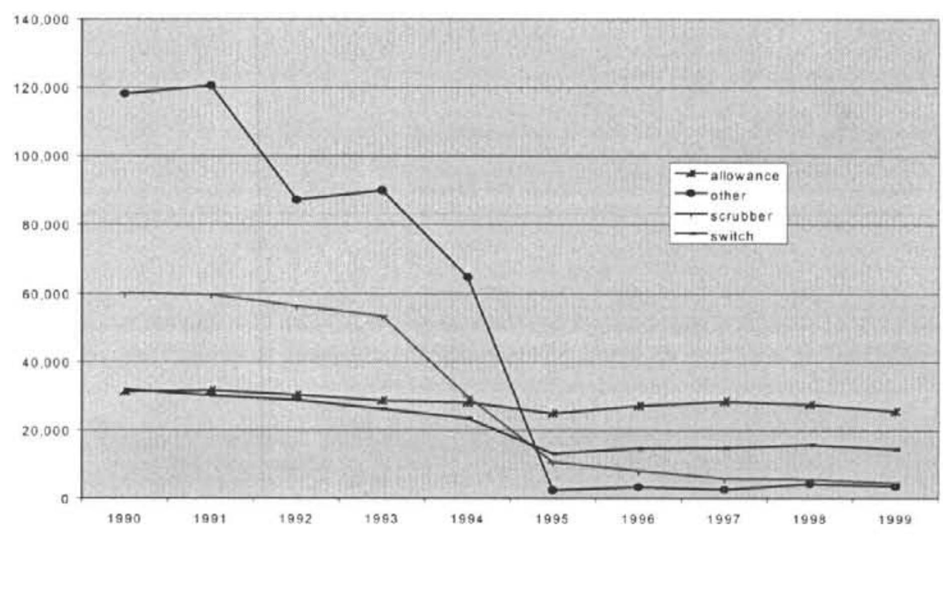


Figure 3.9 Mean Generating Capacity(MW)

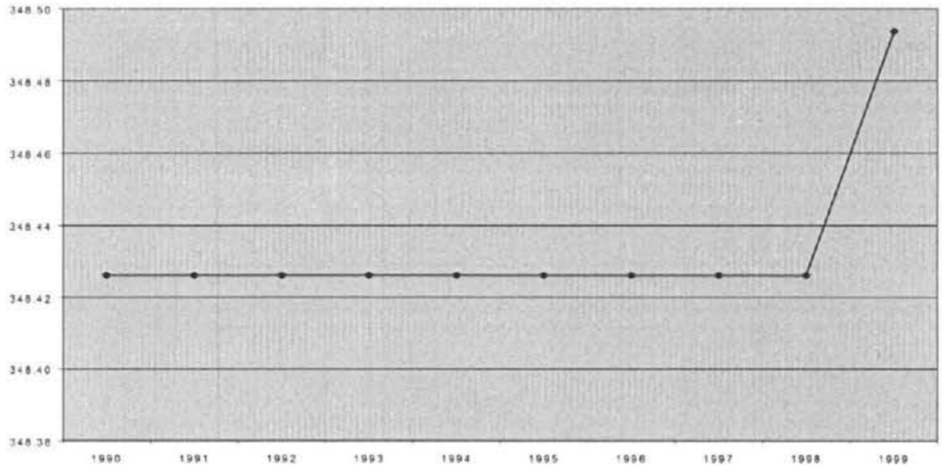


Figure 3.10 Mean Generating Capacity(MW) by Strategy

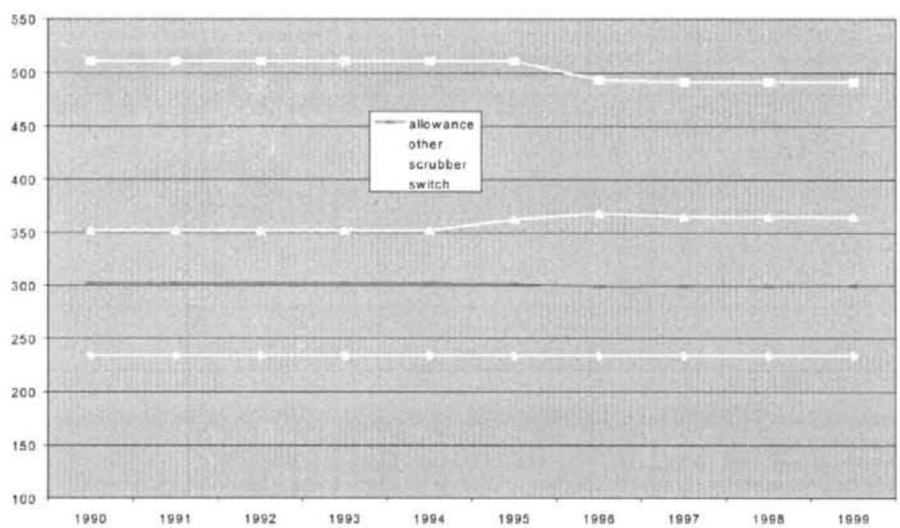


Figure 3.11 Mean Fuel Consumption(mmBTU)

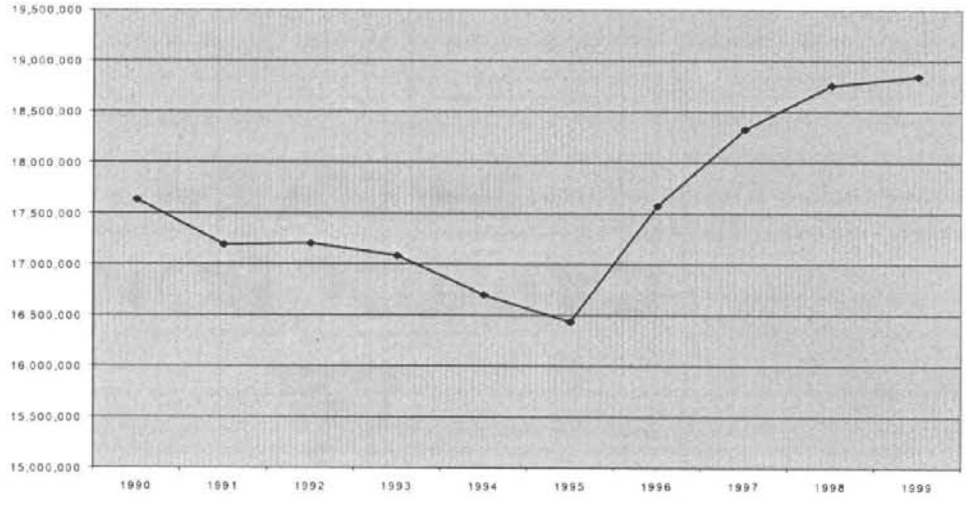


Figure 3.12 Mean Fuel Consumption(mmBTU) by Strategy

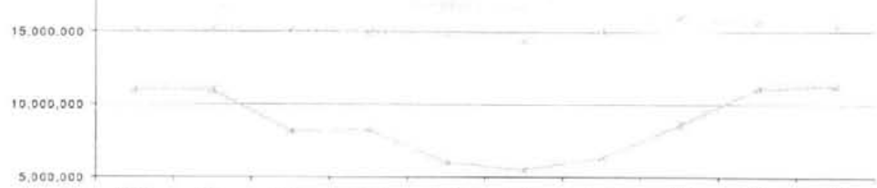


Figure 3.13 Mean Labor(person)

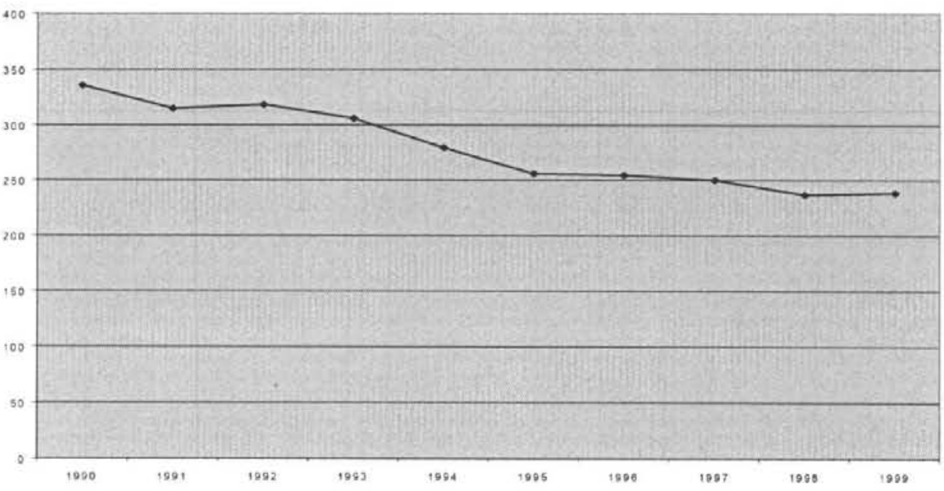
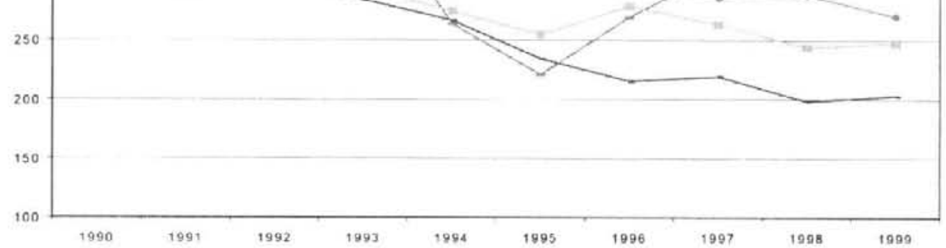


Figure 3.14 Mean Labor(person) by Strategy



3.8 Estimation Result

We estimate the Luenberger productivity indicator and the effect of SO_2 emission regulation on the productivity change using the symmetric directional vector(g_x=-1, g_y=1, g_b=-1). The mean value of efficiency and productivity per year is defined by using the agregation of each generating unit's efficiency score and productivity indicator and dividing it by the number of generating units(209 units per year). The mean value of the efficiency and productivity indicator in the pre-phase I period and during the phase I period is calculated by summing each unit's corresponding value and dividing it by the total number of units. We used the same method for the efficiency and productivity of each compliance strategy. Since we use a symmetric directional vector, there is no aggregation problem.

3.8.1 Efficiency Estimation

3.8.1.1 Efficiency by Time Period

We aggregate the efficiency score and divide it by the number of units(209) each year to get the annual mean efficiency score. We use same method to get the mean efficiency score pre- and during the phase I period.

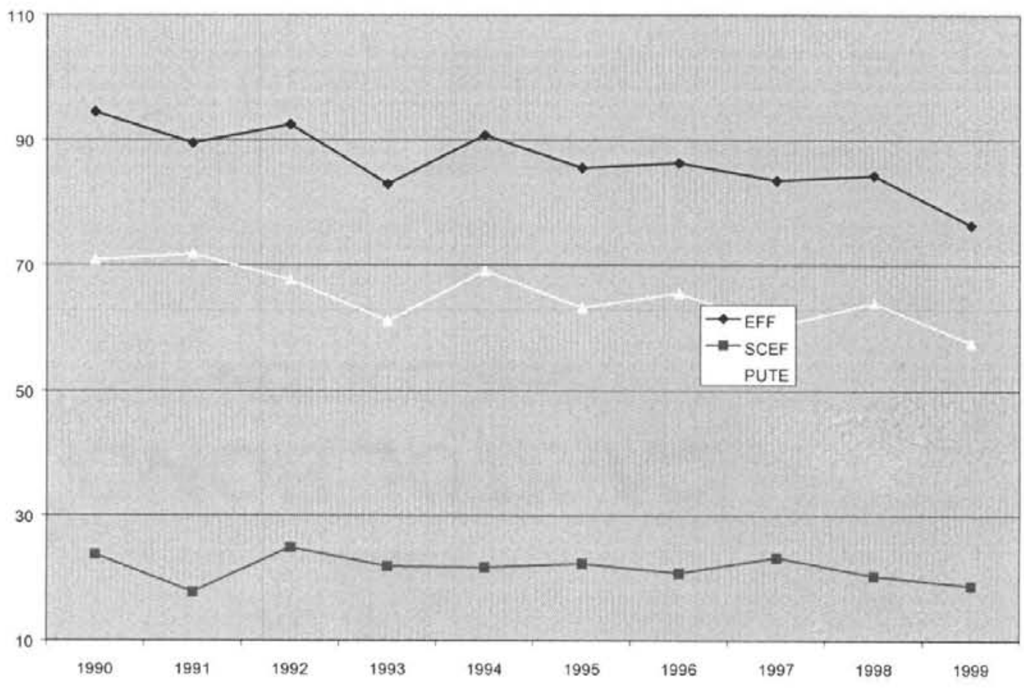
When we evaluate each observation based on the symmetric directional vector(g_x=-1, g_y=1, g_b=-1) under weak disposability of outputs, the mean efficiency of the 209 phase I generating units is 86.59 in 1990-99 period. This efficiency score means that, on average, the units can increase 87 MWh of electricity generation and decrease 87 ton of SO_2 emissions and inputs by 87 units(MW for generating capacity, mmBTU for fuel consumption, person for labor) respectively.

Table 3.4 Mean Efficiency Score in 1990-1999

	weak disposability of output			strong disposability of output		
year	efficiency	scale efficiency	pure tech efficiency	efficiency	scale efficiency	pure tech efficiency
1990	94.48249	23.70794	70.77455	109.32282	25.41995	83.90287
1991	89.44086	17.70397	71.73689	104.56158	21.16325	83.39833
1992	92.47258	24.80636	67.66622	105.66804	28.61163	77.05641
1993	82.89876	21.85086	61.04789	91.22340	18.63057	72.59282
1994	90.74488	21.66612	69.07876	103.16923	28.16000	75.00923
1995	85.50522	22.29660	63.20861	87.16852	22.24153	64.92699
1996	86.27010	20.76000	65.51010	89.31301	21.44067	67.87234
1997	83.47598	23.23100	60.24498	85.18163	24.46938	60.71225
1998	84.24909	20.32785	63.92124	85.07971	20.67622	64.40349
1999	76.32416	18.72431	57.59986	77.92904	20.25230	57.67675
mean(90-99)	86.58641	21.50750	65.07891	93.86170	23.10655	70.75515
mean(90-94)	90.00791	21.94705	68.06086	102.78901	24.39708	78.39193
mean(95-99)	83.16491	21.06795	62.09696	84.93438	21.81602	63.11836

The mean scale efficiency is 21.5, and the pure technical efficiency is 65.1 in the whole time period(1990-1999). So the main source of inefficiency is pure technical inefficiency when we decompose the efficiency scores into scale efficiency and pure technical efficiency. The pure technical inefficiency comes from the manager's capability, but the scale inefficiency is beyond the manager's capability. So, the managers of the phase I units can increase electricity generation and can decrease SO_2 emission and inputs by around 43 units more through reorganizing the production procedure or administrative structure efficiently(pure technical efficiency improvement) than through changing the operation scale(scale efficiency improvement).

Figure 3.15 Mean Efficiency with Weak Disposability of Output



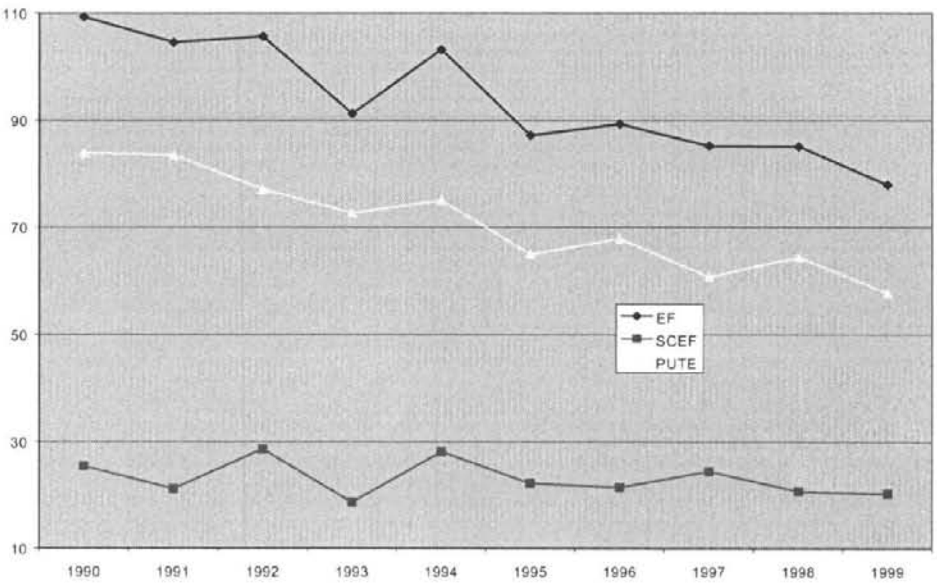
Since scale efficiency is higher than the pure technical efficiency before and during the Phase I period, so the mian source of inefficiency is pure technical inefficiency regardless of time period. This finding means that phase I generating units have more potential to increase to efficiency through pure technical efficiency improvement than scale efficiency improvement.

Even though both the scale efficiency and pure technical efficiency improved after 1995, the degree of pure technical efficiency improvement is greater than the improvement of scale efficiency in the phase I period. Therefore the efficiency improvement in the stronger environmental regulation period was lead by pure technical efficiency improvement.

The trend of efficiency score under the strong disposability of outputs is similiar to the trend of the efficiency score under weak disposability. The mean efficiency under strong disposability is 8% lower than the efficiency under weak disposability. That is, the technology under weak disposability envelopes the data set more closely than the technology under strong disposability. In other words, the efficiency score under the weak disposability technology is better than the efficiency score under strong disposability technology.

The main source of inefficiency is pure technical inefficiency regardless of disposability and time period. So the units have more potential to increase efficiency through pure technical efficiency improvement than through scale operation.

Figure 3.16 Mean Efficiency with Strong Disposability of Output



3.8.1.2 Efficiency by Compliance Strategy

The average efficiency score under weak disposability was highest for generating units that use "other" strategies and next highest for units using allowance strategy in the period between 1990 and 1999. The efficiency of scrubber units was third, and the efficiency of units using fuel switch strategy was lowest.

If we seperate the efficiency score of each strategy group into before and during the phase I period, there is a big change in the efficiency ranking. The efficiency of the units with "other" strategy is the highest before the phase I period, the next being the allowance strategy, followed by fuel switch and scrubber. The ranking in the phase I period, however, is allowance-scrubber-fuel switch-"other" units. In the stronger SO_2 emission regulation, the efficiency of the units with allowance and scrubber is high, but the efficiency of the units with fuel switch and "other" strategy is relatively low. The units using an allowance strategy maintained the high ranking in the efficiency, but the units with "other" strategy fell in the ranking during the whole period.

Table 3.5 Mean Efficiency by Compliance Strategy

	weak disposability of output			strong disposability of output		
strategy	efficiency	scale efficiency	pure tech efficiency	efficiency	scale efficiency	pure tech efficiency
1990-99						
allowance	69.37003	18.84999	50.52004	72.30474	20.40394	51.90080
Other	62.29263	6.46950	55.82313	65.17050	7.43188	57.73863
scrubber	89.56249	42.81857	46.74392	104.10613	49.33470	54.77143
Switch	99.46046	20.10674	79.35372	108.52914	20.78584	87.74330
1990-94						
allowance	85.88892	18.07387	67.81505	92.59419	21.74698	70.84721
Other	15.13375	5.34900	9.78475	15.39175	5.33650	10.05525
scrubber	103.87695	57.44771	46.42924	123.13419	64.80095	58.33324
Switch	94.85612	18.79561	76.06051	110.60272	19.87537	90.72735
1995-99						
allowance	56.64765	19.44773	37.19993	56.67839	19.36956	37.30883
other	109.45150	7.59000	101.86150	114.94925	9.52725	105.42200
scrubber	76.14268	29.10375	47.03893	86.26732	34.83509	51.43223
switch	105.02562	21.69147	83.33415	106.02285	21.88630	84.13655

The major source of inefficiency is pure technical inefficiency except for the units with scrubber in the pre-phase I peirod. The main source of inefficiency in the phase I period is pure technical inefficiency for every compliance strategy.

The ranking of the efficiency score under strong disposability is same as the ranking of the efficiency score under weak disposability regardless of time period. And the main source of inefficiency is the same as the main sources under weak disposability.

The common finding in the efficiency of each compliance strategy is that the efficiency of the units using an allowance strategy is relatively high before and during the phase I period, while the efficiency of the units using scrubber is the next highest in the Phase I period. The main source of inefficiency is pure technical inefficiency regardless of disposability and time period.

Table 3.6 Most Efficient Units Numbers by Strategy Under Weak Disposability

strategy	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
allowance	1	2	2	2	0	12	11	12	11	14
"other"	4	3	5	4	3	1	2	2	3	2
scrubber	0	1	3	3	3	5	4	5	4	5
switch	15	17	14	15	9	6	2	3	6	3
sum	20	23	24	24	15	24	19	22	24	24

Approximately 12%(around 24 units each year) of the total number of units consisted of the frontier units which had efficiency score of zero each year. Before 1995, over half of the frontier units were from units using a fuel switch strategy, during the phase I period most of the frontier units were from units using an allowance strategy. The number of the units with fuel switch and "other" strategy that are on the frontier technology declined in the phase I period, but the number of the units with allowance and scrubber strategy that are in the frontier technology increased.

The proportion of electricity generation that was produced by the generating units in the range of the constant returns to scale increased continuously from 7% in 1990 to around 12% in 1999. But the proportion of the increasing returns to scale also decreased continuously from 36% in 1990 to 23% in 1999. The proportion of the decreasing returns to scale increased from 57% in 1990 to 64% in 1999. The decline in the proportion of increasing returns to scale overweighted the increase in the proportion of constant returns to scale. Over half of the electricity generation was produced by units that were in the range of decreasing returns to scale. Since the proportion of the electricity generation of the units that were in the range of increasing returns to scale and constant returns to scale declined, there was an exhaustion of economies of scale in the 1990s. So, this finding implies that the efficiency of the phase I plants can improve if they decrease their operating scale.

The mean electricity generation of the units in the increasing returns to scale was the lowest, while the units in the constant returns to sclae was next. The highest mean electricity generation was achieved by units in the range of decreasing returns to scale. This finding is consistent with the general trend in production economics. Generally, since regulated industry is not characterized by constant returns to scale, failure to account for scale effects will lead to biased productivity measurement(Cowing et al, 1981). The efficiency of the units that are located in the region of constant returns to scale is almost 20 times the efficiency of decreasing returns to scale. So, if we ignore the scale effects, the efficiency measurement will be distorted. The mean efficiency of the units in the range of constant returns to scale is the highest, and the efficiency of the units in the range of increasing returns to scale is next.

