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Economic evaluation of air pollution reduction of phase I power plants in West Virginia: An output distance function approach

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Economic Evaluation of Air Pollution Reduction of Phase I Power Plants in West Virginia: An Output Distance Function Approach

Huilan Li

**Dissertation submitted to the
Davis College of Agriculture, Forestry and Consumer Sciences
at West Virginia University
in partial fulfillment of the requirements for the degree of**

**Doctor of Philosophy
in Natural Resource Economics**

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Division of Resource Management

**Morgantown, West Virginia
2006**

Keywords: Output Distance Function, SO₂ Allowance, Shadow Values, and Cap-and-Trade

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Abstract

Economic Evaluation of Air Pollution Reduction of Phase I Power Plants in West Virginia: An Output Distance Function Approach

Huilan Li

Air pollutants from coal-fired power plants are nonmarket environmental bads. Title IV of the 1990 Clean Air Act Amendments (CAAA) sets the stage for the dirtiest power plants to reduce emissions of SO_2 and NO_x in two phases. Title IV allocates plants SO_2 allowances as a variation of “pollution rights” based on averaged historical emission levels and allows free-trade of allowances. This is the world’s first large scale pollutant trading market. Trading allows for improved efficiency, flexibility, and reduced pollution.

This study employs the output distance function approach to evaluate the pollution reduction behavior and efficiency of West Virginia power plants. The output distance function only needs input and output data of the electricity production process to estimate virtual or shadow values of outputs including those of nonmarket goods. Sixteen West Virginia power plants were selected for the study and 1995-1999 input and output data collected for three pollutants, SO_2 , NO_x , and CO_2 . Estimates of the shadow values of SO_2 , NO_x , and CO_2 reveal inverse relationships between estimated abatement cost and the emission rate for each pollutant. The evaluation is performed on the shadow values of SO_2 and NO_x for each plant for each year and each plant’s five-year average level against the corresponding estimated shadow value and emission rate.

The cap-and-trade program for SO_2 is fully implemented under the designated provisions of Title IV of the 1990 CAAA. A plant with three units that installed “scrubbers” has the lowest emission rate of SO_2 and the highest estimate of abatement cost of SO_2 . A plant that didn’t take control measures has the highest emission rate and lowest abatement cost. The same patterns are observed in NO_x as well. The estimates of CO_2 indicated relatively low virtual abatement costs compared to SO_2 and NO_x and a relatively high emission rate. Even though there are no current regulations that effect CO_2 emissions in the U.S., these results are indicative of the costs of marginal reductions. As a group, these estimates represent the total cost estimate if emissions of all three pollutants were required to be reduced. West Virginia power plants actively participated in the SO_2 allowance trading market during Phase I.

**In Memory of My Deeply Beloved Father, Mother,
And my elder Sister**

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Chapter 1. Introduction

1.1 Phase I Performances of Acid Rain Program

The world's first large scale control of sulfur dioxide (SO_2) and nitrate oxide (NO_x) emissions from U.S. coal-fired power plants using a market approach has accomplished most of the Phase I (1995-1999) goals outlined in the 1990 Clean Air Act Amendments (CAAA). The 1990 CAAA targeted coal-fired power plants to reduce total emissions of SO_2 and NO_x during the 1995 to 2010 time period. The CAAA were implemented in two distinct phases: 1995-1999 (first phase) and 2000-2010 (second phase). Participants in Phase I were the dirtiest power plants and Phase II participants included all power plants. The aggregate reduction of SO_2 emissions attained during Phase I was lower than that set up in Title IV of the 1990 CAAA and the abatement costs for the SO_2 emissions reductions achieved are lower than most estimates made before Phase I implementation (US Environmental Protection Agency 1990; ICF 1990, 1995; and White et al. 1995, 1997). The number of scrubbers installed during Phase I was lower than expected; investments in scrubbers were delayed. The prices of low-sulfur coal and scrubbers were lower than predicted. These actual and unexpected Phase I experiences provide a rich and broad spectrum for the industry, environmental economists, and policy makers to ponder as they consider future environmental protection and pollution control options.

1.2 Production Externalities in Coal-fired Power Plants

Environmental protection and pollution control are responses to a detrimental externality from either a production process or human consumption activity. Formally, an externality is defined as the actions of one agent that directly affect the welfare of another agent (Varian,

1992)¹. A consumption externality occurs when one's consumption activity causes a change of other consumers' utilities. A production externality occurs when a firm's production activity generates results that directly affect either another firm's production activity or a consumer's consumption activity or welfare through impacts on the environment. Externalities can be either good or bad. For most cases of concern, however, the externalities involve negative effects. These can either cause degradation of environmental quality or directly affect human health. Externalities in the form of emissions of SO_2 , NO_x and CO_2 from coal-fired power plants are the focus of this study. SO_2 and NO_x can cause streams, lakes, and rivers to become acidified; slow down the growth of trees; injure or cause the death of forests; kill or reduce the population of fish; erode walls of buildings and materials; reduce visibility; and cause asthma and bronchitis (EPA, April 2006).