Table 3.7 Efficiency and Returns to Scale Technology

year	tech-nology	efficiency	scale efficiency	pure tech efficiency	total electricity generation(MWh)	mean electricity generation(MWh)	ratio (%)
1990	CRS	0.000	0.000	0.000	25,873,257	1,293,663	0.07
1990	DRS	152.282	44.120	108.162	211,556,459	2,898,034	0.57
1990	IRS	74.399	14.950	59.449	133,727,755	1,152,825	0.36
1991	CRS	0.000	0.000	0.000	29,891,377	1,299,625	0.08
1991	DRS	139.717	32.298	107.419	220,778,727	2,867,256	0.61
1991	IRS	72.798	11.130	61.668	111,651,794	1,024,328	0.31
1992	CRS	5.204	0.000	5.204	35,427,011	1,417,080	0.10
1992	DRS	155.578	57.019	98.559	199,918,078	3,029,062	0.55
1992	IRS	75.665	12.045	63.621	126,485,650	1,071,912	0.35
1993	CRS	8.296	0.000	8.296	36,825,787	1,416,376	0.10
1993	DRS	134.207	48.103	86.104	204,374,268	2,878,511	0.57
1993	IRS	67.692	10.281	57.410	118,255,159	1,055,850	0.33
1994	CRS	6.381	0.000	6.381	22,892,458	1,430,779	0.07
1994	DRS	145.599	40.917	104.681	211,329,206	2,780,647	0.60
1994	IRS	66.650	12.124	54.526	115,834,033	990,034	0.33
1995	CRS	4.675	0.000	4.675	42,507,050	1,771,127	0.12
1995	DRS	134.876	47.861	87.016	219,372,040	2,812,462	0.62

1995	IRS	67.645	8.662	58.983	89,823,610	839,473	0.26
1996	CRS	22.157	0.000	22.157	36,712,543	1,668,752	0.10
1996	DRS	142.653	41.398	101.256	223,380,811	2,901,049	0.60
1996	IRS	59.624	10.466	49.159	114,756,461	1,043,241	0.31
1997	CRS	0.011	0.000	0.011	45,806,969	1,991,607	0.12
1997	DRS	132.747	42.337	90.410	245,701,678	2,613,848	0.64
1997	IRS	54.000	9.517	44.483	90,782,004	986,761	0.24
1998	CRS	4.212	0.000	4.212	50,411,044	2,016,442	0.13
1998	DRS	138.295	40.417	97.879	247,936,006	2,817,455	0.63
1998	IRS	55.550	7.207	48.343	92,984,337	968,587	0.24
1999	CRS	11.412	4.091	7.321	47,595,440	1,903,818	0.12
1999	DRS	122.071	35.824	86.247	253,175,700	2,876,997	0.64
1999	IRS	51.294	6.861	44.433	92,187,392	960,285	0.23
mean	CRS	6.281	0.447	5.835	373,942,936	1,632,939	0.10
mean	DRS	139.127	42.647	96.480	2,237,522,973	2,839,496	0.61
mean	IRS	65.140	10.478	54.662	1,086,488,195	1,012,571	0.29

3.8.2 Productivity Change

3.8.2.1 Productivity Change by Time Period

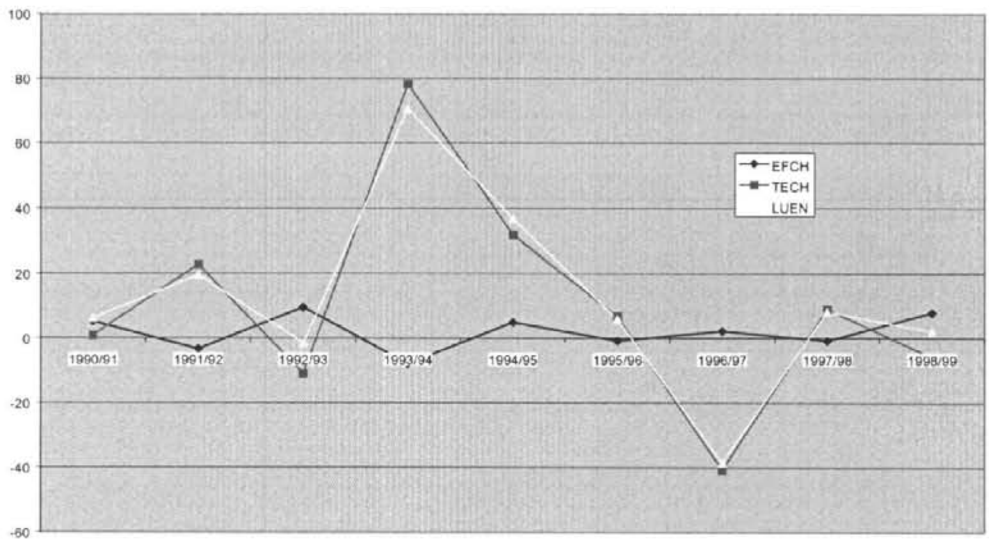
When we measure the Luenberger productivity indicator under the weak disposability of output using the symmetric directional vector(g_x=-1, g_y=1, g_b=-1) in the 1990-1999 period, the average annual productivity of the 209 phase I generating units improved. There were productivity decline only in two time periods(1992/93, 1996/97), but the remaining time periods showed the productivity growth. Furthermore, the two time periods with productivity decline have a common feature that the magnitude of technological decline is greater(five times) than the positive efficiency growth.

Table 3.8 Productivity Change under Weak Disposability

year	scale efficiency change	pure tech. efficiency change	efficiency change	technological change	productivity change
1990/91	7.49364	-2.26411	5.22388	0.94885	6.18239
1991/92	-6.72325	3.46522	-3.25416	22.79684	19.52847
1992/93	3.02861	6.49053	9.51880	-10.97895	-1.45794
1993/94	-0.64421	-7.20191	-7.84804	78.28129	70.43129
1994/95	-0.95751	5.86249	4.90244	31.86866	36.76306
1995/96	1.63789	-2.40301	-0.76612	6.75124	5.97541
1996/97	-2.72904	4.93368	2.20641	-40.78498	-38.57651
1997/98	2.66292	-3.43593	-0.77507	9.00431	8.23129
1998/99	1.60354	6.32139	7.92522	-5.78019	2.15177
mean(1990-99)	0.59695	1.30759	1.90371	10.23412	12.13658
mean(1990-94)	0.78870	0.12243	0.91012	22.76201	23.67105
mean(1995-99)	0.79383	1.35403	2.14761	-7.70240	-5.55451

Both the efficiency growth and the technological growth contributed to the productivity growth in the whole period, but the magnitude of technological growth contribution was greater than the degree of efficiency growth. So during the whole time period, the main source of productivity growth came from technological growth.

Figure 3.17 Luenberger Productivity Change under Weak Disposability of Output



When we decompose the efficiency growth into scale efficiency growth and pure technical efficiency growth, we find that both the scale efficiency and pure technical efficiency improved, but the pure technical growth was greater than the scale efficiency growth. Therefore, the main source of efficiency growth was pure technical efficiency improvement rather than the scale efficiency growth.

There was a high degree of productivity improvement before the phase I period since both the efficiency and the technology improved. In particular, the main source of productivity growth before the phase I period was technological growth. However, there was a productivity decline in the phase I period since the negative technological change was greater than the positive efficiency growth even though the productivity decline was small in terms of magnitude. The productivity change was affected mainly by the technological decline in phase I period. The main source of productivity growth in phase I period was efficiency growth. One interesting finding was that the productivity change was affected mainly by the technological change regardless of the time period.

There was a big technological improvement between 1993 and 1995, but there was a technological decline between 1996 and 1997. This fact may come from the fact that the bad output(SO_2 emission) and some inputs(fuel consumption, labor input) decreased between 1993 and 1995 even though the good output(electricity generation) decreased at the lower degree in the same period. So the frontier production technology improved during the 1993-1995 period. However, there was a big increase of fuel consumption between 1995 and 1996 even though there was an increase in electricity generation in the same time period. But the magnitude of that electricity generation increase was less than the magnitude of the fuel consumption increase. Moreover, the previous time period(from 1993 to 1995) showed major technology improvements. Summing up statement, there was a big technological decline in 1996/97 time period. This fact means that the phase I generating units changed their technologies two years before the beginning of phase I environmental regulation.

The scale efficiency and the pure technical efficiency showed positive growth in both the pre- and phase I period when we decompose the efficiency growth into scale efficiency growth and pure technical efficiency growth. The contribution of scale efficiency growth to the efficiency growth was greater than the pure technical growth before the phase I period, but the contribution of pure technical efficiency growth was greater than that of the scale efficiency growth during the phase I period. In short, the main source of efficiency growth was scale efficiency growth in the pre-phase I period and pure technical efficiency growth in the phase I period.

Table 3.9 Non-Parametric Test for Productivity between pre- and phase I period

	ANOVA test F (prob>F)	Wilcoxon test Z (prob>Z)	Kruskal-Wallis chi-square (prob>chi)	Median test chi-square (prob>chi)	Van-der-Waerden Z (prob>Z)	Savage Z (prob>Z)	Kolmogorov-Smirnov KSa (prob>KSa)
1.1 productivity under WD							
statistics	7.81	-0.1101	0.0122	0.0859	0.3479	1.4326	1.027144
probability	0.0054	0.4562	0.912	0.3847	0.364	0.076	0.242
1.2 productivity under SD							
statistics	1.6703	-2.7988	7.8356	-3.2243	-2.6413	-2.4305	1.907552
probability	0.1969	0.0026	0.0051	0.0006	0.0041	0.0075	0.0014

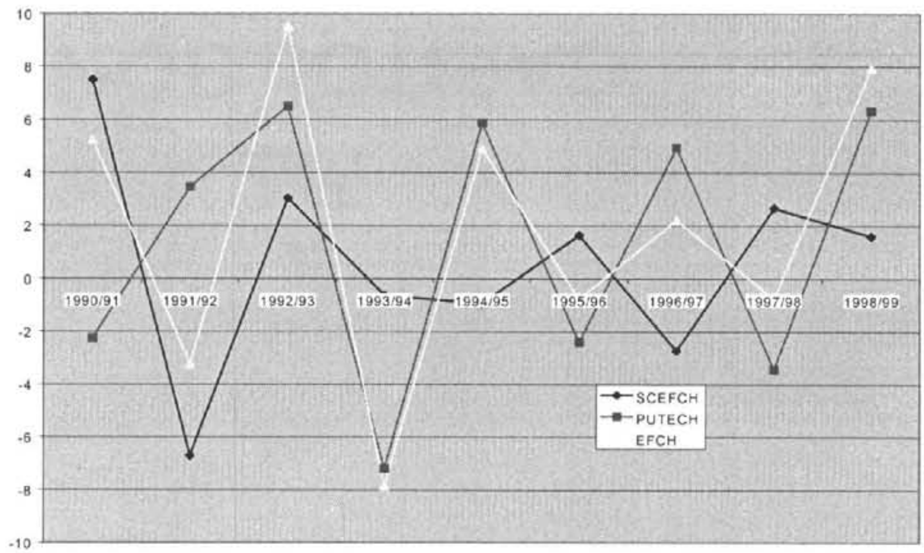
The productivity in phase I period declined, but the magnitude of the decline(-5.6) was small relatively compared with the magnitude of the productivity improvement in the pre-phase I period(23.7). So to test the hypothesis that the cumulative productivity indicator in the pre-phase I period(1990-1994) is the same as the cumulative productivity indicator in the phase I period, we used a non-parameteric test in SAS program. Since we can not reject the null hypothesis at 10% significance level, the productivity decline in the phase I period was not significantly different from the productivity growth in the pre-phase I period.

Table 3.10 Productivity Change under Strong Disposability

	scale efficiency change	pure tech. efficiency change	efficiency change	technological change	productivity change
1990/91	0.50330	4.25871	4.76191	1.71354	6.47316
1991/92	-7.93426	6.82699	-1.10694	-1.84828	-2.96172
1992/93	8.34512	6.09474	14.43885	-14.62316	-0.18086
1993/94	-10.44163	-1.50421	-11.93847	12.68383	0.74048
1994/95	4.35306	11.09909	15.45517	-25.30440	-9.85407
1995/96	0.25072	-2.39804	-2.14928	13.89699	11.74813
1996/97	-3.07612	6.83900	3.76435	-6.96818	-3.20670
1997/98	3.51368	-3.41167	0.09756	6.59569	6.69986
1998/99	0.42392	6.72675	7.14971	1.59019	8.69861
mean(1990-99)	-0.45136	3.83682	3.38587	-1.36264	2.01743
mean(1990-94)	-2.38187	3.91906	1.53884	-0.51852	1.01776
mean(1995-99)	0.27805	1.93901	2.21559	3.77867	5.98498

When we measured the productivity change under strong disposability, there was also productivity improvement in both the pre-phase and phase I periods, even though there wase productivity decline in four time periods. The main source of productivity growth was efficiency growth which was contrary to the finding of the main source under weak disposability. We tested the null hypothesis that the productivity change in the pre-phase I period was the same as the productivity change in phase I period using nonparametric test. Since we rejected the null hypothesis at a 5% significance level, there was a productivity growth in phase I period under strong disposability.

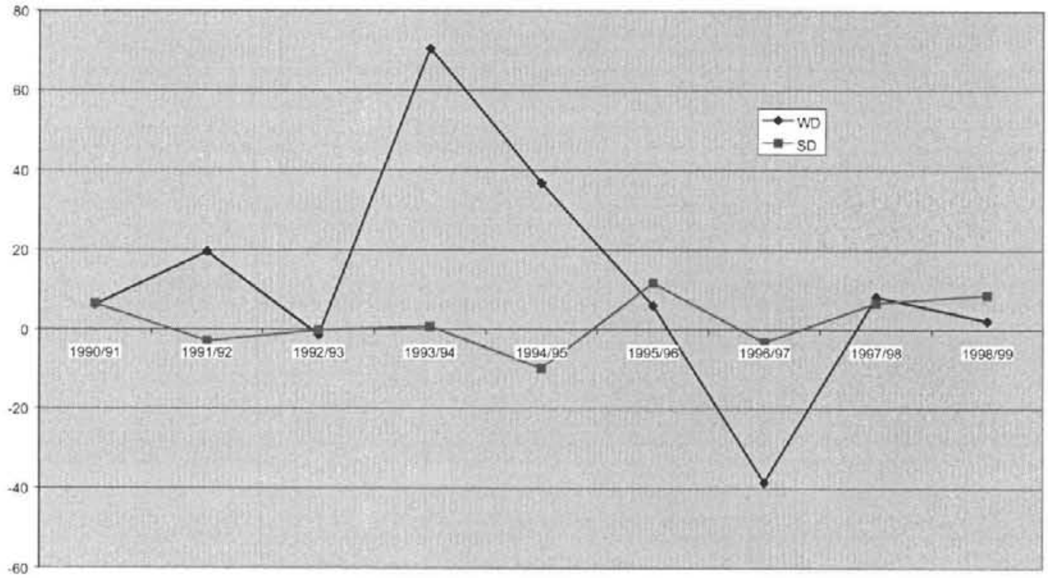
Figure3.18 Luenberger Productivity Change under Strong Disposability of Output



Efficiency growth was the main source of productivity growth before the phase I period. The main source of productivity growth in phase I period was technological growth even though efficiency showed growth both before and during the phase I period. The main source of productivity growth under strong disposability was also contrary to the main source of the productivity growth under weak disposability. That is, productivity improved in the stronger SO_2 emission regulation period under strong disposability, and the efficiency growth, especially, pure technical efficiency growth was the main source of productivity growth before the phase I period, and the technological development was the main source of productivity growth in the phase I period.

When we compare the productivity change under weak disposability with the productivity growth under strong disposability, generally the productivity change under weak disposability was higher than the productivity change under strong disposability before and during the phase I period. The productivity decline under weak disposability was relatively greater than the productivity change under strong disposability in the phase I period, however. And there was a negative productivity change before the phase I period when we measure the productivity change under the weak disposability of outputs(even though it is statistically insignificant at 10% significance level). There was, however, productivity growth in the phase I period under strong disposability. This fact implies that there may be a distortion in the productivity change measurement when we ignore the characteristics of production technology like weak disposability of output. And there is big difference in the productivity change under weak disposability and under strong disposability. Among the nine time periods, four time periods(1991/29, 1993/94, 1994/95, 1996/97) showed a large distortion between productivity change under two different disposabilities. As a result, if we ignore the production technology characteristics, then there is a large distortion in the productivity change measurement.

Figure 3.19 Luenberger Productivity Change



3.8.2.2 Productivity Change by Compliance Strategy

The first finding of the productivity change by compliance strategy under weak disposability is that the productivity improved in the whole period for the generating units using all compliance strategies except "other". The productivity growth of the generating units with scrubber strategy was the highest in the sample period, and the productivity growth rate of the units with allowance was the second. The main source of productivity growth for the generating units applying scrubber and fuel switch was technological growth, and the main source for the units using an allowance strategy was efficiency growth. In case of "other" strategy, both the efficiency change and the technological change declined in the period between 1990 and 1999.

Table 3.11 Productivity Change by Strategy under Weak Disposability

1990-99	scale efficiency change	pure tech. efficiency change	efficiency change	technological change	productivity change
allowance	0.56706	2.82630	3.39173	1.43614	4.83034
other	-1.00111	-7.40403	-8.40403	-6.62417	-15.04097
scrubber	4.81103	0.41557	5.22098	88.33381	93.55763
switch	-0.10598	1.12628	1.02079	1.71514	2.73227
1990-94					
allowance	0.01742	-0.98238	-0.96671	0.72004	-0.24520
other	0.05563	1.55469	1.61031	-5.59250	-4.00250
scrubber	1.05583	1.44857	2.49357	189.69310	192.19310
switch	1.20618	0.38137	1.58863	6.60754	8.19370
1995-99					
allowance	1.67274	0.72579	2.39695	5.61314	8.01509
other	-1.68781	9.12781	7.43844	0.68031	8.12063
scrubber	3.45876	-1.87124	1.58404	-101.60090	-100.02236
switch	-0.35876	1.98543	1.62840	1.91315	3.53904

Second, the productivity of the units with scrubber and fuel switch showed growth, but the units using allowance and "other" strategy showed declines in the pre-phase I period. This may come from the fact that the electricity generation of the units with all strategies except for "other" was constant in the pre-phase I period, but the electricity generation of the units with "other" strategy declined to half of 1990's level. The main source of productivity growth in the pre-phase I period was technological development except for the units with "other" strategy.

Third, only the generating units applying the scrubber strategy showed a productivity decline since there was a big technological decline. All the remaining strategies, however, showed productivity growth in the phase I period. This finding may come from the fact that units with scrubber decreased lots of SO_2 emissions before the phase I period(1993-1994), and could not catch up with the technological growth lead by the units using an allowance strategy. The productivity of the units with allowance and "other" strategy changed from a decline in the pre-phase I period to an improvement in the phase I period. The units with fuel switch showed productivity improvement regardless of time period. The main source of productivity growth for the units with fuel switch and allowance strategy was technological change, but the source for the units with "other" strategies was efficiency growth.

We test the null hypothesis that the productivity change in the pre-phase I period was the same as the productivity change during the phase I period by using a nonparametric test. We reject the null hypothesis of same productivity change for the units with allowance and fuel switch strategy, but can not reject the hypothesis for the units with scrubber and "other" strategy. This test means that we can not say that the productivity of the units with scrubber declined in the phase I period, and that the productivity of the units with "other" strategy increased duringin the phase I period. As a result, the productivity of the units using all compliance strategies except for "other" strategy improved, while the units with "other" strategy showed a decline in productivity during the phase I period.

Table 3.12 Productivity Change by Strategy under Strong Disposability

1990-99	scale efficiency change	pure tech. efficiency change	efficiency change	technological change	productivity change
allowance	0.14090	4.13774	4.27902	1.01425	5.28022
other	-1.22889	-7.27250	-8.48458	-11.68972	-20.20458
scrubber	2.80103	3.24464	6.04727	-0.69093	5.34428
switch	-1.43469	4.57885	3.14315	-2.30410	0.84110
1990-94					
allowance	-2.49579	2.02710	-0.46476	-0.32091	-0.78937
other	-0.08875	1.83719	1.74844	-5.71125	-3.98281
scrubber	-1.60226	0.26476	-1.33131	-0.80595	-2.14893
switch	-2.61724	5.73605	3.11853	-0.21827	2.90113
1995-99					
allowance	1.55491	0.84399	2.39741	6.70305	9.07902
other	-1.70063	10.12969	8.43344	-1.03500	7.39750
scrubber	2.55225	1.08416	3.63191	2.03180	5.65146
switch	-1.16354	2.38641	1.22163	2.09990	3.32253

The productivity change under strong disposability was similar to the productivity change under weak disposability. The productivity change of "other" strategy declined during the whole period since both the efficiency change and the technological change declined. The productivity of the units with all compliance strategies declined in pre-phase I period, but improved in phase I period. The main source of productivity growth was efficiency growth for the units applying fuel switch and "other" strategy in the pre-phase I period. In the phase I period, however, efficiency growth was also the main source of productivity growth for units using "other" and scrubber strategy.

There are several interesting findings when we compare the productivity change under weak disposability and strong disposability. First, the productivity growth of the units using all compliance strategies except for "other" strategy was positive, but the productivity growth of the units with "other" strategy was negative regardless of disposability during the whole time period(1990-1999). Second, the productivity growth of the units with scrubber strategy was the highest regardless of disposability in the 1990s. Third, the productivity growth of the units applying an allowance and "other" strategy changed from a decline in the pre-phase I period to an increase in the phase I period. Fourth, in the phase I period, the main source of productivity growth was efficiency growth for units applying "other" and scrubber strategies. While the main source for the units using allowance and fuel switching strategy was technological change.

3.8.3 Effect of SO_2 Emission Regulation on Productivity Change

3.8.3.1 Opportunity Cost of SO_2 Emission Regulation

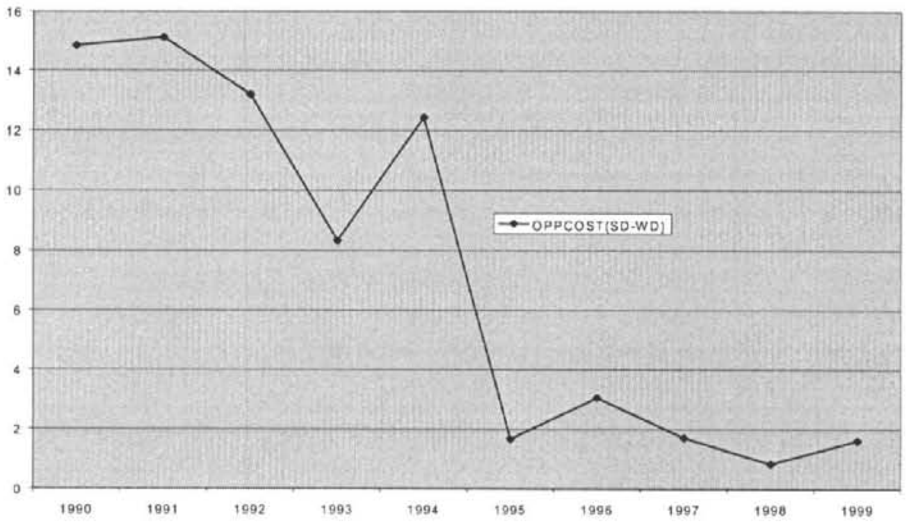
The opportunity cost of SO_2 emission regulation in the sample period was 7.28. This number means that if units could dispose the SO_2 emission freely each generating unit could increase electricity generation by 7.28 MWh, decrease the SO_2 emission by 7.28 tons and decrease the inputs by 7.28 units(7.28 MW of generating capacity, 7.28 mmBTU of fuel consumption, 7.28 person of labor). The opportunity cost of SO_2 emission regulation derived from pure technical efficiency was greater than that derived from scale efficiency. This finding means that units can adjust the good output, bad output, and inputs more through pure technical efficiency improvement than through scale efficiency improvement.

Table 3.13 Opportunity Cost of SO_2 emission Regulation

year	scale efficiency	pure tech efficiency	efficiency
1990	1.71201	13.12833	14.84033
1991	3.45928	11.66144	15.12072
1992	3.80526	9.39019	13.19545
1993	-3.22029	11.54493	8.32464
1994	6.49388	5.93048	12.42435
1995	-0.05507	1.71837	1.66330
1996	0.68067	2.36225	3.04292
1997	1.23837	0.46727	1.70565
1998	0.34837	0.48225	0.83062
1999	1.52799	0.07689	1.60488
mean(90-99)	1.59905	5.67624	7.27529
mean(90-94)	2.45003	10.33107	12.78110
mean(95-99)	0.74807	1.02141	1.76947

The opportunity cost of SO_2 emission regulation in the phase I period(1.77), that is, the difference in the efficiency score under strong disposability of output and the efficiency score under weak disposability, was around one seventh of the opportunity cost before the phase I period(12.78). Because of the stronger SO_2 regulation, the difference in the efficiency score between strong disposability and weak disposability of output became small. We imposed two different kinds of disposability only for the good output and bad output, but imposed one kind of disposability(strong disposability) for the inputs. In other words, the opportunity to increase electricity generation and to decrease SO_2 emission declined under the current technology when the stronger SO_2 emission regulation was introduced. This fact means that the extent to which generating units could increase the good output and decrease the bad output in the phase I period was smaller than the extent they could do so during the pre-phase I period. This is because the frontier production technology under strong disposability and the weak disposability of the output in phase I period moved closer than before the phase I period. In terms of economic meaning, the potential to increase electricity generation and to decrease SO_2 emission declined during Phase I period comparing with the potential before Phase I period. This means that electric units needed more input or more productive production technology to increase electricity generation and to decrease SO_2 emission in the Phase I period compared to the pre-phase I period since the generating units used the resource more efficiently in the stronger environmental regulation.

Figure 3.20 Opportunity Cost(indicator) of SO_2 Emission Regulation



The opportunity cost derived from pure technical efficiency was greater than the opportunity cost derived from scale efficiency before and during Phase I period. This finding means that the electric generating units can increase more electricity generation and decrease more SO_2 emission through the improvement of pure technical efficiency than through the improvement of scale efficiency. This finding was consistent with the source of inefficiency in the previous section. That is, the main source of inefficiency was pure technical inefficiency both before and during the Phase I period regardless of disposabilities. In other words, there was more opportunity to increase electricity generation and to decrease SO_2 emission through the improvement of pure technical efficiency than through the improvement of scale efficiency.

Table 3.14 Opportunity Cost of SO_2 Emission Regulation by Strategy

strategy	scale efficiency	pure technical efficiency	efficiency
1990-99			
allowance	1.55395	1.38076	2.93471
"other"	0.96238	1.91550	2.87788
scrubber	6.51613	8.02751	14.54364
switch	0.67910	8.38958	9.06868
1990-94			
allowance	3.67311	3.03216	6.70527
"other"	-0.01250	0.27050	0.25800
scrubber	7.35324	11.90400	19.25724
switch	1.07976	14.66684	15.74660
1995-99			
allowance	-0.07817	0.10890	0.03073
"other"	1.93725	3.56050	5.49775
scrubber	5.73134	4.39330	10.12464
switch	0.19483	0.80240	0.99723

In the 1990-99 period, the opportunity cost of the units applying scrubber was the greatest among the four strategies, followed by units with fuel switch, then allowance, and finally "other" strategies. The opportunity cost of the units with scrubber was also the greatest before and during the Phase I period. In other words, the units with scrubber could increase electricity generation and decrease SO_2 emission more than units applying any of the other strategies under the current technology. That is, the units with scrubber could increase electricity generation and decrease SO_2 emission and inputs without introducing more productive production technology. The opportunity cost of the units with "other" strategy was the lowest before the Phase I period, but marked second in the Phase I period. The ranking of the opportunity cost of the units with fuel switch was second before the Phase I period, but fell to third in the Phase I period. We can infer that the units with scrubber and "other" strategy could decrease more SO_2 emission and increase more electricity generation in the Phase I period than units applying allowance and fuel switch strategy under the current technology.

The main source of the opportunity cost in the pre-phase I period was pure technical efficiency for all strategies except the allowance strategy. Similarly, in the phase I period, pure technical efficiency was the main source of the opportunity cost for all compliance strategies except for those units employing scrubber. In particularly, the main source of the opportunity cost for the units applying scrubber is scale efficiency even though the degree of scale efficiency was almost same as the degree of pure technical efficiency. This finding may come from the fact that the units with scrubber are in the decreasing returns to scale range since these units are big in terms of electricity generation and generating capacity. As a result, the units with scrubber can increase more electricity generation and decrease SO_2 emission mainly through scale adjustment.

3.8.3.2 Effect of SO_2 Emission Regulation on Productivity Growth Potential

The effect of SO_2 emission regulation on the productivity growth potential iss defined as the difference in the productivity growth under strong disposability of good output and bad output and the productivity growth under weak disposability of good output and bad output. The mean effect of SO_2 emission regulation on the productivity growth potential showed negative value during the the whole period(1990-1999) and pre-phase I period(1990-1994). This negative value means that the environmental regulation reduce the productivity growth potential in 1990s. But there was a positive value of effect in the phase I period which means that the SO_2 emission regulation showed positive productivity growth potential. That is, the productivity growth under the stronger environmental regualtion may be low, or productivity under the strong environmental regulation declined more relativel to the productivity growth under weak environmental regulation.

In the pre-phase I period, three time periods showed a negative value of effect, and two time periods showed a positive value of effect on productivity growth potential. The finding that the mean value of the effect in the pre-phase I period was negative(-22.65) means that each generating unit could improve its productivity by 22.65 units more under the restriction of bad output disposability than under the free disposability of bad output. This finding also means that the extent of the environmental regulation in the pre-phase I period is actually binding on the productivity growth. This finding may come from the fact that there is a big technological improvement in 1992/93 and 1993/94 periods. The phase I generating units reduced lots of SO_2 emission during 1993-95 period to prepare phase I emission regulation in advance. Since our model incorporates the reduction of bad output, there may be a big technological improvement in these periods.

Table 3.15 Effect of SO_2 emission Regulation on Productivity Growth Potential

	scale efficiency change	pure tech. efficiency change	efficiency change	technological change	productivity change
1990/91	-6.99033	6.52282	-0.46196	0.76469	0.29077
1991/92	-1.21100	3.36177	2.14722	-24.64512	-22.49019
1992/93	5.31651	-0.39579	4.92005	-3.64421	1.27708
1993/94	-9.79742	5.69770	-4.09043	-65.59746	-69.69081
1994/95	5.31057	5.23660	10.55273	-57.17306	-46.61713
1995/96	-1.38718	0.00498	-1.38316	7.14574	5.77273
1996/97	-0.34708	1.90531	1.55794	33.81679	35.36981
1997/98	0.85077	0.02426	0.87263	-2.40861	-1.53144
1998/99	-1.17962	0.40536	-0.77550	7.37038	6.54684
mean(1990-99)	-1.04831	2.52922	1.48217	-11.59676	-10.11915
mean(1990-94)	-3.17056	3.79663	0.62872	-23.28053	-22.65329
mean(1995-99)	-0.51578	0.58498	0.06798	11.48108	11.53949

The main source of productivity growth potential was efficiency change in the pre-phase I period. In other words, there is a positive productivity growth potential from efficiency improvement. Moreover, the generating units could improve their productivity change mainly through efficiency improvement if there was no environmental regulation.

However, the finding that the effect of SO_2 emission regulation on the productivity growth potential in phase I period was positive(11.54) means that the SO_2 emission regulation is not actually binding on the productivity change comparing to pre-phase I period. So, if there was no strong environmental regulation in the phase I period, the 209 generating units could improve their productivity change by 11.54 units of indicator. That is, the generating units would have been able to increase 11.54MW more electricity generation per each unit annually.

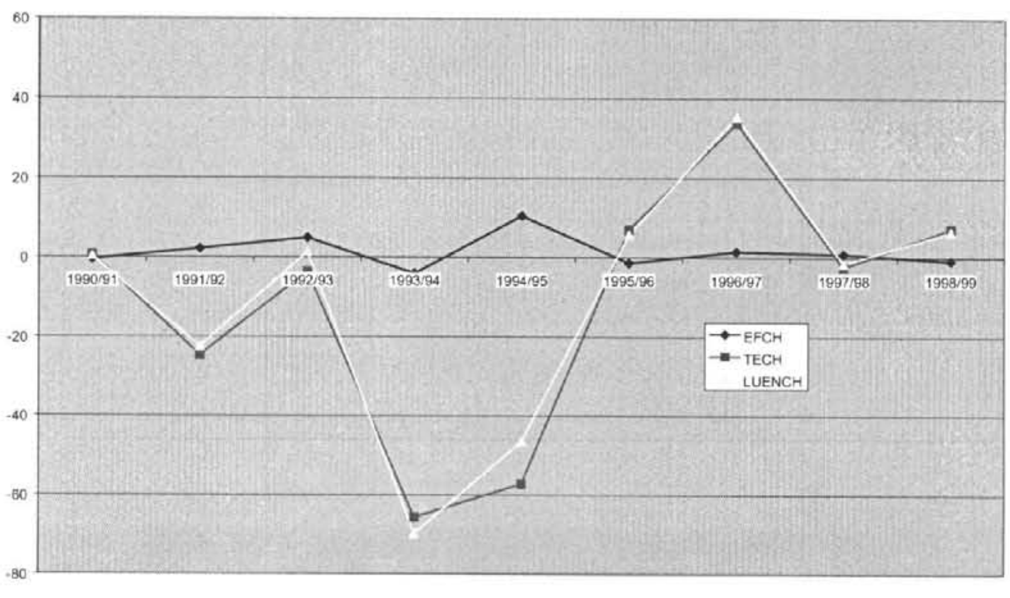
The main source of the potential productivity growth is the technological change in the phase I period, even though efficiency change also had a potentially positive effect on productivity growth. If there was no strong environmental regulation in the phase I period, the phase I generating units could improve the productivity growth mainly through technological improvement.

We test the hypothesis that the effect of SO_2 emission regulation on the productivity growth potential in pre-phase I period was the same as the effect in the phase I period by using a non-parametric test. We reject the null hypothesis at a 1% significance level. So the effect of SO_2 emission regulation in the phase I period was different from the effect in the phase I period. As a result, while there is a productivity growth potential derived from technological development in phase I period, there is a potential derived from efficiency improvement in pre-phase I period.

Table 3.16 Non-Parametric Test for Effect of SO_2 emission Regulation on Productivity Growth Potential between Pre- and Phase I period

	ANOVA test F (prob>F)	Wilcoxon test Z (prob>Z)	Kruskal-Wallis chi-square (prob>chi)	Median test chi-square (prob>chi)	Van-der-Waerden Z (prob>Z)	Savage Z (prob>Z)	Kolmogorov-Smirnov KSa (prob>KSa)
effect of SO2							
statistics	10.082	-4.5035	20.285	-5	-4.4591	-2.1149	3.081431
probability	0.0016	0.0001	0.0001	0.0001	0.0001	0.0172	0.0001

Figure 3.21 Effect of SO_2 Emission Regulation on Productivity Change



The mean effect of SO_2 emission regulation between 1990 and 1999 was negative except for the units applying the allowance strategy. So the phase I generating units with scrubber, fuel switch, and "other" strategies could increase their electricity generation and decrease the SO_2 emission and inputs despite strong environmental regulation. The finding that the effect of SO_2 emission regulation on the technological change was negative for all kinds of compliance strategies means that the phase I units could increase productivity growth mainly through efficiency change improvement, not through technological improvement.

The effect of SO_2 emission regulation in the pre-phase I period was negative for the units except for units with "other" strategy. This finding means that only the units with "other" strategy were affected by the environmental regulation in the pre-phase I period. This finding may come from the fact that the units with "other" strategy decreased lots of SO_2 emission compared with units applying other compliance strategies before the phase I period. The finding that the effect of SO_2 regulation on technological growth potential is negative for all compliance strategies means that the units could increase the productivity growth mainly through efficiency improvement rather than technological development in pre-phase I period.

In the phase I period, the productivity change of the units using the scrubber and allowance strategies were affected by the SO_2 emission regulation, but the units using "other" and fuel switch strategy were not actually affected by the SO_2

emission regulation relatively. In particular, the effect of SO_2 emission regulation was binding on the productivity growth of units using scrubber and allowance through binding on the technological change. On the efficiency change side, the SO_2 emission regulation was binding on the pure technical efficiency improvement. As a result, the production technology improvement for the units applying the scrubber strategy in the phase II period will be the biggest effect on productivity growth potential in the U.S electricity industry.

Table 3.17 Effect of SO_2 emission Regulation on Strategy's Productivity Growth Potential

1990-99	scale efficiency change	pure tec. efficiency change	efficiency change	technological change	productivity change
allowance	-0.42616	1.31145	0.88729	-0.42190	0.44988
other	-0.22778	0.13153	-0.08056	-5.06556	-5.16361
scrubber	-2.01000	2.82907	0.82629	-89.02474	-88.21335
switch	-1.32871	3.45257	2.12236	-4.01925	-1.89117
1990-94					
allowance	-2.51321	3.00948	0.50194	-1.04095	-0.54417
other	-0.14438	0.28250	0.13813	-0.11875	0.01969
scrubber	-2.65810	-1.18381	-3.82488	-190.49905	-194.34202
switch	-3.82342	5.35468	1.52989	-6.82581	-5.29256
1995-99					
allowance	-0.11784	0.11820	0.00046	1.08991	1.06393
other	-0.01281	1.00188	0.99500	-1.71531	-0.72313
scrubber	-0.90652	2.95539	2.04787	103.63270	105.67382
switch	-0.80478	0.40098	-0.40677	0.18674	-0.21651

We test the hypothesis that the SO_2 emission regulation effect on the productivity growth potential in the pre-phase I period was the same as the effect in the phase I period for each compliance strategy. We reject the null hypothesis for all strategies except for "other" strategies. While there is evidence that the SO_2 emission regulation affected the productivity growth potential of the units using scrubber, fuel switch and allowance strategies, the SO_2 emission regulation did not affect the productivity growth potential of the units applying "other" strategies.

Table 3.18 Non-Parametric Test for Effect of SO_2 emission Regulation on Productivity Growth Potential by Compliance Strategy between Pre- and Phase I period

	ANOVA test F (prob>F)	Wilcoxon test Z (prob>Z)	Kruskal-Wallis chi-square (prob>chi)	Median test chi-square (prob>chi)	Van-der-Waerden Z (prob>Z)	Savage Z (prob>Z)	Kolmogorov-Smirnov KSa (prob>KSa)
1. allowance							
statistics	0.0255	-1.7436	3.0412	-2.2213	-1.2429	3.8893	4.428136
probability	0.8731	0.0406	0.0812	0.0132	0.1069	0.0001	0.0001
2. "other"							
statistics	0.0807	1.3312	1.7906	1.6595	1.1341	-0.8006	1.75
probability	0.7773	0.0916	0.1809	0.0485	0.1284	0.2117	0.0044
3. scrubber							
statistics	10.6772	-1.6513	2.7318	-1.4432	-2.1452	-2.5624	1.285552
probability	0.0013	0.0493	0.0984	0.0745	0.016	0.0052	0.0734
4. switch							
statistics	17.8836	5.4807	30.0399	6.7032	4.6969	-0.5942	4.844246
probability	0.0001	0.0001	0.0001	0.0001	0.0001	0.2762	0.0001

3.9 Discussion

We used the directional technology distance function to measure the productivity change, opportunity cost of SO_2 emission regulation, and the effect of SO_2 emission regulation on the productivity growth potential of the 209 phase I generating units before and during phase I period using symmetric directional vector.

There is more potential to increase efficiency through pure technical efficiency improvement rather than scale efficiency improvement. The main source of inefficiency was pure technical inefficiency, regardless of time period and disposability of outputs. The generating units using allowance and "other" strategies showed high efficiency in the pre-phase I period, while the units applying allowance and scrubber strategy showed high efficiency in the phase I period.

The mean productivity of phase I generating units improved during the 1990-1999 period, and the main source of productivity growth was technological change. There was a productivity growth in the pre-phase I period, and the main source of productivity growth was technological improvement. Under the stronger SO_2 emission regulation in the 1995-99 period, the phase I units showed productivity decline, but that decline did not differ significantly from the productivity growth in the pre-phase I period. Efficiency improvement, especially the pure technical efficiency improvement, contributed to productivity growth in the phase I period. Scale efficiency improvement contributed to productivity growth more in the pre-phase I period than phase I period. The units using all compliance strategies except for "other" strategies showed productivity growth in the sample period. In the phase I period, all the strategies except for the scrubber strategy showed productivity growth.

The opportunity cost of SO_2 emission regulation, that is, the difference between efficiency under strong disposability of outputs and the efficiency under weak disposability, declined in the phase I period because of the stronger environmental regulation. The main source of opportunity cost decline was pure technical efficiency both in the pre- and phase I periods. This finding means that the stronger SO_2 emission regulation was binding on efficiency, and the generating units could improve the efficiency through pure technical efficiency improvement. The opportunity cost of the units using scrubber and fuel switch strategy was high in the sample period, but the units using scrubber and "other" strategy showed high opportunity cost in the phase I period. So the units with scrubber could increase efficiency more than units using the remaining strategies.

The effect of SO_2 emission regulation on productivity growth potential showed negative in pre-phase I period, but showed positive value in phase I period. The main source of productivity growth potential is efficiency improvement in pre-phase I period, and technological change in phase I period. This finding means that there is a more potential to increase productivity through technological development than through efficiency improvement in phase I period. The units with scrubber strategy showed big number of positive potential from technological development. So the policy should be focused on the introduction of more productive production technology to achieve productivity growth in the Phase II period, especially for scrubber strategy.