When negative externalities are an inherent output of a production process, the market has no price mechanism to automatically adjust to reach a socially efficient level in allocating resources. Therefore, special attention or treatment has to be taken to correct or minimize the negative effects. A market failure for this kind of externality arises for two primary reasons: the receptor of the pollution is a common property resource, e.g., air or water, and there are no well-defined property rights for the receptors. Intervention vehicles to correct a market failure of this sort include command and control methods and transferable (or marketable) pollution permits which create a right to emit a specified amount of a specific pollutant. The latter approach has been long advocated by economists. While the U.S. had adopted some experimental market mechanisms for water and air pollution controls prior to the 1900 CAAA (e.g., a transferable discharge allowance system for water pollutants on the Fox River in Wisconsin, which was not

¹ There are different externality definitions. Tietenberg's (1998) definition is that the decision-making agent does not bear all of the consequences of his or her action.

successful (Tietenberg, 1998; Field and Field, 2002), the 1990 CAAA was the first legislation to introduce a market permit system for the electricity industry to control air pollution.

1.3 Title IV of the 1990 Clean Air Act Amendments

Coal-fired power plants generated 2/3 of the total sulfur dioxide and 1/4 of the total nitrogen oxide emissions in the U.S. in the 1980s (U.S. EPA). Historically, these emissions have been regulated under the Clean Air Act first passed in 1963. Amendments to the Clean Air Act were made in 1965, 1966, 1967, 1969, 1970, and 1990. The Clean Air Act of 1963 set up emission standards for stationary sources, e.g., power plants. The Clean Air Act Amendments of 1970 set new and demanding emission standards for stationary and mobile sources as well as ambient air quality standards. The 1990 CAAA addressed five areas due to growing environmental concerns with air quality. The centerpiece of the 1990 CAAA is Title IV, called the Acid Rain Program, which specifically aims to reduce the emissions of SO₂ and NO_x from electric power plants.

Title IV of the 1990 CAAA adopted a tradable permit approach that had been long advocated by many economists to achieve SO₂ emission reductions. Tradable permits provide a more flexible alternative along with other approaches, including fuel-switching and scrubber installation, for electric power plants to lower the cost of pollution control. Title IV also sets out aggregate annual caps on national SO₂ emissions from electric plants. Implementation is carried out in two distinct phases for the reduction of the emissions of sulfur dioxide (SO₂) and nitrogen oxides (NO_x) by coal burning electric utilities. Phase I, which began January 1, 1995 and ended December 31, 1999, required 263 generating units within 110 of the most polluting plants to reduce emission levels to 2.5 pounds of SO₂ per million Btu (mmBtu) based on 1985-87 production levels. The U.S. Environmental Protection Agency allocated free allowances to each

of the generating units included in Phase I based on average emissions of 1985-87. One allowance is one ton of SO₂ emissions. At the end of each year, every Phase I unit must have enough allowances in their account to cover the SO₂ emissions it released in that year. The plant has flexible options to meet the emission cap, e.g., switching fuel from high sulfur coal to low sulfur coal, switching fuel from coal to oil or gas, installing flue gas desulphurization equipment (scrubbers), purchasing emission allowances (emission permits) from the allowance market, reducing its utilization rate, or simply shutting down the unit.

The NO_x emission reduction program was also implemented in two phases in the 1990 CAAA. The first phase began January 1, 1995 and the second phase began January 1, 2000. The 1990 CAAA requires NO_x emissions reduction of two million tons by coal-fired power plants based on 1980's emission levels. The NO_x reductions required by Title IV is based on boiler type in power plants and does not cap NO_x emissions as the SO₂ program does nor does it utilize an allowance trading system since the NO_x reductions are also required in Title I of the 1990 CAAA.

1.4 Motivation of the Study

Compared to previous studies completed before and during Phase I, there is now a rich body of evidence from Phase I performance in the allowances market, plants' compliance options, and regulatory rules available for analysis. These data allow several questions to be addressed. What contributed to the unexpected SO₂ and NO_x reduction levels during Phase I of the Acid Rain Program: fuel switching from high sulfur to low sulfur coal, the installation of scrubbers, or trading in the allowances market for SO₂ emissions? Why is the trading price

lower than expected? What is the actual abatement costs attributed to SO₂ and NO_x reductions, respectively, by the electric power plants? Four specific factors motivated this study:

1. Phase I is completed and Phase II was initiated in 2000. Information on the allowance market during Phase I provides practical evidence for examining the factors that led to an apparently lower cost of SO₂ emission reductions and the behavior of electric power plants that choose different alternatives for SO₂ reduction.
2. Better economic insights are needed into the cost of reducing SO₂ emissions by coal-fired power plants and the reasons that costs vary among plants. Most past studies focused on industry-level cost calculations of marginal and average cost. As Burtraw (2004) pointed out, an industrial marginal cost does not apply equally well to individual firms since costs presumably differ among firms. A plant level study by Coggins and Swinton (1996) developed an estimate of plant abatement cost for Wisconsin, Minnesota, and Illinois before Phase I was effective (see, also, Swinton 1998, 2002, 2004).
3. Estimates of the actual abatement costs of SO₂ and NO_x at the plant level for Phase I performance are needed.
4. No such study has been done in West Virginia.