3.10 References

Curtis Carlson, Dallas Burtlaw, Maureen Cropper, Karen L.Palmer, "Sulfur Dioxide Control by Electric Utilities : What are the Gains from Trade", Journal of Political Economy, vol 108, no 6, December 2000, 1292-1326

Chambers,R.G, Fare,R., Grosskopf,S. "Productivity Growth in APEC Countries", Pacific Economic Review, vol 1, no3, 1996, December 1996, 181-190

Laurits R. Christensen and William H. Greene, "Economies of Scale in U.S. Electric Power Generation" Journal of Political Economy, vol 84, no4, August 1976, 655-676

Y.H.Chung, Fare,R., Grosskopf,S. "Productivity and Undesirable Outputs:A Directional Distance Function Approach" Journal of Environmental Management vol 51, 1997, 229-240

Thomas G. Cowing and Rodney E. Stevenson, "Productivity Measurement and Regulated Industries" in Productivity Measurement in Regulated Industries edited by Thomas G. Cowing and Rodney E. Stevenson, New York, Academic Press, 1981

Thomas G. Cowing, Jeffrey Small, and Rodney E. Stevenson, "Comparative Measures of Total Factor Productivity in the Regulated Sector : The Electric Utility Industry" in Productivity Measurement in Regulated Industries edited by Thomas G. Cowing and Rodney E. Stevenson, New York, Academic Press, 1981

Ellerman,A.D, Schmalensee.R., Joskow,P.L., Montereo, J.P., Bailey, E.M." Emissions Trading under the U.S Acid Rain Program" Center for Energy and Environmental Policy Research, MIT, 1997

Department of Energy(DOE)/Energy Information Administration(EIA). "The Effects of Title IV of the Clean Air Act Amendments of 1990 on Electric Utilities"(DOE/EIA-0582(97), Washington D.C.:Department of Energy, March 1997

Department of Energy(DOE)/Energy Information Administration(EIA), "Electric Utility Phase I Acid Rain Compliance Strategies for The Clean Air Act Amendments of 1990"(DOE/EIA-0578, Washington D.C.:Department of Energy, March 1994

Phoebus J. Dhrymes and Mordecai Kurz, "Technology and Scale in Electricity Generation", Econometrica, vol 32, no 3, 1964, 321-349

Fare,R., Grosskopf,S., C.Pasurka, "Effects on Relative Efficiency in Electric Power Generation due to Environmental Controls" Resources and Energy, vol 8, 1986, 167-184

Rolf Fare, Shawna Grosskopf, C.A.K.Lovell and Carl Pasurka, "Multilaterial Productivity Comparisons When Some Outputs are Undesirable : A Nonparametric Approach" The Review of Economics and Statistics, vol 71, no 1, February 1989, 90-98

Fare,R., Grosskopf,S., S.Yaisawarng, Li,S.K, Wang,Zhaoping, "Productivity Growth in Illinois Electric Utilities" Resources and Energy, vol 12, no 4, December 1990, 383-398

Fare,R., Grosskopf,S., N.Marry, Z.Zhongyang, "Productivity Growth, Technical Progress, and Efficiency Change in Industrialized Countries" American Economic Review, vol 84, no 1, March 1994, 66-83

Fare,R., Primont,D, Multi-output Production and Duality:Theory and Applications, Boston, Kluwer Academic Publishers, 1995

Fare,R., Grosskopf, S., Intertemporal Production Frontiers:with Dynamic DEA, 1996, Boston, Kluwer Academic Publishers

Fare,R., Grosskopf,S., Tyteca,D., "An Activity Analysis Model of the Environmental Performance of Firms-Application to Fossil-Fuel Fired Electric Utilities" Ecological Economics, vol 18, no 2, August 1996, 161-175

Fare,R., Grosskopf,S. "Theory and Application of Directional Distance Functions" Journal of Productivity Analysis, vol 13, no 2, March 2000, 93-103

Fare,R., Primont,D, "Luenberger Productivity Indicator:Aggregation Across Firms" memo, 2001, Oregon State University

Frank A. Gollop, Mark J. Roberts, "The Sources of Economic Growth in the U.S Electric Power Industry" in Productivity Measurement in Regulated Industries edited by Thomas G. Cowing and Rodney E. Stevenson, 1981, New York, Academic Press, 1981

Frank M. Gollop, Mark J. Roberts, "Environmental Regulation and Productivity Growth : The Case of Fossil-fueled Electric Power Generation" Journal of political Economy, vol 91, no 4, August 1983, 654-674

Frank M. Gollop, Mark J. Roberts, "Cost-Minimizing Regulation of Sulfur Emissions : Regional Gains in Electric Power", Review of Economics and Statistics, vol 67, no 1, February 1985, 81-90

Andrew N. Kleit and Dek Terrell, "Measuring Potential Efficiency Gains from Deregulation of Electricity Generation : A Bayesian Approach" Review of Economics and Statistics vol 83, no 3, August 2001, 523-530

S.Yaisawarng, J.D.Klein, "The Effects of Sulfur Dioxide Controls on Productivity Change in the U.S Electric Power Industry" Review of Economics and Statistics vol 76, no 3, August 1994, 447-460

Appendix

Emissions Factor

Table A3. Sulfur Dioxide, Nitrogen Oxide, and Carbon Dioxide Emission Factors

Fuel	Boiler Type/ Firing Configuration	Emission Factors		
		Sulfur Dioxide	Nitrogen Oxides	Carbon Dioxide
Utility				
Coal and Other Solid Fuels		lbs per ton	lbs per ton	lbs per 106 Btu
Bituminous	cyclone	38.00 x S	33.00	see Table A4
	fluidized bed	31.00 x S	5.00	see Table A4
	spreader stroker	38.00 x S	11.00	see Table A4
	tangential	38.00 x S	15.0(14)	see Table A4
	all others	38.00 x S	22.0(31)	see Table A4
Subbituminous	cyclone	35.00 x S	17.00	see Table A4
	fluidized bed	31.00 x S	5.00	see Table A4
	spreader stroker	35.00 x S	8.80	see Table A4
	tangential	35.00 x S	8.40	see Table A4
	all others	35.00 x S	12.0(24)	see Table A4
Lignite	cyclone	30.00 x S	15.00	see Table A4
	fluidized bed	10.00 x S	3.60	see Table A4
	front/opposed	30.00 x S	13.00	see Table A4
	spreader stroker	30.00 x S	5.80	see Table A4
	tangential	30.00 x S	7.10	see Table A4
	all others	30.00 x S	7.10(13)	see Table A4
Petroleum Coke	fluidized bed	39.00 x S	21.00	225.13
	all others	39.00 x S	21.00	225.13
Refuse	all types	3.90	5.00	199.82
Wood	all types	0.08	1.50	0.00
Petroleum and Other Liquid Fuels				
Residual Oil	tangential	157.00 x S	32.00	173.72
	vertical	157.00 x S	47.00	173.72
	all others	157.00 x S	47.00	173.72
Distillate Oil	all types	157.00 x S	24.00	161.27
Methanol	all types	see Table A5	see Table A5	138.15
Propane(liquis)	all types	86.5	19.00	139.04
Coal-Oil-Mixture	all types	see Table A5	see Table A5	173.72

Natural Gas and Other Gaseous Fuels				
Natural Gas and Other Gaseous Fuels	tangential	0.6	170.00	116.38
	all others	0.6	280.00	116.38
Blast Furnace Gas	all types	950	280.00	116.38

s : sulfur content in percent of weight

coal types are categorized by Btu content as follows

- Bituminous : greater than or equal to 9,750 Btu per pound
-Subbituminous : equal to 7,500 to 9,750 Btu per pound
- Lignite : less than 7,500 Btu per pound

oil types are categorized by Btu as follows

- Heavy : greater or equal to 144,190 Btu per gallon
- light : less than 144,190 Btu per gallon

Table A6. Nitrogen Oxide Reduction Factors

Nitrogen Oxide Control Technology	EIA-767 Code(s)	EIA-860B Code(s)	Reduction Factor (Percent)
Advanced Overfire Air	AA		30
Alternate Burners	BF		20
Flue Gas Recirculation	FR	FG	40
Fluidized Bed Combustor	CF		20
Fuel Reburning	FU		30
Low Excess Air	LA	LE	20
Low Nitrogen Oxide Burners	LN	LN	30
Other(or Unspecified)	OT	OT	20
Overfire Air	OV	OA	20
Selective Catalytic Reduction	SR	CC	70
Selective Catalytic Reduction with Low Nitrogen Oxide Burners	SR asnd LN	CC and LN	90
Selective Noncatalytic Reduction	SN		30
Selective Noncatalytic Reduction with Low Nitrogen Oxide Burners	SN and LN		50
Slagging	SC		20
Steam or Water Injection		SW	20

4. REGUALTORY EFFECT ON CHOICE OF COMPLIANCE STRATEGY OF PHASE I ELECTRIC GENERATING UNITS

4.1 Introduction

The Clean Air Act Amendments(CAAA) of 1990 requires 261 Phase I generating units with generating capacity of 100MW or more to reduce sulfur dioxide(SO_2) emissions to the level of 2.5 pounds per million BTU of fuel input in Phase I period(1995-1999)(Winebrake at al, 1995). The Environmental Protection Agency(EPA) set the target of 5.7 million tons of SO_2 emissions, and this target was calculated by multiplying this emission rate by the average heat input in 1985-87 period for each unit(Carlson et al., 2000). Allowances are given to each generating units from EPA each year and each generating unit had to keep the sufficient allowances to cover the emission standard. One allowance is equivalent to the right to emit one ton of SO_2.

All phase I units adopted a compliance strategy to reduce SO_2 emissions from a menu of strategies including buying additional allowances, installing a scrubber, fuel switching, retiring units or boiler repowering and switch to natural gas or low-sulfur oil. Phase I units reduced emissions over target level(DOE/EIA, 1997) in the first year(1995). Over half(136 units) units switched their fuel from high-sulfur coal to low-sulfur coal(fuel-switch strategy) because of cost advantege. The estimated cost of fuel switch($113/ ton of SO_2 removal annually) is lower than that of scrubber($322/ton)(Ellerman et al,1997).

Since the 1990 CAAA introduced the market-based system of tradable pollution permit for SO_2 emission reduction, the electric units can choose the least-cost strategy to comply with SO_2 emission reduction. Since each electric unit and each compliance strategy uses different combination of inputs, the abatement cost differs among strategy and generating units. So the choice of compliance strategy depends on the characteristics of each electric unit. If one unit that can decrease the SO_2 emission over the emission rate standard at lower cost than allowance price, then the unit can sell surplus allowances. And the units of which marginal abatement cost(MAC) is higher than allowance price can buy allowances. So the CAAA of 1990 gave the electricity industry the flexibility to choose the compliance strategy.

However, the electric utility may not achieve the least-cost compliance strategy because of inappropriate regulatory regime, uncertainty and etc. Some state public utility commission(PUC) restricted the choice of strategy, fuel and allowance trade through raw or guideline. For example, high-sulfur coal producing states worried about the job loss in coal mines, and the public utility commission or the legislative body made or tried guideline/rules to encourage the electric units to use in-state high-sulfur coal. These regulations will affect the compliance strategy choice, and the compliance cost will be higher than least-cost.

Environmental economists are interesting in the success of this policy since the phase I provides a test of the economic theory of environmental policy. Only one study estimated regulatory effects on strategy choices(Arimura, 2002). However, this study focused only on the effect of state public utility commissions regulation and high-sulfur coal usage encouragement, but ignored other types of regulation. Moreover, it considered only two strategies of allowance and fuel switch.

The goal of this paper is to identify the factors affecting the compliance strategy choices including regulatory effect in phase I period. Since all of the phase I generating units chose one strategy out of several available strategies, we use multinomial logit model to find factors. We use generating unit's level data for 1995-99 since the SO_2 emission regulation is applied to the generating unit, not to the the electric plant.

4.2 Literature Review

The CAAA 1990 was preceded by several acts. There was no direct regulation from electricity industry until CAAA 1970 set National Ambient Air Quality Standards(NAAQS) for six pollutants in 274 air quality control regions (DOE/EIA,1994,EPA,2001). The CAAA 1970 introduced the New Source Performance Standards(NSPS) that applied to coal-fired boilers built or modified after August 1971 and with 73 MW or greater capacity. The NSPS was 1.2 pounds of SO_2 emission per million BTU for coal-fired generators, 0.8 pounds for oil-fired generators. NAAQS and NSPS are still in place. The EPA imposed furthur regualtion that new plants built after or modified after September 1978 or of which capacity is 73 MW or more install emission desulfurization system (scrubber) under CAAA of 1977(Gollop et al, 1984), but SO_2 emission standard is same as before standard.

U.S electricity industry had experience of almost 20 years with limited type of emission trading in air pollution from 1972(Klaassen et al, 1997). This system in 1970s and half of 1980s was evaluated as successful, and total expected cost saving of four systems(netting, offset, buble, banking) are from $1 billion to $13 billion, and the annual cost saving ranges from $100 million to $1,400 million. Netting system's annual cost saving was highest($53-1,230 million). Regulatory restrictions on trade, uncertainty on status of property right and high transaction cost negatively affected the cost-effectiveness of the trading system.

Cronshaw et al(1996) made theoretical model for the dynamic effect of allowance banking on the efficiency of emission trading system with perfect competition and perfect foresight. Each firm will maximize the present value of profit subject to output, the environmental regulation and profit regulation. At optimal solution, permit price is not equal to marginal abatement cost(MAC) and allowance price exceeds MAC of scrubber or other strategies by regulatory profit to cover the cost of allowance purchase. If there is at least one economic agent or firm that are not subject to profit regulation, then the permit price is equal to MAC and the present value permit prices are not increasing over time, however. Firms will bank the permit only if permit price rises with the interest rate. But firms which are subject to profit regulation will bank permits even though permit prices rises more slowly with the rate of interest since the firm may gain in profit as the result of favorable regulation of permits.

Winebrake et al.(1995) simulated the cost of regulatory and legislative intervention in the tradable permit market for 110 phase I electric plants. Direct intervention takes the form of restrictions on the choice of fuel, abatement technologies and amount of allowance trading by regulatory body. The indirect interventions are policy uncertainty that is the lack of clarity in future regulatory treatment of allowance sales and purchases, and uncertainty in utility decision making, technological uncertainty like the characteristics of different type of coals, and the economic uncertainties associated with fuel price and allowance price estimates. The MAC under the unrestricted emission trading system is \$143/ton of SO_2 in 1995-2005 period. The emission trading within same utility(bubble system) increase the total production cost by 60%. The command-and-control system increased the cost by 85% comparing with the cost under emission trading system. The restriction of allowance trade increased the MAC by 240% for New York and 22% for Wisconsin. The compliance cost and allowance price will be stabilized at the equilibrium price(\$143/SO_2 ton) if the participation level is greater than 30%, where only firms with marginal cost almost equal to the market price are affected. And the total cost and allowance price in the range between 20% and 30% participation rate increases moderately. However, compliance cost and allowance price increase rapidly when market participation rate fall below 20%.

Fullerton et al.(1997) estimated the effect of state Public Utility Commission (PUC)'s regulation on the cost of SO_2 emission reduction using numerical model. The compliance cost to protect local pollution is 1.6 times that of minimum social costs of compliance which model utility only buy the allowances at assumed price of \$150 to comply with the environmental regulation. When the model utility switches the fuel in large plant to low-sulfur coal, and install scrubber in the small plant, the complaince cost is 6 times that of minimum social cost. The utility only maximize the profit of allowance selling since the installation of scrubber and fuel switch cost can be compensated by the electricity price change. The cost of forced scrubbing to protetct local high-sulfur coal mining is 5 times as that of minimum social cost.

Arimura(2002) estimated the effect of cost recovery regulation and the PUC regulation on the choice of compliance strategy of allowance strategy and fuel switch strategy using probit model. He used only 175 generating units out of 261 phase I units, and used the observations only in the first year of phase I period(1995). The choice set is composed of only two compliance strategy(fuel switch and allowance strategy) in the probit model. He assumed that the state PUC's rulings had uncertainty about the treatment of the allowance market and electric units that are regulated by state public utility commission(PUC) would more likely to choose self-sufficient strategy(fuel switching/blending strategy). If the electric units were located in five high-sulfur coal producing states, units would more likely to choose the allowance strategy since allowance strategy generally uses high-sulfur coal. These two parameters are significant at 1% significance level.

Gollop et al(1984) estimated marginal abatement cost(MAC) of SO_2 emission reduction of 56 electric utilities in 1973-79 period. They separated the time period into 1973-75 and 1976-79 period, and separated the U.S into five subregions. Since the 1976 is the first full year in which EPA's ambient air standards were to met by electric plants, they expected that the regulatory intensity will vary across sub-time period and sub-regions. The estimated MAC is from \$177/ton of SO_2

emission reduction for Midwest in 1973-1975 to $1022 for Northeast in 1976-1979. The main factors affecting the differentials in MAC of SO_2 emission among sub-time period and sub-regions were the price difference between high-sulfur coal and low-sulfur coal, and the differentials in the regulatory intensity. Cost saving will be 7.5% to 75.3% of current cost at the fixed level of SO_2 emission and the electric plants can reduce SO_2 emission by 1.3% to 33.2% at the fixed expenditure.

Chao et al.(1993) estimated the option value of compliance strategy. Allowance strategy has the flexibility to adapt to uncertainty of emissions allowance demand while scrubber strategy does not have flexibility(irreversibility). So the allowance price may exceed the marginal cost of scrubber by the amount of option value. They considered the allowance strategy, scrubber, fuel switch and alternative technologies(non-coal fired electric power including renewable electric power). The option value is estimated as $89(using 10% of interest rate, zero drift, and a $40/ton of standard deviation of the change in the maximum demand price for allowances over a year).

Ellerman et al.(1998) explained the reasons that the actual allowance price was lower than the expected price in phase I period. One factor for the allowance price decline is that the electric utilities complied with SO_2 emission earlier than the beginning of phase I period. The anothet factor is that the rail road rate from PRB to Midwest declined because of rail road deregulation and also PRB mine-mouth prices declined derived from mining technological development. One interesting regulatory effect is that the existence of local government's strong SO_2 emission regulation and the regulation to protect the high-sulfur coal mining job affect the choice of coal significantly.

National Regulatory Research Institute(NRRI, 1993) figured out the possible regulatory type that will affect the allowance trade. Ohio, Pennsylvania and Kentucky introduced rule or guideline to restrict the allowance trade through by inappropriate treatment of allowance accounting, and pointed that this restriction will increase the abatement cost for electric industry.

4.3 Regulatory Effect on the Choice of Compliance Startegy

4.3.1 Choice of Compliance Startegy

The electric power generating units can choose one or combination of strategy to comply with the SO_2 emission reduction. "Other" strategy includes Demand Side Management(DSM), the purchase of electricity from Independent Power Producers(IPP) or other non-regulated power units, retiring of the unit and fuel switching to natural gas or low-sulfur oil. Fuel switch means that the electric generating units switch their fuel from cheap high-sulfur coal to expensive low-sulfur coal. The third strategy is to install the technology to reduce the emission from the coal burning process. The fourth compliance strategy is to buy the right to emit the pollutants when the property right is well defined. This is called allowance purchasing strategy.

In a perfectly competitive market, the choice of the strategy depends on several factors including market situation of each input factors and the unit owners' expectation about the market. If the capital price is, or is expected to be relatively cheap comparing to the low-sulfur coal price or allowance price to achieve the given emission target, then the unit's owner will choose the capital intensive strategy of scrubber. When the low-sulfur coal price is low, or is expected to be, compared to the capital price or allowance price, then some units will switch their fuel from high-sulfur coal to low-sulfur coal. If some units' owner expects the allowance price is low, then the owners will buy the allowances instead of fuel switch or scrubber strategy. Basically, each unit will choose the compliance strategy such that the cost of the strategy is expected to be the lowest among available strategies in a competitive market. So the price of inputs, and output will affect the choice of strategy, and other variable, like vintage of the electric unit, will affect the choice of compliance strategy.

Generating units with lower MAC than allowance price at the regulated SO_2 emission level will abate SO_2 emission over the emission rate, and will abate up to the SO_2 emission level where it's own MAC is equal to the allowance price. These units will sell the surplus allowances in the allowance market or bank them. So these units can reduce the abatement cost. Generating units with MAC higher than allowance price at the emission rate will buy allowances to meet the SO_2 emission regulation. As a result, the MAC for all generating units will be same as the allowance price in the equilibrium. This condition is necessary for electricity industry to achieve abatement at minimum cost(Bohi, 1992).

Since the CAAA introduced the trade of allowance, the supply and demand of allowances will represent the comparative marginal abatement cost of each compliance strategy. In the long-run, the marginal abatement cost of SO_2 emission will converge to allowance price in the allowance market since the allowance market reflects the supply and demand of SO_2 emission. When the allowance market functions well, the allowance price is expected to be a equilibrium price as MAC even though there is an uncertainty about the market information and the decision making.

4.3.2 Cost Minimization

Each electric plant has to supply the sufficient amount of electricity considering the reserve ratio to cover the electricity consumption in it's jurisdiction(Cronshaw et al, 1996). That is, the electric plant does not have the choice to reduce the electricity supply below the electricity consumption level. This strategy is equivalent to the DSM strategy or retire or substitution of generators.

Electric utilities are subject to federal government and state regulation generally through electricity price regulation. State Public Utility Commission adjusts the electricity price when there is a change through fuel adjustment clause, and state government allows prices to reflect the cost of capital. So the price of electricity is assumed to be given to the utilities. This kind of regulation means that electricity utilities can not maximize the revenue, that is, the utilities are not expected to change the quantity of electricity output based on the profit maximization principle. Instead, electric utilities choose input levels to minimize cost. Even though new regime like deregulation and restructuring was partly introduced in California(Tschirhart et al. 1999), we do not include these variables in our model since our data set does not includes generating units in California.

We assume that electric generating unit will choose optimum level of inputs to minimize the total cost subject to output and environmental constraints as;

$$Min\ C = k.P_k + l.P_l + fhs.P_{fhs} + fls.P_{fls} + a.P_a$$

subject to

$$q(k, l, fhs, fls, a, E_i) \geq Q$$

$$E(k, l, fhs, fls, a, \alpha) = W + N + S_{-1} - S$$

where

C : total cost

k : capital

l: labor

fhs : high-sulfur coal

fls : low-sulfur coal

a : net traded(purchased) allowances

P_k : capital price

P_l : wage rate,

P_{fhs} : high-sulfur coal price

P_{fls} : low-sulfur coal price

P_a : allowance price

q : electricity generation function or actual electricity generation

Q : output constraint

E : SO_2 emission function or actual SO_2 emission level

W : allocated allowances

N : net purchased allowances(purchase-sell) $=a$

S_{-1} : previous period's allowance

S : bank of allowance

α : factors affecting the emission

The electric unit will minimize the production cost and emission reduction cost subject to output constraint and environmental regulation. Output constraint is that each generating should supply sufficient electricity to their customers. Emission constraint is that the actual emission level should be equal to the sum of given allowance from federal government(EPA)(W) and the net purchased allowance(N) in the auction market or second hand market and the carried-over allowances from previous period(S_{-1}) minus the carried-over allowances to the next period or the current period's banked allowances(S). In the optimization(cost minimization), the optimum inputs are function of input prices, output and emission constraint. That is, $X_i = X_i^*(P_i$, Q, E). So the cost function is a function of input prices(capital, labor, high-sulfur coal and low-sulfur coal), allowance price, output constraint and actual emission level. That is,

$C = C(P_i, Q, E)$ where $P_i = P_k, P_l, P_{fhs}, P_{fls}, P_a$

The electric generating unit will choose the input quantity such that the marginal rate of technical substitution is equal to the ratio of input prices.

4.3.3 Regulatory Effect

However, the shadow price of the inputs will be different from the actual price since the electricity utilities are regulated by the government. We assume that electric generating unit will minimize the behavioral cost subject to output and environmental constraints to avoid misspecfication bias(Kerkvliet, 1991). In the optimum, behavioral cost function is a function of shadow input prices, output and SO_2 emission level as;

$C^B = C\,(\phi_i P_i,\ Q,\ E)$ *where* $\phi_i P_i = \phi_k P_k,\ \phi_l P_l,\ \phi_{fhs} P_{fhs},\ \phi_{fls} P_{fls},\ P_a$

We also assume that shadow input prices are function of regulatory variables as;

$\hat{P_i} = \phi_i\, P_i$ where $i = k,\ l,\ fhs,\ fls,\ a$

ϕ_i will measure the difference in the divergence between shadow input price and actual input price. If $\phi_i > 1$, then shadow price is greater than actual price, and the corresponding input will be underused inefficiently. If $\phi_i < 1$, then the input will be overused inefficiently. If $\phi_i = 1$, then shadow price is equal to actual price. For example, high-sulfur coal states worried about the job loss in the high-sulfur coal mines implement the policy favoring the capital intensive compliance strategy like scrubber, then the shadow capital price may be lower than the actual capital price.

We assume that the actual prices of allowance, capital and high-sulfur coal are different from the shadow prices of allowance, capital and high-sulfur coal because of regulation. We assume that the actual price of low-sulfur coal and labor are same as the shadow prices. This assumption is not an arbitrary one since there is no regulation on the labor market, and the low-sulfur coal price can reflect the market situation very well.

The shadow allowance price is assumed to be a linear function of the restriction of allowance transactions(D_{tr}), the restriction of allowance sale(D_{se}), the restriction of allowance purchase(D_{bu}), and other unidentified effect(β_0). And the shadow capital price is a function of high-sulfur coal encouragement(D_{hs}), the existence of cost recovery for the capital expenditure(D_{co}), and unknown effect(γ_0). The shadow price of high-sulfur coal is a function of encouragement of high-sulfur coal usage(D_{hs}) and other unidentified effect(δ_0). The government regulation is assumed to affect shadow input prices and to affect the choice of input bundles and to affect the choice of compliance strategy. One special thing is that the encouragement of high-sulfur coal usage is assumed to affect both capital price and high-sulfur coal price.

We assume that, while the above regulations will affect the cost through the effect on the shadow input prices, some regulations will affect the cost of compliance strategy directly. That is, the direct regulatory(R) is assumed to affect the cost of each compliance strategy directly. This effect will be dependent on the adopt of allowance strategy(D_{al}), the ownership of the units(D_{np}), existence of previous regulation or local government's stringent emission regulations(D_{pr}) and the existence of substitution/compensation boiler(D_{su}). The intercept of direct regulatory variable(α_0) will measure the uncertainty effect of state PUC regulation and the technical inflexibilities up to some level since this intercept includes all kinds of unidentified effects including the uncertainty effect of state PUC.

$\phi_a P_a = (\beta_0 + \beta_{tr} D_{tr} + \beta_{se} D_{se} + \beta_{bu} D_{bu})P_a$

$\phi_k P_k = (\gamma_0 + \gamma_{hs} D_{hs} + \gamma_{co} D_{co})P_k$

$\phi_{fhs} P_{fhs} = (\delta_0 + \delta_{hs} D_{hs})P_{fhs}$

$\phi_{fls} P_{fls} = P_{fls}$

$\phi_l P_l = P_l$

$R = \alpha_0 + \alpha_{al} D_{al} + \alpha_{np} D_{np} + \alpha_{pr} D_{pr} + \alpha_{su} D_{su}$

where

D_{tr} : *Dummy variable for the states that restricts the allowance trasactions*

D_{se} : *Dummy variable for the states that restricts the allowance sales*

D_{bu} : *Dummy variable for the states that restricts the allowance purchase*

D_{hs} : *Dummy variable for states that encouraged in-state high-sulfur coal usage*

D_{co} : *Dummy variable for the states that have the cost recovery for capital expenditure of compliance strategy investments*

R : direct regulatory variables

D_{al} : *dummy variable for the units that adopted allowance strategy*

D_{np}: *dummy variable for the units that are non-privately owned units*

D_{pr} : *Dummy variable for the units that are regulated by the previous regulation*

D_{su} : *Dummy variable for the units that have substitution/compensation boilers*

We add vintage variable(*srvmonth*) in cost function since we suspect that the old units will not likely use capital intensive compliance strategy. That is, this old units will not adopt the scrubber or "other" strategy since the operation life of scrubber is different from the life of unit, and the operation and maintenance cost of scrubber is more expensive comparing with the cost of new units.

We assume linear behavioral cost function, and cost is a function of shadow input prices, other actual input prices, actual output, actual SO_2 emission level, vintage and the other direct regulatory variables.

$C^B = C(\phi_i P_i, Q, E, V, R)$

Where

$P_i = P_k, P_l, P_{fhs}, P_{fls}, P_a$

Q : *electricity production*

E : *actual SO_2 emission*

V : *vintage variable*

That is,

$$C^B = \alpha_0 + \alpha_{al} D_{al} + \alpha_{np} D_{np} + \alpha_{pr} D_{pr} + \alpha_{su} D_{su} + (\beta_0 + \beta_{tr} D_{tr} + \beta_{se} D_{se} + \beta_{bu} D_{bu}) P_a + (\gamma_k + \gamma_{hs} D_{hs} + \gamma_{co} D_{co}) P_k + (\delta_0 + \delta_{hs} D_{hs}) P_{fhs} + P_{fls} + P_l + \beta_q Q + \beta_e E + \beta_{srv} srvmonth$$

4.3.4 Types of Regulation

4.3.4.1 Existence of Substitution/Compensation Boilers

Many utilities in the Midwest and East had incentive to run clean boilers that are not applied by phase I regulation even though this benefit was disappeared in 1995. Some utilities used substitution/compensation boilers to produce electricity instead of dirty phase I boilers. These units can comply with the SO_2 emission standard of phase I generating units since the units can use more efficient subtitution/compensation boilers(Klaassen et al, 1997). If the generating units have the substitution/compensation boiler, then the MAC of allowance strategy will be lower than other strategy and the units can sell or bank the unused allowances. That is, the shadow allowance price will be lower for these units. So these units are more likely to choose allowance strategy and less likely to choose other kinds of strategies.

4.3.4.2 Option Value of Allowance Strategy

If one unit installed scrubber or switched the fuel to low sulfur coal, it will be different for the unit to change it's compliance strategy. However, the units with allowance strategy can change it's compliance strategy easily. The inflexibility of strategy change will induce the higher compliance cost compared with the flexible strategy. Allowance strategy has option value of flexibility compared with scrubber, fuel switch and "other" strategy. We expect that the shadow allowance price will be lower for these units and the marginal compliance cost of allowance strategy will be lower than the cost of capital intensive strategies(scrubber, fuel switch, "other" strategy).

4.3.4.3 Compliance with Local Stringent Regulation

The electric plants that constructed after 1971 had to comply with National Ambient Air Quality Standard(NAAQS) SO_2 emission standards by Title I of

CAAA 1990. And the plants that were built or modified after August of 1971 had to comply with the NSPS of SO_2 emission(1.2 pounds of SO_2 per mmBTU of heat input)(Klaassen et al, 1997). Before phase I period, some states or some local governments imposed stronger SO_2 emission standards to protect the local environment than phase I SO_2 emission standard. Three states of Wisconsin, Minnesota and New Hampshire had enacted acid rain laws or taken regulatory actions to reduce SO_2 emissions(Ellerman et al., 1998). These standards should be met by utilities irrespective of allowance possessing, and there was actually no allowance market before 1995. So the electric plants will not choose allowance strategy, instead will choose scrubber, fuel switch or "other" strategy.

4.3.4.4 Restriction of Allowance Purchase

Georgia Public Service Commission Order required the utilities to buy allowance only when the allowance price is below it's compliance cost. Connecticut PUC decided that the future sale of allowances should provide the sufficient detail on the transaction(Klaassen et al, 1997). This restriction of allowance purchase will cost for the allowance strategy since the units with allowance strategy have to buy allowances. However, the allowance purchase restriction will reduce the demand for allowance in the market, and the allowance prices will go down. As a result, we do not know the combined effect of the allowance purchase restriction for the allowance strategy. But this restriction will impose high cost for other kinds of strategies since the units with other kinds of strategies generally sell the surplus allowances in the market.

4.3.4.5 Restriction of Allowance Sale

Nwe York restricted the selling of allowances, and restricted the banking of allowance to avoid the acid deposition(Winebrake et al, 1995). West Virginia allowed the revenue from allowance sales of the units with scrubber to go to the ratepayers. Missouri law specified that allowances are utility property and that the allowance sale must be approved by the PUC(Bohi, 1993). This regulation will affect the shadow allowance price indirectly. That is, the shadow allowance price may increase since this restriction will reduce the supply of allowances in the market. This effect will mainly affect the MAC of compliance strategy that can produce surplus allowances like scrubber and fuel switch strategy since these units will sell the surplus allowances. As a result, the MAC of scrubber, fuel switch and "other" strategy will be high. There is a possibility that this restriction will raise the MAC of allowance strategy through by indirect effect since the reduced supply of allowances will raise allowance price in the market. However, we can not expect the prior negative effect of this regulation on the MAC of allowance strategy.

4.3.4.6 Restriction of Allowance Trading

Ohio Public Utilities Commission issued the guideline for the treatment of allowances that all gains and losses from allowance transactions would go to the ratepayers by fuel-adjustment-clause in the law passed in 1991(Bohi, 1993, Rose et al,1993). The guideline encouraged utilities to trade allowances only when it is economically justified. Pennsylvania ruled that allowances will be valued at original costs for ratemaking purposes, that is, zero cost for allowances originally allocated by EPA, and the purchase price plus broker fee for purchased allowances. Allowances are to be considered as fuel inventory and will be ratebased consistent with other operating inventory item. Allowance expenses are to be recovered through fuel-adjustment-clause. The gains or losses from allowance trading will go to ratepayers by fuel-adjustment clause. Iowa PUC's guideline is similiar to Ohio and Pennsylvania's guideline. Illinoise, Indiana, Kentucky, Florida and Georgia do not have any guideline for the treatment of allowance trade. Since the electric utility is regulated, we assume that the revenue and the cost from allowance trading will go to the ratepayers when there is no specific guideline for allowance trade. The restriction of allowance trade will reduce the trade volume of allowances in the market. So this restriction will make the shadow allowance price high. The allowance trade restriction will make the MAC higher for all kinds of compliance strategies. However, we do not know the relative intensity of this restriction on the MAC of each compliance strategy. The relative effect of this regulation will be decided by the data.

4.3.4.7 Encouragement of High-Sulfur Coal Usage

Some state governments worried about the job loss in the coal industry when the in-state electric plants change their fuel from the in-state high-sulfur coal to low-sulfur coal or other kinds of fuels. Illinoise considered the law that utilities except two utilities should use certain proportions of Illinoise high-sulfur coal to avoid the high-sulfur coal mining job loss(Winebrake et al, 1995). Illinoise law required that utilities can not reduce the usage of Illinoise high-sulfur coal without Illinoise Commerce Commissions' permission. In 1991, Ohio passed a law that provided tax credits for clean coal technology using Ohio high-sulfur coal, and allowed the cost recovery for the capital expenditure of compliance strategy investment. Indiana state law required the continuing use of Indianian high-sulfur coal unless there is an economic justification for the use of out-of-state coal that compensates for any negative impact on the Indian coal industry(Bohi, 1994). Pennsylvania and Kentucky state also encouraged to use in-state high-sulfur coal.

The encouragement of high-sulfur coal usage will mainly affect the MAC of scrubber and allowance strategy through the shadow price of high-sulfur coal and the shadow price of capital since electric units can use high-sulfur coal through two kinds of compliance strategy, that is, scrubber and allowance strategy. If the high-sulfur coal states offered the law in favor of capital expenditure, then the electric plant will more likely install scrubbers and the shadow capital price will be lower for the scrubber strategy. In case that the states gave the benefit for the high-sulfur coal price, the shadow price of high-sulfur coal is low, and the electric plant will more likely use allowance strategy.

4.3.4.8 Cost Recovery of Compliance Strategy Investment

Many states have the favoring cost recovery clause for the capital expenditure of compliance strategy investment(Bohi, 1994). Ohio allowed for the cost recovery of capital expenditure resulting from compliance investment by the law passed in 1991. The Indian law allowed for cost recovery of construction work in progress for pollution control equipment tilting the cost recovery rules in favor of capital expenditures over other compliance options. Pennsylvania law allowed also the cost recovery of capital expenditure on construction work in progress for pollution reduction project. West Virginia Public Service Commission allowed Monongahela Power Co. and Potomac Edison Co. to recover the cost of scrubbing the Harrison plant while construction work is in progress. Wisconsine also allowed the cost recovery for the capital expenditure of scrubber strategy. Illinoise law allowed the cost recovery. Kentucky allowed the quick recovery of capital cost for environmental compliance through monthly surcharge. Florida law provided that all environmental compliance cost be recovered through an Environmental Cost Recovery Factor(ECRF). Florida and Kentucky passed legislation that allowed recovery of compliance costs through a surcharge system that is distinct from base rate(Rose et al, 1993). This system was designed to allow quick cost recovery for planned scrubbers especially for Kentucky. Maryland, Washington D.C and Mississippi had similiar system.

Cost recovery will affect the shadow capital price. It is unclear whether the states will favor the scrubber strategy over fuel switch or "other" strategy except for West Virginia and Wisconsin that allowed the cost recovery for the capital expenditure of scrubber. The five high-sulfur coal states are already tested through shadow high-sulfur coal price and shadow capital price in the previous section. So we include in the cost recovery variable the states that have cost recovery clause but were not included in high-sulfur coal states. The cost recovery will lower the shadow capital price for capital intensive compliance strategy, and then lower the MAC for these strategies.

4.3.4.9 Type of Ownership

The privately-owned generating units are regulated by state PUC, But the federal project of TVA is not subject to state regulation. The state PUC is representated by uncertainty of regulation since the PUCs were not clear about the treatment of allowance transaction in the accounting rule(Rose et al, 1993). If the units are regulated by state PUC, the units will less likely to use allowance strategy. Instead, they will more likely choose technically proven strategies like scrubber and fuel switch. Moreover, the private generating units will not take the risky strategy of allowance strategy, but the non-private units will take the challenging strategy. The degree that the manager of private units have the responsibility for the risky strategy will be higher than the degree of non-private units' manager. So non-private units will more likely to use allowance strategy.

4.3.5 Multinomial Logit Model

Multinomial logit model is a appropriate qualitative choice models when the dependent variable is discrete choice, and decision maker chooses one alternative among several alternatives based on the observed characteristics of decision maker (Train, 1993). Assume that there are n decision makers and a set of alternatives j_n that the decision maker faces.

The qualitative choice situation, which qualitative choice models are used to describe, has to satisfy the following criteria; That is, (1) the number of alternatives in the set is finite, (2) the alternatives are mutually exclusive and (3) the set of alternatives is exhaustive.

Suppose that each decision maker will choose one specific alternative from a set of alternatives. Let the objective function a cost function and r_n the vector of all relevant characteristics of decision maker n that will affect the value in the objective function. The decision maker n will choose alternative i from a set of alternatives j_n if and only if

$C_{in} < C_{jn}$ for all j in j_n, j   i.

where j_n is a set of alternatives

However, the researcher does not observe all relevant characteristics of decision maker n, and he does not know the cost function exactly. All relevant characteristics of decision maker n can be decomposed into observed characteristics by researcher(s_n) and unobserved part. So the objective function can be decomposed into two parts. That is, the cost function can be decomposed into one part(V_{in}) that depends only on the observed characteristics of decision maker by researcher and whose form is known by the researcher up to a vector of parameters(β) that are either known a priori by the researcher or estimated, and the another part that represents all factors and the aspects of objective function that are unknown by the researcher(e_{in}). That is,

$C_{in} = C(r_n) = V_{in}(s_n, \beta) + e_{in}$

The probability(PR_{in}) that decision maker n will choose alternative i is the limit of the proportion of times, as the number of times increases without bound. We can rewrite the probability that decision maker n will choose alternative i if and only if the objective value of alternative i is less than the objective value of any other alternative, given the observed components of objective function for each alternative.

$PR_{in} = Prob(C_{in} < C_{jn}, \text{ for all } j \text{ in } j_n, j \quad i)$

Substituting the previous functions, then

$PR_{in} = Prob(V_{in} + e_{in} < V_{jn} + e_{jn}, \text{ for all } j \text{ in } j_n, j \quad i)$

By rearranging, we get the following probability equation.

$PR_{in} = Prob(e_{in} - e_{jn} < V_{jn} - V_{in}, \text{ for all } j \text{ in } j_n, j \quad i)$

Since the researcher can calculate the difference in the objective value(V_{jn} - V_{in}) using limited information, this part is deterministic. However, the researcher does not observe the e_{in} and e_{jn}. Since e_{in} and e_{jn} are random variables, the difference between two random variables(e_{in}-e_{jn}) is also random variable. So the probability(PR_{in}) that decision maker n will choose alternative i is just the probability that each random variable(e_{in}-e_{jn}) is below the known value(V_{jn}-V_{in}) for all j in j_n, j i.

If the researcher knows the distribution of the random variables(e_{in}, e_{jn}), he can derive the distribution of each difference in the random variables(e_{in}-e_{jn}). And the researcher can calculate the probability(PR_{in}) that decision maker n will choose alternative i as a function of the difference in the objective value(V_{jn}-V_{in}, for all j in j_n, j i).

The logit model assumes that each random variable(e_{in}, for all j in j_n) is distributed independently, identically in accordance with the extreme value distribution. Given this distribution, the probability(PR_{in}) that the decision maker will choose alternative i is defined as(Train, 1993);

$$PR_{in} = \exp(V_{in}) / [\Sigma_j \exp(V_{jn})\ ] = \exp(z_i\beta_j) / \sum_{j=1}^{J} \exp(z_i\beta_j), \text{ for all i in } j_n.$$

There are three properties in multinomial logit model(Train, 1993). First, each of the choice probabilities is necessarily between zero and one. Second, the choice probabilities necessarily sum to one since the set of alternatives is exhaustive;

$\Sigma_i\ (PR_{in}) = \Sigma_i \{exp(V_{in})\ /\ [\Sigma_j\ exp(V_{jn})\ ]\} = 1$

Third, the relation of the choice probability for an alternative to the objective value(V_{in}) of that alternative, holding the objective values of the other alternatives fixed, is sigmoid, or S-shaped.

The marginal effect of the probability is defined as the extent to which the probabilities change in response to a change in some observed characteristics. More specifically, the change in the probability that decision maker n will choose alternative i given a change in one of observed characteristics(s_{ikn} is the kth characteristics of observed characteristics of decision maker n(s_{in}) who choose alternative i) being included in the objective function of alternative i is(Long, 1997)

$$PR_{in}/\quad s_{ikn} = PR_{in}\ [(\quad V_{in}/\quad s_{ikn}) - \sum_{j=1}^{J} (\quad V_{jn}/\quad s_{jkn})(PR_{jn})\ ]$$

If the coefficient of s_{ikn} is β_{ik} in case that the observed objective function is linear in the observed characteristics, then $V_{in}/\quad s_{ikn} = \beta_{ik}$. So the marginal effect can be rewritten as;

$$PR_{in}/\quad s_{ikn} = PR_{in}[\beta_{ik} - \sum_{j=1}^{J} \beta_{ik}\ (PR_{jn})]$$

The changes in the choice probabilities sum to zero when one observed variable changes since the probabilities must sum to one before and after the change.

$$\Sigma_i\quad PR_{in}/\quad s_{in} = (\quad V_{jn}/\quad s_{jn})PR_{jn}(1-PR_{jn}) + \Sigma_i\ (-\quad V_{jn}/\quad s_{jn})PR_{jn}PR_{in} = 0$$

This means that, if one alternative is improved so that its probability of being chosen increases, the additional probability necessarily declines from other alternatives. That is, to increase the probability of one alternative necessitates decreasing the probability of another alternatives.

We estimate the logit model using maximum likelihood estimation technique. The likelihood function is(Ben Akiva and Lerman);

$$L(\beta_1,,,,\beta_j|y, S_{in}) = \prod_{n=1}^{N} \prod_{j=1}^{J} [\ PR_{in}]^{yin} = \prod_{n=1}^{N} \prod_{j=1}^{J} [\exp(S_{in}\beta_m)/ \sum_{j=1}^{J} \exp(S_{in}\beta_j)]^{yin}$$

And the log-likelihood function is ;

$$LL(\beta\ ) = \sum_{n=1}^{N} \sum_{j=1}^{J} y_{in}[S_{in}\beta_m - \log \sum_{j=1}^{J} \exp(S_{in}\beta_j)]$$

The likelihood ratio index is used to test hypothesis for each variable or several variables(Train, 1993). Let β^H the constrained maximum likelihood estimate of the parameters. The ratio of likelihood is defined as

$$R = L(\beta^H) / L(\beta^*)$$

where $L(\beta^H)$ is the constrained maximum value of the likelihood function under the null hypothesis

$L(\beta^*)$ is the unconstrained maximum value of the likelihood function.

The test statistic defined as -2*log(R) is distributed chi-squared with degree of freedom equal to the number of restrictions implied by the null hypothesis. That is,

$-2 * \log(R) = -2 * [\log L(\beta^H) - \log L(\beta^*)] = -2 * [LL(\beta^H) - LL(\beta^*)$

where $LL(\beta^H)$ is the log of constrained liglikelihood function

$LL(\beta^*)$ is the log of unconstrained likelihood function

If this statistic exceeds the critical value, then we can reject the null hypothesis.

The other test is Wald test, which is easier to apply when there are many variables(Long,1997). Let $\beta^{\wedge}_k = (\beta^{\wedge}_{jk})'$ be the maximum likelihood estimates for variable k. $Var^{\wedge}(\beta^{\wedge}_k)$ be the estimates' covariance matrix. The Wald test statistic is $W_k = (\beta^{\wedge}_k)' [var^{\wedge}(\beta^{\wedge}_k)]^{-1}(\beta^{\wedge}_k)$. If the null hypothesis is true, the Wald statistic is distributed as chi-square wuth j-1 degree of freedom.

Hypothesis test for two alternatives using LR test is simple but statistically less powerful than Wald test. Select the observations that chose the alternatives being considered and estimate the binary logit on the new sample. Then calculate LR test that all coefficients(except for intercept) are zero. If this is true, then statistic is distributed with degree of freedom of j-1.

Wald test statistic is $(Q\beta^{\wedge*})' [Qvar^{\wedge}(\beta^{\wedge*})Q']^{-1}(Q\beta^{\wedge*})$

Where Q is the linear combination of restrictions, $\beta^{\wedge*}$is the estimates from all parameters.

Independence of Irrelevant Alternatives(IIA) property requires that if a new alternative becomes available, then all probabilities for the prior choices must adjust in precisely the amount necessary to retain the original odds among all outcomes(Long,1997). This property means that multinomial logit model should be used in cases where the outcome catogeries are distinct and weighted independently for decision maker. Hausman test can be used for testing IIA(Long,1997). The basic idea is that if the alternatives are irrelevant in computing the odds for two outcomes, then omitting those alternatives should not affect the estimates of the parameters that affect the two outcomes. The statistic is

$$H_{IIA}= (\hat{\beta}_R-\hat{\beta}^{*}_F)' \, [\hat{var}(\hat{\beta}_R)-\hat{var}(\hat{\beta}^{*}_F)]^{-1}(\hat{\beta}_R-\hat{\beta}^{*}_F)$$

Where $\hat{\beta}_R$ is stack of estimates of restricted model that eliminate one or more outcomes, $\hat{\beta}^{*}_F$ is stack of estimates of full model. Degree of freedom is the row in $\hat{\beta}_R$, that is the number of included choices.

4.3.6 Empirical Specification

We define that the SO_2 emission reduction compliance strategies as alternatives. So the set of compliance strategy is composed of four kinds of strategies of allowance, "other", scrubber and fuel switch, which are ones that each generating unit actually chose in Phase I period. Each unit chose only one compliance strategy among four kinds of strategies and we include whole units excluding only 4 retired units that do not have observations. So the strategy set satisfies the conditions of alternative set, which is finite, mutually exclusive and exhaustive. We define the observed characteristics of unit are the shadow and actual prices of input factors(capital, labor, high-sulfur coal and low-sulfur coal), electricity generation level, the actual SO_2 emission, allowance price and regulatory dummy variables and vintage variable.

If we substitute behavioral cost function, then probability that compliance strategy *i* will be chosen by generating unit *n* is

$PR_{in} = \exp(V_{in}) / [\Sigma_j \exp(V_{jn})]$, for all i in j_n.

That is,

$$PR_i = exp[\alpha_0 + \alpha_{al} D_{al} + \alpha_{np} D_{np} + \alpha_{pr} D_{pr} + \alpha_{su} D_{su} + (\beta_0 + \beta_{tr} D_{tr} + \beta_{se} D_{se} + \beta_{bu} D_{bu})P_a + (\gamma_k + \gamma_{hs} D_{hs} + \gamma_{co} D_{co})P_k + (\delta_0 + \delta_{hs} D_{hs})P_{fhs} + P_{fls} + P_l + \beta_q Q + \beta_e E + \beta_{srv} srvmonth] /$$

$$\{\Sigma_{j=1}^{4} exp[\alpha_0 + \alpha_{al} D_{al} + \alpha_{np} D_{np} + \alpha_{pr} D_{pr} + \alpha_{su} D_{su} + (\beta_0 + \beta_{tr} D_{tr} + \beta_{se} D_{se} + \beta_{bu} D_{bu})P_a + (\gamma_k + \gamma_{hs} D_{hs} + \gamma_{co} D_{co})P_k + (\delta_0 + \delta_{hs} D_{hs})P_{fhs} + P_{fls} + P_l + \beta_q Q + \beta_e E + \beta_{srv} srvmonth]\}, \text{ for all } i \text{ in } j_n.\ j=1,2,3,4$$

In the estimation, we set the allowance strategy as the reference strategy. So we normalize the parameters of reference strategy(allowance strategy) to be zero. However, there is a separation problem for the dummy variable D_{al} for the units that adopted allowance strategy since the generating units with this dummy variable do not have any other kinds of compliance strategy. Even though this variable does not affect the consistency, we can not get the estimate for this variable since the probability approaches zero or infinity(Amemiya, 1985, Albert, 1984), we exclude this variable. So the intercept of shadow allowance price will measure the option value and the technical inflexibilities up to some level since we drop the allowance dummy variable.

However, the allowance price is same for all generating units and all kind of compliance strategies since there is only one allowance market price each year. So the actual allowance price does not explain the choice of compliance strategy. We drop the actual allowance price. Instead we assume that the two regulatory dummy variables of allowance trade restriction and allowance sale restriction will represent the shadow allowance price.

Units that are located in the state(Georgia) that restricted the allowance purchase do not have allowance and "other" strategy. We drop this variable in the shadow allowance price because of separation problem. So the shadow allowance price is function of allowance trade restriction and allowance sale restriction.

Since the emission is an endogenous variable, we use the estimated value for emission to avoide endogeneity problem. We estimate the emissions using observed input prices, output, allocated allowance, previous period's allowances, current period's allowance banking, SO_2 emission removal efficiency rate for the case of scrubber. We add one more variable of sulfur content of coal to estimate SO_2 emission. Actually we used the proxy variable for the sulfur content of coal. That is, we use SO_2 emission level before scrubbing for the proxy variable of sulfur content. Since we use the SO_2 emission level as a dependent variable, the use of proxy variable for SO_2 emission level before scrubbing will not give the biased estimates.

$E_i = E(P_i, Q_i, W_i, S_{-1i}, S_i, remeffc, sulfur)$

4.4 Data

4.4.1 Definition and Source

We get the annual electricity production(***gen*** in KWh) of each generating unit from EIA767(Annual Steam Electric Unit Operation and Design Report) of Energy Information Administration of Department of Energy(DOE/EIA). We assume that the fuel consumption and the SO_2 emission of generating units are proportional to the ratio that each boiler contributed to the total electricity generation of each unit in case of multiple relationship between boiler and generating unit.

We separate the coal into low-sulfur coal and high-sulfur coal based on the sulfur content of 1.2 pound SO_2 emission per million BTU heat input since many units are applied by NSPS, NAAQS and stringent local emission regulation of which emission standard is at least 1.2 pound of SO_2 emission per million BTU heat input, even though the emission rate standard in Phase I is 2.5 pound of SO_2 emission per million BTU(Carlson et al,2000). We calculate low-sulfur coal prices(***lcoalp1*** in cents/mmBTU) and high-sulfur coal(***hcoalp1*** in cents/mmBTU) from EIA-423(Monthly Cost and Quality of Fuels for Electric Units Data) data at the unit level. This database offerd only electric plant level's fuel cost. So we assume that coal prices are same as the other unit's prices if all these units belong to the same electric plant. Since each unit used only one kind of coal, we used the state average price weighted by the heat for missing price. If there is no price available in the corresponding state, we use the adjacent state's average price or US average price.

We get the annual wage rate(***wage*** in \$/employee) from FERC-1(Electric Utility Annual Report) of Federal Energy Regulatory Commission. We divide the sum of total salary, the pension and the benefit by the number of employees to get the annual wage rate for utility. The labor of the half-time employee is assumed to be the half of the full-time employee. We assumed that all the generating unit's wage rate is same as the wage rate of the electric utility to which the corresponding unit belongs.

We calculated the capital price(***rent*** in \$/\$) from FERC-1 form data. Capital is the sum of long-term debt, common stock issued and preferred stock issued, and capital cost is the sum of interest for long-term debt, dividends for common stock and preferred stock. We divide each component's cost by the total amount of capital, and multiply it by the component ratio. We deflate all the price data using Consumer Price Index(1982-1984=100).

In case of the rent and the wage rate, same method as that of high-sulfur and low-sulfur coal price was used to estimate the rent and the wage of the units that do not have the price. We used the weighted average rent and wage rate of the state where the utility is located for the units of which rent and wage are missing. If the rent and the wage are not available in that state, we use the mean value of the United States.

We get the SO_2 emission(***emis*** in ton) data of each boiler from Acid Rain Program data base of Environmental Protection Agency(EPA). This emission data is measured from Continuous Emissions Monitoring System(CEMS). We multiplied boiler's SO_2 emission by electricity production ratio to get the SO2 emission of each generating unit. In the period of 1995-1997, we can not get the separate SO_2 emission for some boilers that share the stack. In this case, we divide the total SO_2 emission of common stack by the electricity generation ratio of each unit. From 1998, we can get the separate CEMS SO_2 emission data of each boiler, however.

The vintage(***srvmonth*** in months) is the in-service months of the generating unit from the commercial operation to the December of 1999 in terms of months using the data from EIA767 data set. We used SO_2 emission before scrubbing for proxy variable for sulfur content of coal.

The data of allowance are from EPA's Acid Rain Database. The other variables like location(state), ownership type of electric unit are available. We get the monthly allowance price in the second market where private transactions were taken place from EPA data base. We get the simple allowance price by dividing the sum of monthly price by twelve. We use the private brokerage firms's(Fieldstone) data base.

4.4.2 Identification of Compliance Strategy Change

All of the phase I generating units reported their SO_2 emission reduction compliance strategy to Department of Energy(DOE) in 1993. This information is the only available data to identify the compliance strategy of each generating unit. However, many units changed their compliance strategy in phase I period since there were time lag between the report and the implementation of the strategy, and the market situation was changed.

We checked the scrubber(FGD) data for each generating unit from EIA 767 data base, and identified the scrubber strategy and the year when the unit installed and operated scrubber before phase I period. One additional unit used scrubber strategy from 1995, and the other additional unit operated scrubber from 1997. These two units changed strategy from reported fuel switch to scrubber. Even though two other units installed scrubber in 1999, these units are assumed to be applied to phase II period(from 2000) since they did not operate scrubber in 1999. The realized number of units that installed and used scrubber strategy in phase I period is 29 units.

If the SO_2 emission of the generating units in phase I period that reported allowance strategy as a compliance strategy is continuously below the emission standard and did not buy allowance, then we identified these units changed strategy from reported allowance purchasing strategy to fuel switch strategy. Four generating units changed their strategy to fuel switch from allowance strategy.

If the SO_2 emission of the generating units with reported fuel switch is continuously over the emission standard and bought the allowance instead, then we define that their strategy were changed from reported fuel switch to allowance strategy. 23 generating units changed the compliance strategy to allowance strategy from fuel switch.

Instead of 7 units, only 4 generating units retired. 7 units used "other" strategy including switch to natural gas or oil. Finally, 29 generating units used scrubber strategy as SO_2 emission reduction compliance strategy, 102 units used allowance strategy, 115 units used fuel switch strategy and 11 units were "other" strategy among 261 Phase I generating units at the end of phase I period(1999).

Especially, the number of units(23) that changed their strategy from fuel switch to allowance is greater than the number of the units(4) that changed their strategy from allowance to fuel switch. This comes from the fact that the initially forecasted price of allowance before 1993 was much higher than the actual price when the allowance market was opened in 1993. The allowance price was between $100 and $150, but the forecasted price was over $200. The reported compliance strategy was made before the opening of allowance market. So the electric utility may based their compliance strategy on the forecasted price of allowance.

Table 4.1 Number of Generating Units by Compliance Strategy

allowance strategy	1995	1996	1997	
- reported	83	83	83	
- change from fuel switch	22	1	0	
- change to fuel switch	1	0	3	
- estimated	104	105	102	
"other" strategy				
- reported	11	11	11	
scrubber strategy				
- reported	27	27	27	
- change from fuel switch	1	0	1	
- estimated	28	28	29	
fuel switch strategy				
- reported	136	114	113	
- changed from allowance	1	0	3	
				0
- change to allowance	22	1		
- estimated	114	113	116	

* "other" strategy includes 4 retired units

4.4.3 Data Statistics

The mean electricity generation(MWh) of the 257 phase I generating units increased phase I period(1995-1999). SO_2 emission(ton) increased until 1997, but declined after that year. The capital price(rent) declined in 1996, but increased in 1997-1998 period, and declined in 1999. Both prices of high-sulfur and low-sulfur coal declined continuously in phase I period. The allowance price declined in 1996, but increased continuously, and the allowance price at the end of phase I period(1999) was highest during phase I period. The net traded volume of allowance was positive in 1995, which means the net purchase of allowances. However, the net traded volume of allowances was negative after 1995, which means that the units sold surplus allowances. This statistics means that the units over abated in phase I period.

Table 4.2 Data Statistics of 257 units in 1995-99

Variable	Label	Mean	Std Dev	Minimum	Maximum
gen	(KWh)	1800600289	1546583689	2679000.00	10266594000
so2	(ton)	17847.45	18581.46	3.0000000	173285.00
rent	($/$)	0.0850058	0.0546187	0	1.1259843
hcoalp	(c/mmBTU)	77.0626555	20.0698055	30.7202040	257.3602207
lcoalp	(c/mmBTU)	80.1854326	16.1258495	10.4312860	151.4897414
hcoalp1	(c/mmBTU)	80.2224275	18.0196531	31.2433145	222.5817167
lcoalp1	(c/mmBTU)	82.8283206	17.1097886	27.6244468	133.2175920
wage	($)	31573.59	12264.23	2986.69	99917.02
srvmonth	(month)	420.1284047	92.6669320	96.0000000	588.0000000
alocalow	(ton)	23038.42	21405.65	0	192637.00
heldalow	(ton)	30207.04	30280.32	0	277612.00
dedcalow	(ton)	17905.10	18614.93	3.0000000	173285.00
caryalow	(ton)	12309.76	22147.48	0	236801.00
netrade	(ton)	-1868.69	21530.88	-163445.00	181290.00
alowprice	($/ton)	83.2517853	22.6074296	55.0223072	116.4945978
emissulf1sum	(standard)	3251.74	10323.49	0	88446.00
emissulf2sum	(standard)	0.4902724	6.6270902	0	90.0000000
avgremeffc	(%)	0.0982428	0.2871283	0	0.9930000
so2ebbtu	(pound/mmBTU)	2.6006818	1.4853384	0.1540820	7.0858937

Table 4.3 Data Statistics of units with allowance strategy in 1995-99

Variable	Label	Mean	Std Dev	Minimum	Maximum
gen	(KWh)	1525355990	1139528842	48880000.00	7182524000
so2	(ton)	27002.10	23108.92	1855.01	173285.00
rent	($/$)	0.0796335	0.0747544	0	1.1259843
hcoalp	(c/mmBTU)	76.5409035	23.4630619	31.2433145	257.3602207
lcoalp	(c/mmBTU)	79.1869103	12.6380191	39.4372162	118.6855306
hcoalp1	(c/mmBTU)	77.6722713	18.9338000	31.2433145	185.2192111
lcoalp1	(c/mmBTU)	83.2052811	15.2495334	33.6547222	133.2175920
wage	($)	33027.89	13400.03	4664.89	99917.02
srvmonth	(month)	449.7101167	85.1886086	249.0000000	585.0000000
alocalow	(ton)	19567.26	14941.99	0	135688.00
heldalow	(ton)	33727.43	30676.58	0	277612.00
dedcalow	(ton)	27175.71	23110.24	836.0000000	173285.00
caryalow	(ton)	6573.52	13265.87	0	107454.00
netrade	(ton)	9017.40	15980.69	-38973.00	181290.00
alowprice	($/ton)	83.0895167	22.6351203	55.0223072	116.4945978
emissulf1sum	(standard)	2125.18	5955.11	0	45054.00
emissulf2sum	(standard)	0	0	0	0
avgremeffc	(%)	0.0038132	0.0610711	0	0.9800000
so2ebbtu	(pound/mmBTU)	3.3673560	1.1655485	1.4108414	7.0858937

Table 4.4 Data Statistics of units with "other" strategy in1995-99

Variable	Label	Mean	Std Dev	Minimum	Maximum
gen	(KWh)	809262107	589959107	2679000.00	1997621000
so2	(ton)	3199.77	2411.04	3.0000000	10502.00
rent	($/$)	0.0733014	0.0218135	0.0297726	0.1236667
hcoalp	(c/mmBTU)	78.2751711	11.0443890	63.0506826	100.8756000
lcoalp	(c/mmBTU)	85.1311636	13.7824401	63.2465199	117.2705263
hcoalp1	(c/mmBTU)	83.3124387	12.4893490	63.2021385	106.2439000
lcoalp1	(c/mmBTU)	89.3043328	12.7106208	70.1238816	119.6960077
wage	($)	31936.11	12196.34	6779.63	55390.88
srvmonth	(month)	442.6250000	75.1731975	317.0000000	540.0000000
alocalow	(ton)	13907.45	7525.55	4385.00	25783.00
heldalow	(ton)	10388.10	7736.56	33.0000000	32397.00
dedcalow	(ton)	3199.68	2411.12	3.0000000	10502.00
caryalow	(ton)	7146.25	6468.13	26.0000000	26289.00
netrade	(ton)	-8636.90	7691.94	-27817.00	7975.00
alowprice	($/ton)	83.2517853	22.8865235	55.0223072	116.4945978
emissulf1sum	(standard)	2.3050000	1.8389448	1.0000000	6.0000000
emissulf2sum	(standard)	0	0	0	0
avgremeffc	(%)	0	0	0	0
so2ebbtu	(pound/mmBTU)	2.8738739	0.5133078	2.2775154	3.6974621

Table 4.5 Data Statistics of units with scrubber strategy in 1995-99

Variable	Label	Mean	Std Dev	Minimum	Maximum
gen	(KWh)	3139685711	2710748706	207725000	10266594000
so2	(ton)	6709.09	8633.77	103.0000000	73364.00
rent	($/$)	0.0812469	0.0346299	0.0204447	0.2731926
hcoalp	(c/mmBTU)	73.2383236	15.7323635	31.2433145	113.7477069
lcoalp	(c/mmBTU)	78.8397440	16.8100396	10.4312860	118.6855306
hcoalp1	(c/mmBTU)	74.3152940	16.1639175	31.2433145	113.7477069
lcoalp1	(c/mmBTU)	86.4814113	14.9564371	42.7971188	129.6519162
wage	($)	32979.78	13512.22	2986.69	99917.02
srvmonth	(month)	360.6619718	89.3637786	237.0000000	579.0000000
alocalow	(ton)	43845.84	41698.99	4703.00	192637.00
heldalow	(ton)	31275.68	48198.81	2003.00	245652.00
dedcalow	(ton)	6737.58	8680.07	103.0000000	73364.00
caryalow	(ton)	24538.10	46715.30	28.0000000	236801.00
netrade	(ton)	-30178.04	37841.40	-163445.00	47032.00
alowprice	($/ton)	83.4325234	22.7920601	55.0223072	116.4945978
emissulf1sum	(standard)	1410.11	10496.97	0.2000000	88446.00
emissulf2sum	(standard)	1.9014085	12.9884345	0	90.0000000
avgremeffc	(%)	0.8688873	0.2429563	0	0.9930000
so2ebbtu	(pound/mmBTU)	4.5159024	1.1716016	1.0528269	6.8382983

Table 4.6 Data Statistics of units with fuel switch strategy in 1995-99

Variable	Label	Mean	Std Dev	Minimum	Maximum
gen	(KWh)	1785284444	1318628092	3661000.00	6570722000
so2	(ton)	13538.55	11548.85	22.5423858	58818.00
rent	($/$)	0.0913951	0.0352268	0.0261552	0.3755116
hcoalp	(c/mmBTU)	78.3576216	18.0634828	30.7202040	257.3602207
lcoalp	(c/mmBTU)	81.0453631	18.5587798	43.3950150	151.4897414
hcoalp1	(c/mmBTU)	83.6621437	17.2244584	39.4146308	222.5817167
lcoalp1	(c/mmBTU)	81.1788520	19.0549333	27.6244468	131.3393393
wage	($)	29940.84	10636.64	2986.69	52570.14
srvmonth	(month)	407.1222411	91.1454433	96.0000000	588.0000000
alocalow	(ton)	21671.30	16199.72	0	113801.00
heldalow	(ton)	28223.23	24049.27	0	151649.00
dedcalow	(ton)	13505.97	11529.16	22.5423858	58818.00
caryalow	(ton)	14718.16	17860.40	0	120236.00
netrade	(ton)	-4083.97	11705.84	-86919.00	64903.00
alowprice	($/ton)	83.3498181	22.5769310	55.0223072	116.4945978
emissulf1sum	(standard)	4899.51	13038.22	0.0336203	55555.00
emissulf2sum	(standard)	0.6112054	7.3978263	0	90.0000000
avgremeffc	(%)	0.0015280	0.0370839	0	0.9000000
so2ebbtu	(pound/mmBTU)	1.4670250	0.7034313	0.1540820	4.9289996

4.5 Estimation Result

Table 4.7 Hypothesis Test Result

Hypothesis	Restrictions	Test Statistic	χ^2 Critical Value(α=0.05)
no regulatory effect	$\alpha_{np}=\alpha_{pr}=\alpha_{su}=\beta_{tr}=\beta_{se}=\gamma_{hs}=\gamma_{co}=\delta_{hs}=0$	240.23	36.42
no effect on shadow allowance price	$\beta_{tr}=\beta_{se}=0$	40.452	12.59
- no effect of allowance trade restriction	$\beta_{tr}=0$	10.894	7.81
- no effect of allowance sale restriction	$\beta_{se}=0$	22.05	7.81
no effect on shadow capital price	$\gamma_{hs}=\gamma_{co}=0$	17.046	12.59
- no effect of high-sulfur coal usage	$\gamma_{hs}=0$	15.276	7.81
- no effect of cost recovery	$\gamma_{co}=0$	3.558	7.81
no effect on shadow high-sulfur coal price	$\delta_{hs}=0$	3.086	7.81
no effect of ownership	$\alpha_{np}=0$	8.694	7.81
no effect of local stringent regulation	$\alpha_{pr}=0$	32.766	7.81
no effect of sub/comp. Boilers	$\alpha_{su}=0$	28.028	7.81
no effect of high-sulfur coal states	$\gamma_{hs}=\delta_{hs}=0$	71.14	12.59
no effect of generation	$\beta q_{=0}$	552.15	7.81
no effect of capital price	$\beta Pk_{=0}$	20.892	7.81
no effect of wage	$\beta w_{=0}$	6.89	7.81
no effect of high sulfur coal price	$\beta_{fhs=0}$	43.192	7.81
no effect of low-sulfur coal price	$\beta_{fls=0}$	158.25	7.81
no effect of SO2 emission	$\beta emishat_{=0}$	731.848	7.81
no effect of vintage	$\beta srvmonth_{=0}$	32.436	7.81

The null hypothesis of no regulatory effect, that is, all of the coeficient of regulatory variables are zero can be rejected at 1% significance level. So we can say that the regulation significantly affected the choice of compliance strategy of phase I generating units. Since the hypothesis that the restriction of allowance strategy and allowance sale doe not affect the shadow allowance price is also rejected, these restrictions affect the choice of compliance strategy. Both of the restriction have statistically significant effect on the shadow allowance price. The encouragement of high-sulfur coal usage affect capital price, thereby the strategy choice at 10% significance level. But the cost recovery variable does not significantly affect the shadow capital price. The regulatory variables of ownership type, existence of local stringent emission regulation, existence of substitution/compensation boilers affect the strategy choice. The encouragement of high-sulfur coal usage does not affect shadow high-sulfur coal price.

The coefficient of ownership variable(D_{NP}) is significant for the choice of fuel switch at 1% significance level, and significant for the choice of scrubber strategy at 5% significance level, but has weak explanatory power for "other" strategy in terms of relative probability compared to the probability of allowance strategy. The probability for all kinds strategy except for allowance is negative in marginal effect table. That is, the non-private electric utilities are more likely to choose allowance strategy. Contrary to non-private units, private units are less likely to choose allowance strategy, and more likely to choose technically confirmed scrubber, fuel switch strategy. The non-private units are more likely to adopt challenging compliance strategy of allowance strategy. One explanation for non-private unit's choice of allowance strategy may be the fact that the non-private

Table 4 Estimation Result

LOG OF LIKELIHOOD FUNCTION = -656.236

parameters	"other" strategy		scrubber strategy		fuel switch strategy	
constant	-14.3849	(-3.77306)	-3.63373	(-1.37696)	0.869827	(0.81615)
$\alpha_{np}D_{np}$	-1.81152	(-1.47222)	-1.0937	(-1.67228)	-0.5428	(-2.40876)
$\gamma_{co}D_{co}$	1.56582	(0.186851)	9.41177	(1.7416)	-0.12529	(-0.05434)
$\alpha_{pr}D_{pr}$	4.64138	(5.05707)	2.36037	(2.38725)	0.783438	(2.37046)
$\alpha_{su}D_{su}$	2.21794	(3.31323)	-1.80507	(-3.2434)	-0.09413	(-0.45293)
$\delta_{hs}D_{hs}$	0.030539	(1.52236)	-8.15E-03	(-0.47844)	-2.17E-03	(-0.37044)
$\beta_{tr}D_{tr}$	0.016092	(1.18953)	-1.62E-03	(-0.19853)	9.30E-03	(2.84677)
$\beta_{se}D_{se}$	0.031155	(2.88155)	-7.52E-03	(-0.87016)	-9.82E-03	(-2.57541)
$\gamma_{hs}D_{hs}$	-2.15897	(-0.1165)	24.1526	(1.8052)	-12.3275	(-2.69727)
Gen	1.50E-09	(2.51917)	5.80E-09	(14.5118)	2.97E-09	(10.9287)
Rent	8.29014	(0.450513)	-24.0098	(-1.90931)	14.3508	(3.20625)
wage	3.35E-05	(1.3462)	1.38E-05	(0.724331)	-1.18E-05	(-1.55426)
hcoalp1	-0.05737	(-2.40203)	-0.11286	(-5.60249)	-0.02634	(-3.36358)
lcoalp1	0.208957	(9.24085)	0.19244	(9.57582)	0.101174	(8.16302)
Emishat	-5.12E-04	(-8.7868)	-7.43E-04	(-15.356)	-4.78E-04	(-11.8504)
β_{srv}srvmonth	-3.98E-03	(-1.04793)	-3.85E-03	(-1.31027)	-6.80E-03	(-5.4051)

( ) are t-ratios

<marginal effect>

parameters	allowance	"other"	scrubber	fuel switch
constant	0.0021786	-0.2331	-0.085284	0.3162
$\alpha_{np}D_{np}$	0.079601	-0.023185	-0.013202	-0.043214
$\gamma_{co}D_{co}$	-0.029056	0.019092	0.20902	-0.19905
$\alpha_{pr}D_{pr}$	-0.13064	0.065038	0.034854	0.030749
$\alpha_{su}D_{su}$	0.0034503	0.037308	-0.039816	-0.00094249
$\delta_{hs}D_{hs}$	0.000090146	0.00050918	-0.00016379	-0.00043553
$\beta_{tr}D_{tr}$	-0.0011947	0.00017505	-0.00021271	0.0012324
$\beta_{se}D_{se}$	0.00098804	0.00058546	-0.000014181	-0.0015593
$\gamma_{hs}D_{hs}$	1.38273	0.056069	0.75419	-2.19299
Gen	-3.80919D-10	-6.35466D-12	7.44008D-11	3.12873D-10
Rent	-1.66133	0.02336	-0.79144	2.42941
wage	1.13115D-06	6.23771D-07	4.90154D-07	-2.24507D-06
hcoalp1	0.0038833	-0.00059735	-0.0019835	-0.0013025
lcoalp1	-0.013974	0.0022889	0.0023019	0.0093836
emishat	0.000062416	-3.39785D-06	-7.55000D-06	-0.000051468
β_{srv}srvmonth	0.00084253	-8.34314D-07	0.000038703	-0.0008804

manager generally have lower responsibility for the risky management. So more electric generating units will choose allowance strategy under the restructuring regime. And most of new entrants in generation sector are Independent Power Producers(IPP). So these firms are more likely to choose allowance strategy in phase II period.

The existence of local stringent environmental regulation(D_{PR}) is significant for all kinds of compliance strategy choice at 1% significance level. The relative probability and the marginal effect is negative only for allowance strategy, but the probability and the marginal effect for all other strategy is positive. The generating units that located in the region where imposed stronger emission regulation are less likely chose allowance strategy. Instead, these units are more likely to choose "other" strategy considering the coefficient magnitude of positive marginal effect of this variable. This fact can be explained by the fact that the generating units could not choose the allowance strategy before 1995, since the previous regulation was effective before 1995. As a result, the units that were regulated by strong local environmental regulation had to pay higher cost since these units could not utilize market-based allowance system. That is, these units had to use command-and-control options. So the effort of local governments to protect local environment imposed higher cost on the electricity industry and on the ratepayers which is consistent with previous study.

The existence of substitution/compensation boilers(D_{SU}) is significant for the choice of allowance, "other" and scrubber strategy, but insignificant for fuel switch strategy at 5% level. The marginal effect on "other" and allowance strategy is positive, but negative for scrubber and fuel switch strategy. As expected, the units that have substitution boilers more likely to choose "other" strategy and allowance strategy, but less likely to choose scrubber and fuel swutch strategy. There are less substitution/compensation boilers since most of the fossil fuel-fired generating units are applied by the phase II regulation. So more units will choose scrubber and fuel switch strategy in phase II period holding other variable constant.

The restriction of allowance trade(D_{TR}) significantly and positively affected the choice of fuel switch strategy, but is insignificant for scrubber and "other". The marginal effect is negative for the allowance and scrubber strategy, but positive for the fuel switch and "other" strategy. That is, more units that are located in states that restricted allowance trade chose fuel switch and "other" strategy and less units chose allowance strategy and scrubber strategy. If there is no restriction of allowance trade, more units will choose allowance strategy and scrubber strategy. But the negative marginal effect on the increased choice of allowance strategy is 50 times the marginal effect of scrubber strategy under no restriction of allowance trade. The positive marginal effect of fuel switch is greater than the marginal effect of "other" strategy. So many units with fuel switch will change their strategy to allowance strategy when the restriction of allowance trade is eliminated.

The restriction of allowance sale(D_{SE}) negatively and significantly affected for the choice of fuel switch strategy, and positively and significantly affected "other" strategy. The marginal effect of this variable is negative for the fuel switch and scrubber strategy and positive for allowance and "other" strategy. The generating units with scrubber and fuel switch generally sell the surplus allowances, and the units with allowance strategy buy the allowances. So the effect of allowance sale restriction will affect the units with scrubber and fuel switch that have surplus allowances negatively.

The combined marginal effect of allowance trade and allowance sale($D_{TR}+D_{SE}$) , that is, the effect of shadow allowance price, is negative for three kinds of compliance strategies of allowance, scrubber and fuel switch strategy, but positive for "other" strategy. The combined effect is negative not only for these units with scrubber and fuel switch that can sell surplus allowances, but also for the units with allowance strategy that have to buy allowances in the market. This means that the negative direct effect(increase of MAC) of the allowance transaction is dominant over the positive indirect effect(increase of allowance price). The combined effect for the allowance strategy is also negative since the negative marginal effect from allowance trade restriction is bigger than the positive marginal effect from allowance sale restriction.

The capital price effect of the high-sulfur coal states($D_{HS} \circ P_k$) is significant and positive for the scrubber strategy choice, and significant and negative for the choice of fuel switch strategy choice, but insignificant and negative for "other" strategy choice. The marginal effect on the scrubber, allowance and "other" strategy is positive, but is negative for the fuel switch strategy. This finding is consistent with expectation that the high-sulfur coal states will give the benefit to the electric plants to use in-state high-sulfur coal through by lower capital price. So the electric units that are located in high-sulfur coal states more likely to choose scrubber and allowance strategy, and less likely to choose fuel switch strategy.

The price effect that high-sulfur states affected the high-sulfur coal price($D_{HS} \circ P_{fhs}$) is low since the variable has weak in statistical terms, that is weak positive for "other" strategy, but the insignificant negative for scrubber and fuel switch strategy. As expected, the marginal effect of this variable is positive for allowance strategy, but negative for fuel switch strategy. As a result, the high-sulfur states' encouragement of high-sulfur coal usage was effective for the choice of allowance strategy through the lower high-sulfur coal price. So the generating units that located in the high-sulfur coal states more likely to choose allowance strategy and enjoyed the lower high-sulfur coal price even though the probability is low.

The combined marginal effect of high-sulfur coal price and capital price that high-sulfur coal states affected the compliance strategy choice($D_{HS} \circ P_{fhs} + D_{HS} \circ P_k$) is positive for allowance, "other" and scrubber strategy, but negative for the fuel switch strategy. The marginal effects of both high-sulfur coal price and capital price are positive for allowance and "other" strategy, and the marginal effect of both effect is negative for fuel switch. However, the marginal positive effect of capital price is greater than the negative marginal effect of high-sulfur coal price. As a result, the electric units that located in high-sulfur coal states more likely to choose scrubber strategy through by lower capital price effect rather than through by the lower high-sulfur coal price.

The cost recovery of capital expenditure($D_{CO} \circ P_k$) is significant and positive for scrubber strategy at 5% significance level, but insignificant for other strategies. The marginal effect is positive for scrubber and "other" strategy, but is negative for the choice of allowance and fuel switch strategy. That is, the generating units more likely chose the scrubber and "other" strategy because of the cost recovery effect, but less likely to choose allowance and fuel switch strategy.

The electricity production level, capital price, low-sulfur and high-sulfur coal price, emission level have significant explanatory power for strategy choices. Vintage is negatively significant only for fuel switch strategy choice. Wage rate is insignificant for "other", scrubber and fuel switch strategy.

The electricity production level(***gen***) positively affects for scrubber and fuel switch, and negatively for allowance and "other" strategy. That is, the bigger generating units in terms of electricity generation more likely chose the scrubber and fuel switch to comply with the SO_2 emission reduction. Considering a positive marginal effect on scrubber and fuel switch, but negative on allowance and "other" strategy and the relative degree of this marginal effect, units will more likely change their compliance strategy from allowance strategy and "other" strategy to fuel switch and scrubber strategy when the electricity generation increases.

The actual capital price(*rent*) is a significant variable to explain the relative probability for the choice of scrubber and fuel switch at 5% and 1% significance level respectively, but insignificant for "other" strategy. The marginal effect of capital price on the probability of the scrubber strategy is negative that is consistent with the expectation.

The high-sulfur coal price(*hcoalp1*) has negative and significant effect on scrubber, fuel switch and "other", but positive for allowance strategy. As expected, the high-sulfur coal price has negative marginal effect on scrubber, but positive effect on allowance strategy, which is contrary to expectation. This may be explained by the fact that the units with allowance strategy used more low-sulfur coal since the low-sulfur coal price was low compared to expected price.

The marginal effect of low-sulfur coal price(*lcoalp1*) is negative for the choice of allowance strategy, but positive for fuel switch, which is contrary to the expectation. One interesting finding is that the marginal effect of low-sulfur coal price for the choice of allowance strategy is negative, but the marginal effect of high-sulfur coal is positive for the allowance strategy. This marginal effect can be explained by the fact that the units with allowance strategy use more low-sulfur coal than high-sulfur coal. So these units are more sensitive with low-sulfur coal price than high-sulfur coal price.

The estimated SO_2 emission level(*emishat*) is significant for all kinds of compliance strategy, and the marginal effects are negative for scrubber, "other" and fuel switch in terms of magnitude of effect. Especially, the negative marginal effect on fuel switch is the greatest comparing with the negative effect on the scrubber and "other" strategy. This finding means that many generating units will change their compliance strategies from allowance strategy mainly to fuel switch strategy when the stronger SO_2 emission rate standard is introduced in phase II period.

The vintage variable of the generating boilers(*srvmonth*) is significant and negative probability for fuel switch strategy, but insignificant and negative for "other" and scrubber strategy. We expected that the units will not install capital intensive strategy like scrubber, "other" and fuel switch strategy if the units are old. The marginal effect of the vintage on fuel switch and "other" strategy is negative, but the marginal effect on the allowance and scrubber strategy is positive. This finding can be explained in terms of capital intensity of each compliance strategy. That is, the fuel switch and "other" strategy are capital intensive, and the allowance strategy is not capital intensive strategy. So the capital intensive strategy will be affected by the vintage variable. The marginal effect is negative for fuel switch and "other" strategy, but positive for allowance and scrubber strategy. One unexpected result is that the marginal effect on scrubber is positive, which is contrary to expectation.

4.6 Discussion

The CAAA of 1990 introduced the tradable permits to regulate the SO_2 emission from electricity industry in phase I period. This is the market-based environmental policy. Environmental economists are interesting in the success of this policy. This paper finds the major factors affecting the choice of compliance strategy and the regulatory effect on the choice of compliance strategy in 1995-1999. If the generating units chose the compliance strategy based on cost minimization principle, then we expect that thisenvironmental policy can save lots of cost comparing with the command-and-control environmental policy.

Even though the Phase I is the test of economic theory on the environmental policy, only one study that estimated the regulatory effect of state PUC regulation and high-sulfur coal usage encouragement on the choice of compliance strategy. However, this study focused only two regulatory variables, moreover, focused on the choice of two strategies of allowance strategy and fuel switch strategy.

Since the SO_2 emission regulation in Phase I period(1995-1999) is applied to each generating unit, we used 257 phase I generating unit's level data which only 4 retired units are excluded in the sample out of 261 whole units. We assumed the cost minimization and behavioral cost is a function of shadow input prices, output, actual SO_2 emission, regulatory variables and other relevant variable. We figured out the main factors and regulatory effect that affected the choice of compliance strategy using multinomial logit model. Multinomial logit model is appropriate since each unit chose only one compliance strategy out of several strategies based on the characteristics of each generating unit.

The regulation of state government was significantly effective on the choice of compliance strategy. Because of the uncertainty of state PUC's regulation, the privately owned units are less likely choose challenging allowance strategy, instead chose the technically confirmed compliance strategy like scrubber and fuel switch. The non-private units are more chosed the challenging allowance strategy and got benefits of market-based SO_2 emission system.

Because of strong local government's emission regulation, more units chose "other", scrubber and fuel switch strategies, and less chose the allowance strategy. The effort to protect local environment imposes higher cost on society. The units that have substitution/compensation boilers more chose allowance and "other" strategies. The combined effect of the restriction of allowance trade and allowance sale negatively affected for the choice of allowance, scrubber and fuel switch strategy. So the restriction of allowance trade and sale significantly affected the shadow allowance price. The generating units that are located in high-sulfur coal states more chose scrubber, allowance and "other" strategy mainly through by the effect of capital price, rather than through by the effect of high-sulfur coal price.

The cost recovery positively affected the choice of scrubber strategy and "other" strategy, but this variable is insignificant for the choice of fuel switch strategy.

The allowance strategy will compete with the fuel strategy in terms of regulatory variabled. As a result, we can predict that many generating units that used allowance strategy will change their strategy to fuel switch strategy in Phase II period(from 2000) if the low-sulfur coal price keeps the current low level.

Most of the traditional variables can significantly explain the probability for choosing compliance strategies. The electricity production level is the important variable to explain the probabilistic relationship with the strategy choice for all strategies. The capital price is especially important for the choice of capital intensive strategies like scrubber and fuel switch strategy. The high-sulfur coal price is especially important variables for the scrubber strategy. Contrary to expectation, low-sulfur coal price will negative effect for allowance strategy, but positive for fuel switch strategy. SO_2 emission rate is the significant variable for the choice of all strategies, and the vintage is significant variables for the choice of fuel switch strategy. Under the stronger SO_2 emission regulation, less units will likely choose allowance strategy. Wage rate has weak probabilistic relationship.

4.7 References

A.Albert and J.A.Anderson, "On the Existence of Maximum Likelihood Estimation in Logistic Models" Biometrika, vol 71, no1, April 1984, 1-10

Takeshi Amemiya, Advanced Econometrics, Basil Blackwell, Great Braitain, 1985

Toshi Arimura, "An Empirical Study of the SO_2 Aoowance Market : Effects of PUC Regulations" Journal of Environmental Economics and Management, vol 44, no 2, September 2002, 271-289

Scott E. Atkinson and Joe Kerkvliet, "Measuring the Multilateral Allocation of Rents : Wyoming Low-Sulfur Coal" Rand Journal of Economics, vol 17, no 3, Autumn 1986, 416-430

Scott E. Atkinson and Joe Kerkvliet, "Dual Measures of Monopoly and Monopsony Power : An Application to Regulated Electricity Utilities" Review of Economics and Statistics, vol 71, no 2, May 1989, 250-257

Ben-Akiva and Lerman, Discrete Choice Analysis, The MIT press, Cambridge, Massachesuttes, 1997

Douglas R. Bohi, "Utility Investment Behavior and the Emission Trading Market" Resources and Energy, vol 14, no 2, April 1992, 129-153

Douglas R. Bohi, "Utilities and State Regulators are Failing to Take Advantage of Emission Allowance Trading" The Electricity Journal, vol 17, no 2, March 1994, 20-27

Douglas R. Bohi, "SO_2 Allowance Trading : How Do Expectations and Experience Measure Up?" The Electricity Journal, vol 10, no 7, August /September 1997, 67-75

Curtis Carlson, Dallas Burtlaw, Maureen Cropper, Karen L.Palmer. "Sulfur Dioxide Control by Electric Utilities : What are the Gains from Trade", Journal of Political Economy, vol 108, no 6, December 2000, 1292-1326

Mark B. Cronshaw, Jamie Brown Kruse, "Regulated Firms in Pollution Permit Marketing with Banking" Journal of Regulatory Economics, vol 9, no 2, March 1996, 179-189

Department of Energy(DOE)/Energy Information Administration(EIA). "Financial Statistics of Major U.S Investor-Owned Electric Utilities 1995",(DOE/EIA-0437(95)), Washington D.C.:Department of Energy, December 1997

Department of Energy(DOE)/Energy Information Administration(EIA). "The Effects of Title IV of the Clean Air Act Amendments of 1990 on Electric Utilities"(DOE/EIA-0582(97), Washington D.C.:Department of Energy, March 1997

Department of Energy(DOE)/Energy Information Administration(EIA), "Electric Utility Phase I Acid Rain Compliance Strategies for The Clean Air Act Amendments of 1990"(DOE/EIA-0578, Washington D.C.:Department of Energy, March 1994

Department of Energy(DOE)/Energy Information Administration(EIA), "Challenges of Electric Power Industry Restructuring for Fuel Suppliers"(DOE/EIA-0623), Washington D.C.:Department of Energy, September 1998

Department of Energy(DOE)/Energy Information Administration(EIA), "EIA759 : Monthly Power Unit Report 1995"
http://www.eia.doe.gov/cneaf/electricity/page/data.html

Department of Energy(DOE)/Energy Information Administration(EIA), "EIA860 : Annual Electricity Generator Report, 1995"
http://www.eia.doe.gov/cneaf/electricity/page/data.html

Department of Energy(DOE)/Energy Information Administration(EIA), "Acid Rain Data Base" http://www.eia.doe.gov/cneaf/electricity/page/data.html

Department of Energy(DOE)/Energy Information Administration(EIA), " EIA423 : Monthly Report of Cost and Quality of Fuels for Electric Units,1995" http://www.eia.doe.gov/cneaf/electricity/page/data.html

Department of Energy(DOE)/Energy Information Administration(EIA), "FERC1 form : Annual Report of Major Electric Utilities,Licensee, and Others, 1995" http://www.eia.doe.gov/cneaf/electricity/page/data.htm

Ellerman,A.D, Schmalensee.R., Joskow,P.L., Montereo, J.P., Bailey, E.M., Emissions Trading under the U.S Acid Rain Program, Center for Energy and Environmental Policy Research, MIT, 1997

A.Denny Ellerman, "The Declining Trend in Sulfur Dioxide Emissions : Implifications for Allowance Prices" Journal of Environmental Economics and Management, vol 36, no 1, July 1998, 26-45

Environmental Protection Agency(EPA), "The United States Experience with Economic Incentives for Protecting the Environment", EPA-240-R-01-001, Washington, DC 20460, January 2001

Don Fullerton, Shaun P.McDermott, Jonathan P.Caulkins, "Sulfur Dioxide Compliance of a Regulated Utility", The Journal of Environmental Economics and Management, vol 34, no 1, September 1997, 32-53

Frank M.Gollop, Mark J.Roberts, "Environmental Regulation and Productivity Growth : The Case of Fossil-fueled Electric Power Generation", The Journal of Political Economy, vol 91, no 4, August 1983, 654-674

Frank M.Gollop and Mark J.Roberts, "Cost-Minimizing Regulation of Sulfur Emissions : Regional Gains in Electric Power" Review of Economics and Statistics vol 67, no 1, February 1985, 81-90

Joe Kerkvliet, "Efficiency and Vertical Integration : The Case of Mine Mouth Electric Generating Plants" The Journal of Industrial Economics, vol 34, no5, September 1991, 467-482

Ger Klaassen and Andries Nentjes, "Sulfur Trading under the 1990 CAAA in the US : An Assessment of First Experiences" Journal of Institutional and Theoretical Economics, vol 153, no 2, June 1997, 384-410

J,Scott Long, Regression Models for Categorical and Limited Dependent Variables, SAGE publication, London,1997

David W.Pearce, R.Kerry Turner, Economics of Natural Resources and the Environment, The Johns Hopkins University Press, Baltimore, 1990

Kenneth Rose, Alan S.Taylor and Mohammad Haruzzaman, Regulatory Treatment of Electric Utility Compliance Startegies, Costs, and Emission Allowances, The National Regulatory Research Institute, Ohio State University, Colombus, Ohio, 1993

Kenneth Train, Qualitative Choice Analysis, Theory, Econometrics, and an Application to Automobile Demand, The MIT Press, 1993

John Tschirhart, Shiow-Ying Wen, "Tradable Allowances in a Regulated Electric Industry" The Journal of Environmental Economics and Management, vol 38, no 2, September 1999, 195-214

James J. Winebrake, Alexander E. Farrell, Mark A. Bernstein, "The Clean Air Act's Sulfur Dioxide Emissions Market : Estimating the Costs of Regulatory and Legislative Intervention" Resource and Energy Economics, vol 17, no 3, November 1995, 239-260

Appendix

Table Regulatory Variables and States

	AL	FL	GA	IA	IL	IN	KS	KY	MD	MI	MN
Dal											
Dnp	25	0	0	0	9	10	5	60	0	0	0
Dpr	20	0	0	0	0	10	0	5	0	10	0
Dsu	5	20	75	0	35	10	0	15	25	10	5
Dtr	0	25	95	25	85	180	0	85	0	0	0
Dse	0	0	0	0	0	0	0	0	0	0	0
Dbu	0	0	0	0	0	0	0	0	0	0	0
Dhs	0	0	0	0	85	180	0	85	0	0	0
Dco1	0	25	0	0	0	0	0	0	30	0	0
total	50	25	95	25	85	180	5	85	30	10	5

	MO	MS	NH	NJ	NY	OH	PA	TN	WI	WV	sum
Dal											
Dnp	25	0	0	0	6	10	12	95	5	0	262
Dpr	20	0	0	0	25	1	25	0	0	0	116
Dsu	65	5	10	0	35	70	25	0	30	20	460
Dtr	0	0	0	0	0	200	115	0	0	0	810
Dse	85	0	0	0	50	0	0	0	0	70	205
Dbu	0	0	0	0	0	0	0	0	0	0	0
Dhs	0	0	0	0	0	200	115	0	0	0	665
Dco1	0	10	0	0	0	200	0	0	45	70	380
total	85	10	10	10	50	200	115	95	45	70	1285

* the numbers are numbers of corresponding generating units

5. CONCLUSION

This thesis addresses three topics on applied microeconomics. First, we investigate issues of market power and tax incidence in the U.S brewing industry. Since alcohol consumption can be addictive, we derive a structural econometric model of addiction from a dynamic oligopoly game. This model is capable of identifying the degree of market power in a dynamic setting and allows us to test the hypothesis that the tax incidence differs for federal and state excise tax. Our empirical results indicate that beer producers have a modest amount of market power. Being consistent with the results of Barnett et al.(1995) for cigarettes, we find that an increase in federal excise tax causes a greater increase in price and a greater decrease in consumption than the same increase in average state excise taxes. So the policy should focus on the raise of federal excise tax to mitigate the impact of negative externalities derived from excessive beer consumption.

We analyzed the productivity growth in the second essay. The Clean Air Act Amendment(CAAA) of 1990 required phase I generating units to reduce sulfur dioxide(SO_2) emissions to 2.5 pounds of SO_2 emission per million BTU of fuel input during the period between 1995 and 1999. We use directional technology distance function to estimate the Luenberger productivity indicator, opportunity cost of SO_2 emission regulation, and the effect of SO_2 emission regulation on productivity growth potential before and during the phase I period using a symmetric directional vector(g_y=1,g_b=-1,g_x=-1) for 209 phase I units.

There is a more potential to increase efficiency through pure technical efficiency improvement than scale efficiency improvement since the main source of inefficiency is pure technical inefficiency. The generating units with allowance and scrubber strategy show high efficiency during the phase I period. Productivity improved in pre-phase I period, and the main source of productivity growth is technological improvement. Productivity declined in phase I period, but it is not significantly different from the productivity growth in the pre-phase I period. Efficiency improvement contributes to the productivity growth in phase I period. In the phase I period, all the strategies except for the scrubber strategy show productivity growth. So the productivity decline in phase I period comes from scrubber strategy's productivity deterioration.

The opportunity cost of SO_2 emission regulation in the phase I period is smaller than the opportunity cost in pre-phase I period because of the stronger environmental regulations. The main source of opportunity cost decline was pure technical efficiency both in the pre- and phase I periods. So the potential that generating units can improve efficiency through pure technical efficiency improvement is greater than through scale efficiency improvement. The opportunity cost of the units with scrubber and "other" strategies showed high opportunity cost in the phase I period. So the units with scrubber and "other" strategy could increase efficiency more than any other strategies.

The potential of productivity growth derived from SO_2 emission regulation in phase I period can be increased mainly through technological development since the main source of potential is technological change. The effect of SO_2 emission regulation on productivity growth potential is biggest for the units with scrubber strategy through the effect on the technological change. So the policy should focus on the introduction of more productive production technology to achieve the productivity growth in Phase II period. In a conclusion, the U.S environmental policy is successful to reduce SO_2 emission without sacrificing productivity growth. The appropriate policy to improve productivity in the Phase II period will be to introduce more productive production technology in the electricity industry.

We estimate the regulatory effect on the choice of compliance strategy of phase I generating units in phase I period in the third essay. Since the CAAA of 1990 introduced the tradable permits to regulate the SO_2 emission from electricity industry in phase I period, generating unit can achieve least-cost compliance strategy. The third essay figures the factors affecting the compliance strategy choice and the regulatory effect on strategy choice. Since the SO_2 emission regulation in Phase I period(1995-1999) is applied to each generating unit, we use 257 phase I generating unit's level data which only 4 retired units are excluded from 261 whole phase I units. We assume cost minimization for the electric units instead of profit maximization and assume that cost is a function of shadow input prices, output, actual SO_2 emission, regulatory variables. Multinomial logit model is used since each unit chose only one compliance strategy out of several strategies based on the characteristics of each generating unit.

Most of the variables except for wage, that is, electricity production level, capital price, high-sulfur and low-sulfur coal prices, SO_2 emission rate and vintage variable significantly explain the probability for choosing compliance strategy based on cost minimization assumption. Wage rate has weak explanatory power for choice probability.

The regulation of state government significantly affected the choice of compliance strategy. While the privately owned units are less likely choose allowance strategy because of the uncertainty of state PUC's regulation, the non-private units are more likely to choose the challenging allowance strategy. Because of stringent local government's emission regulation, less units are more likely to choose allowance strategy. So this regulatory variable will impose higher MAC for the units that are regulated by local government's effort to protect the local environment. The units that have substitution/compensation boilers are more likely to choose allowance and "other" strategies. The combined effect of the allowance trade restriction and the allowance sale restriction negatively affect the choice of allowance, scrubber and fuel switch strategy. So the restriction of allowance trade and sale significantly affect the shadow allowance price. The generating units that are located in high-sulfur coal states are more likely to choose scrubber, allowance and "other" strategy mainly through by the effect of shadow capital price, rather than through by the effect of shadow high-sulfur coal price. The cost recovery positively affects the choice of scrubber strategy and "other" strategy, but this variable is insignificant for the choice of strategy.

The allowance strategy will compete with the fuel strategy in terms of regulatory variable. As a result, we can predict that many generating units that use allowance strategy will change their strategy to fuel switch strategy in Phase II period(from 2000) if the low-sulfur coal price keeps the current low level.

BIBLIOGRAPHY

A.Albert and J.A.Anderson, "On the Existence of Maximum Likelihood Estimation in Logistic Models" Biometrika, vol 71, no1, April 1984, 1-10

Takeshi Amemiya, Advanced Econometrics, Basil Blackwell, Great Braitain, 1985

Toshi Arimura, "An Empirical Study of the SO_2 Aoowance Market : Effects of PUC Regulations" Journal of Environmental Economics and Management, vol 44, no 2, September 2002, 271-289

Scott E. Atkinson and Joe Kerkvliet, "Measuring the Multilateral Allocation of Rents : Wyoming Low-Sulfur Coal" Rand Journal of Economics, vol 17, no 3, Autumn 1986, 416-430

Scott E. Atkinson and Joe Kerkvliet, "Dual Measures of Monopoly and Monopsony Power : An Application to Regulated Electricity Utilities" Review of Economics and Statistics, vol 71, no 2, May 1989, 250-257

Barnett, Paul G., Theodore E. Keeler, and The-wei Hu, "Oligopoly Structure and the Incidence of Cigarette Excise Taxes," *Journal of Public Economics*, vol 57, no 3, July 1995, 457-470.

Beatty, Sally Goll and Yumiko Ono, "Liquor Industry Is Divided Over Use of TV Ads," *Wall Street Journal*, June 12, 1996, B1.

Beer Industry Update: A Review of Recent Developments, West Nyack, NY: Beer Marketer's Insights, Inc., 1992.

Ben-Akiva and Lerman, Discrete Choice Analysis, The MIT press, Cambridge, Massachesuttes, 1997

Douglas R. Bohi, "Utility Investment Behavior and the Emission Trading Market" Resources and Energy, vol 14, no 2, April 1992, 129-153

Douglas R. Bohi, "Utilities and State Regulators are Failing to Take Advantage of Emission Allowance Trading" The Electricity Journal, vol 17, no 2, March 1994, 20-27

Douglas R. Bohi, "SO_2 Allowance Trading : How Do Expectations and Experience Measure Up?" The Electricity Journal, vol 10, no 7, August /September 1997, 67-75

Brewers Almanac, U.S. Brewers Association Inc., Washington D.C., various issues.

Curtis Carlson, Dallas Burtlaw, Maureen Cropper, Karen L.Palmer, "Sulfur Dioxide Control by Electric Utilities : What are the Gains from Trade", Journal of Political Economy, vol 108, no 6, December 2000, 1292-1326

Chaloupka, Frank J., "Rational Addictive Behavior and Cigarette Smoking," *Journal of Political Economy*, vol 99, no 4, August 1991, 722-742.

Chambers,R.G, Fare,R., Grosskopf,S. "Productivity Growth in APEC Countries", Pacific Economic Review, vol 1, no3, 1996, December 1996, 181-190

Laurits R. Christensen and William H. Greene, "Economies of Scale in U.S. Electric Power Generation" Journal of Political Economy, vol 84, no4, August 1976, 655-676

Y.H.Chung, Fare,R., Grosskopf,S. "Productivity and Undesirable Outputs:A Directional Distance Function Approach" Journal of Environmental Management vol 51, 1997, 229-240

Cook, Philip J., "Editorial: Increasing the Federal Excise Taxes on Alcoholic Beverages," *Journal of Health Economics*, vol 7, no 1, March 1988, 89-91.

Corts, K. S., "Conduct Parameters and the Measurement of Market Power," *Journal of Econometrics*, vol 88, no 2, February 1999, 227-250.

Coulson, N. Edward, John R. Moran, and Jon P. Nelson, "The Long-run Demand for Alcoholic Beverages and the Advertising Debate: A Cointegration Analysis," in *Advances in Applied Microeconomics: Advertising and Differentiated Markets*, Michael R. Baye and Jon P. Nelson, editors, New York: JAI Press, 2001, 31-54.

Thomas G. Cowing and Rodney E. Stevenson, "Productivity Measurement and Regulated Industries" in Productivity Measurement in Regulated Industries edited by Thomas G. Cowing and Rodney E. Stevenson, New York, Academic Press, 1981

Thomas G. Cowing, Jeffrey Small, and Rodney E. Stevenson, "Comparative Measures of Total Factor Productivity in the Regulated Sector : The Electric Utility Industry" in Productivity Measurement in Regulated Industries edited by Thomas G. Cowing and Rodney E. Stevenson, New York, Academic Press, 1981

Mark B. Cronshaw, Jamie Brown Kruse, "Regulated Firms in Pollution Permit Marketing with Banking" Journal of Regulatory Economics, vol 9, no 2, March 1996, 179-189

Delipalla, Sophia, and Owen O'Donnell, "Estimating Tax Incidence, Market Power, and Market Conduct: The European Cigarette Industry," *International Journal of Industrial Organization*, vol 19, no 6, May 2001, 885-908.

Phoebus J. Dhrymes and Mordecai Kurz, "Technology and Scale in Electricity Generation", Econometrica, vol 32, no 3, 1964, 321-349

Diewert, Erwin, "Applications of Duality Theory," in Michael Intriligator and D. Kendrick, editors, *Frontiers of Quantitative Economics*, Amsterdam: North-Holland, 1974.

Department of Energy(DOE)/Energy Information Administration(EIA), "Electric Utility Phase I Acid Rain Compliance Strategies for The Clean Air Act Amendments of 1990"(DOE/EIA-0578, Washington D.C.:Department of Energy, March 1994

Department of Energy(DOE)/Energy Information Administration(EIA). "The Effects of Title IV of the Clean Air Act Amendments of 1990 on Electric Utilities"(DOE/EIA-0582(97), Washington D.C.:Department of Energy, March 1997

Department of Energy(DOE)/Energy Information Administration(EIA). "Financial Statistics of Major U.S Investor-Owned Electric Utilities 1995",(DOE/EIA-0437(95)), Washington D.C.:Department of Energy, December 1997

Department of Energy(DOE)/Energy Information Administration(EIA), "Challenges of Electric Power Industry Restructuring for Fuel Suppliers"(DOE/EIA-0623), Washington D.C.:Department of Energy, September 1998

Department of Energy(DOE)/Energy Information Administration(EIA), "EIA759 : Monthly Power Unit Report 1995" http://www.eia.doe.gov/cneaf/electricity/page/data.html

Department of Energy(DOE)/Energy Information Administration(EIA), "EIA860 : Annual Electricity Generator Report, 1995" http://www.eia.doe.gov/cneaf/electricity/page/data.html

Department of Energy(DOE)/Energy Information Administration(EIA), "Acid Rain Data Base" http://www.eia.doe.gov/cneaf/electricity/page/data.html

Department of Energy(DOE)/Energy Information Administration(EIA), " EIA423 : Monthly Report of Cost and Quality of Fuels for Electric Units,1995" http://www.eia.doe.gov/cneaf/electricity/page/data.html

Department of Energy(DOE)/Energy Information Administration(EIA), "FERC1 form : Annual Report of Major Electric Utilities,Licensee, and Others, 1995" http://www.eia.doe.gov/cneaf/electricity/page/data.htm

Ellerman,A.D, Schmalensee.R., Joskow,P.L., Montereo, J.P., Bailey, E.M." Emissions Trading under the U.S Acid Rain Program" Center for Energy and Environmental Policy Research, MIT, 1997

A.Denny Ellerman, "The Declining Trend in Sulfur Dioxide Emissions : Implifications for Allowance Prices" Journal of Environmental Economics and Management, vol 36, no 1, July 1998, 26-45

Elyasiani, Elyas, and Seyed Mehdian, "Measuring Technical and Scale Inefficiencies in the Beer Industry: Nonparametric and Parametric Evidence," *Quarterly Review of Economics and Finance*, vol 33, no 4, Winter 1993, 383-408.

Elzinga, Kenneth G. "The Beer Industry," in *The Structure of American Industry*, Walter Adams, editor, New York: Macmillan, 1990, 128-60.

Elzinga, Kenneth G., “Beer,” in Walter Adams and James W. Brock (editors), *The Structure of American Industry*, Upper Saddle River, NJ: Prentice Hall, 2001, 87-113.

Environmental Protection Agency(EPA), The United States Experience with Economic Incentives for Protecting the Environment, EPA-240-R-01-001, Washington, DC 20460, January 2001

Fare,R., Grosskopf,S., C.Pasurka, "Effects on Relative Efficiency in Electric Power Generation due to Environmental Controls" Resources and Energy, vol 8, 1986, 167-184

Rolf Fare, Shawna Grosskopf, C.A.K.Lovell and Carl Pasurka, "Multilaterial Productivity Comparisons When Some Outputs are Undesirable : A Nonparametric Approach" The Review of Economics and Statistics, vol 71, no 1, February 1989, 90-98

Fare,R., Grosskopf,S., S.Yaisawarng, Li,S.K, Wang,Zhaoping, "Productivity Growth in Illinois Electric Utilities" Resources and Energy, vol 12, no 4, December 1990, 383-398

Fare,R., Grosskopf,S., N.Marry, Z.Zhongyang, "Productivity Growth, Technical Progress, and Efficiency Change in Industrialized Countries" American Economic Review, vol 84, no 1, March 1994, 66-83

Fare,R., Primont,D, Multi-output Production and Duality:Theory and Applications, Boston, Kluwer Academic Publishers, 1995

Fare,R., Grosskopf, S., Intertemporal Production Frontiers:with Dynamic DEA, 1996, Boston, Kluwer Academic Publishers

Fare,R., Grosskopf,S., Tyteca,D., "An Activity Analysis Model of the Environmental Performance of Firms-Application to Fossil-Fuel Fired Electric Utilities" Ecological Economics, vol 18, no 2, August 1996, 161-175

Fare,R., Grosskopf,S. "Theory and Application of Directional Distance Functions" Journal of Productivity Analysis, vol 13, no 2, March 2000, 93-103

Fare,R., Primont,D, "Luenberger Productivity Indicator:Aggregation Across Firms" memo, 2001, Oregon State University

Farr, Stephen J., Carol Horton Tremblay, and Victor J. Tremblay, "The Welfare Effect of Advertising Restrictions in the U.S. Cigarette Industry," *Review of Industrial Organization*, vol 18, no 2, March 2001, 147-160.

Fortune, "Why There's No Yeast in Brewers' Stocks," November 1975, 91.

Don Fullerton, Shaun P.McDermott, Jonathan P.Caulkins, "Sulfur Dioxide Compliance of a Regulated Utility", The Journal of Environmental Economics and Management, vol 34, no 1, September 1997, 32-53

Genesove, D. and W. P. Mullen, "Testing Static Oligopoly Models: Conduct and Cost in the Sugar Industry, 1890-1914," *Rand Journal of Economics*, vol 29, no 2, Summer 1998, 355-377.

Frank A. Gollop, Mark J. Roberts, "The Sources of Economic Growth in the U.S Electric Power Industry" in Productivity Measurement in Regulated Industries edited by Thomas G. Cowing and Rodney E. Stevenson, 1981, New York, Academic Press, 1981

Frank M. Gollop, Mark J. Roberts, "Environmental Regulation and Productivity Growth : The Case of Fossil-fueled Electric Power Generation" Journal of political Economy, vol 91, no 4, August 1983, 654-674

Frank M. Gollop, Mark J. Roberts, "Cost-Minimizing Regulation of Sulfur Emissions : Regional Gains in Electric Power", Review of Economics and Statistics, vol 67, no 1, February 1985, 81-90

Greene, William H., *Econometric Analysis*, New York: Macmillan, 1997.

Greer, Douglas F., "Causes of Structural Change," in Larry L. Duetsch (editor), *Industry Studies*, New York: M.E. Sharpe, 1998, 28-64.

Jarmin, Ronald S., "Learning by Doing and Competition in the Early Rayon Industry," *Rand Journal of Economics*, vol 25, no 3, Autumn 1994, 441-454.

Keeler, Theodore E., The-wei Hu, Willard G. Manning, and Hai-Yen Sung, "State Tobacco Taxation, Education, and Smoking: Controlling for the Effects of Omitted Variables," *National Tax Journal*, vol 54, no 1, January 2001, 83-102.

Kenkel, Donald S., "New Estimates of the Optimal Tax on Alcohol," *Economic Inquiry*, vol 34, no 2, April 1996, 296-319.

Joe Kerkvliet, "Efficiency and Vertical Integration : The Case of Mine Mouth Electric Generating Plants" The Journal of Industrial Economics, vol 34, no5, September 1991, 467-482

Kerkvliet, Joe R., William Nebesky, Carol Horton Tremblay, and Victor J. Tremblay, "Efficiency and Technological Change in the U.S. Brewing Industry," *Journal of Productivity Analysis*, vol 10, no 3, November 1998, 271-288.

Ger Klaassen and Andries Nentjes, "Sulfur Trading under the 1990 CAAA in the US : An Assessment of First Experiences" Journal of Institutional and Theoretical Economics, vol 153, no 2, June 1997, 384-410

Andrew N. Kleit and Dek Terrell, "Measuring Potential Efficiency Gains from Deregulation of Electricity Generation : A Bayesian Approach" Review of Economics and Statistics vol 83, no 3, August 2001, 523-530

Lee, Byunglak and Victor J. Tremblay, "Advertising and the US Market Demand for Beer," *Applied Economics*, vol 24, no 1, January 1992, 69-76.

J,Scott Long, Regression Models for Categorical and Limited Dependent Variables, SAGE publication, London,1997

Modern Brewery Age, October 11, 1993, 44 (41), 1-3.

Nelson, Jon P., "Broadcast Advertising and U.S. Demand for Alcoholic Beverages," *Southern Economic Journal*, vol 65, no 4, April 1999, 774-790.

Novshek, William, *Mathematics for Economists*, New York: Academic Press, 1993.

David W.Pearce, R.Kerry Turner, Economics of Natural Resources and the Environment, The Johns Hopkins University Press, Baltimore, 1990

Phelps, Charles, "Death and Taxes: An Opportunity for Substitution," *Journal of Health Economics*, vol 7, no 1, March 1988, 1-24.

Pogue, T. F. and L. G. Sgontz, "Taxing to Control Social Costs: The Case of Alcohol." *American Economic Review*, vol 79, no 1, March 1989, 235-43.

Kenneth Rose, Alan S.Taylor and Mohammad Haruzzaman, Regulatory Treatment of Electric Utility Compliance Startegies, Costs, and Emission Allowances, The National Regulatory Research Institute, Ohio State University, Colombus, Ohio, 1993

Kenneth Train, Qualitative Choice Analysis, Theory, Econometrics, and an Application to Automobile Demand, The MIT Press, 1993

Tremblay, Carol Horton, and Victor J. Tremblay, "The Impact of Cigarette Advertising on Consumer Surplus, Profit, and Social Welfare," *Contemporary Economic Policy*, vol 13, no 1, January 1995a, 113-124.

__________, "Advertising, Price, and Welfare: Evidence From the U.S. Brewing Industry," *Southern Economic Journal*, vol 62, no2, October 1995b, 367-381.

Tremblay, Victor J., "Strategic Groups and the Demand for Beer," *Journal of Industrial Economics*, vol 34, no 2, December 1985, 183-198.

__________, "Scale Economies, Technological Change, and Firm Cost Asymmetries in the U.S. Brewing Industry," *Quarterly Review of Economics and Business*, vol 27, no 2, Summer 1987, 71-86.

__________, *The U.S. Brewing Industry: Data and Economic Analysis*, mimeo, Oregon State University, 2002.

Tremblay, Victor J., and Carlos Martins-Filho, "A Model of Vertical Differentiation, Brand Loyalty, and Persuasive Advertising," in Michael Baye and Jon Nelson, editors, *Advances in Applied Microeconomics: Advertising and Differentiated Markets*, New York: JAI Press, 10, 2001.

Tremblay, Victor J., and Sephen Polasky, "Advertising with Subjective Horizontal and Vertical Product Differentiation," *Review of Industrial Organization*, vol 20, no 3, May 2002, 253-276

John Tschirhart, Shiow-Ying Wen, "Tradable Allowances in a Regulated Electric Industry" The Journal of Environmental Economics and Management, vol 38, no 2, September 1999, 195-214

James J. Winebrake, Alexander E. Farrell, Mark A. Bernstein, "The Clean Air Act's Sulfur Dioxide Emissions Market : Estimating the Costs of Regulatory and Legislative Intervention" Resource and Energy Economics, vol 17, no 3, November 1995, 239-260

S.Yaisawarng, J.D.Klein, "The Effects of Sulfur Dioxide Controls on Productivity Change in the U.S Electric Power Industry" Review of Economics and Statistics vol 76, no 3, August 1994, 447-460