A study that evaluates the performance of West Virginia's electric utilities under Phase I of the 1990 CAAA and provides insight into the possible long-run effects of Phase II provides economic insight into future direction for policy development and implementation.

1.5 Research Objectives

This study focuses on West Virginia coal-fired power plants and estimates marginal abatement costs of Phase I at the plant level. In Phase I, 14 units in six coal-fired power plants in West Virginia were specifically required to reduce their SO₂ emissions by Title IV of the 1990

CAAA. It is appropriate to examine the effectiveness of the Acid Rain Program, especially in West Virginia.

The research objectives follow from the motivations discussed. They are to:

1. Explore the factors that contributed to the reduction of SO₂ emissions from West Virginia coal-fired power plants during Phase I, including the installation of scrubbers and switching from high-sulfur to low-sulfur coal.
2. Estimate the shadow price of SO₂, i.e., the marginal abatement cost for one additional ton of SO₂ reduction, for individual electric plants in West Virginia. The shadow prices provide an indication of the true marginal cost to West Virginia utilities for reducing SO₂ emissions.
3. Examine the relationships between abatement costs and the demand for allowances for each plant, considering the abatement activities taken by individual plants. It is assumed that the marginal abatement cost is high for plants that invested in new abatement technology while the demand for allowances is low and vice versa (Swinton 1996, 1998).
4. Expand the estimates of abatement costs to NO_x, which is also required and monitored under Title IV of CAAA and traded in the allowance market, and CO₂, which is not monitored under Title IV of CAAA. The study will examine if there is a relationship, which either increases the efficiency of a firm's emission reduction approach or increases the total abatement costs.
5. Consider the implications for future policy development designed to reduce SO₂ emissions or similar pollutants from electric power plants.

1.6 Overview of the Dissertation

The rest of the dissertation is arranged as follows. Chapter 2 provides an overview of the economic theory of externalities, the design of pollution control policies, and economic modeling of production including pollutants. It also introduces the primary approach used in this study, a distance function model. Chapter 3 and Chapter 4 present the output distance function approach in detail. While Chapter 3 gives a general economic model of output production technology and its dual, the revenue function, Chapter 4 proceeds with the further partitioning of the output vector into two subvectors, desirable outputs and undesirable outputs. Chapter 4 specifies the empirical output distance-translog production function. Chapter 5 presents the empirical estimation of the translog production function using Phase I data from 16 coal-fired power plants in West Virginia. Based on these results, shadow prices for SO_2 and NO_x are estimated. This analysis is followed by an interpretation of the results and an analysis of the policies based on the estimations and market performances of WV power plants in Phase I. Chapter 6 provides the summary, conclusions, and recommendations for further research.

Chapter 2. Literature Review

2.1 Introduction

Dales (1968) asserts: “to live is to pollute.” His assertion has several implications. First, it points out that environmental pollution is a ubiquitous phenomenon associated with all human activities, i.e., from production and consumption (Ayres and Kneese 1969; Pearce and Turner 1990). This is because we obtain what we need through production activities from the Earth but we also use the same planet to dispose of wastes from these production and consumption activities. Second, pollution has to be dealt with. Although waste disposal has long coexisted with production and consumption activities, it was not a serious social-economic problem until after World War II² (Mishan 1971; Cornes and Sandler 1996; Pearce and Turner 1990). At least two reasons prompted attention to the pollution problem. First, after World War II, industrialization and economic development accelerated productivity and simultaneously generated tremendous wastes. The wastes were, as they had been before, dumped into the environment, e.g., water, air, and ecological systems, and degraded environmental quality. The result of this degradation, in turn, adversely affected human health and caused premature deaths (Field and Field 2002; Freeman 2003). In addition to health problems, water and air pollution affect beneficial recreation uses. Second, the awareness of improving living standards or quality of life had raised concerns about environmental deterioration in the developed economies. These two factors put forward challenges to a wide spectrum of socio-economic systems, e.g., public policies, economics and related natural sciences, etc., to deal with environmental pollution. Environmental pollution inevitably challenged conventional economics that is based on a set of well-defined competitive market conditions to establish its theoretical framework and systematic

² The discussions of externalities in the economics literature noticeably increased after the end of World War II.

analyses of resource allocation, production and consumption to achieve a general equilibrium. A general equilibrium is an ideal allocation of resource such that nobody can be made better off unless someone else is made worse off by any change in the allocation. This is also called Pareto optimality. In this economic situation, pollutants generated from the production or consumption processes are assumed absent. When the problem of pollution cannot be ignored and has to be taken into account, new economic theories and approaches are needed.

In this literature review the approach is to begin, in Section 2, with theoretical building blocks, the definition of pollution and theory of externalities. Section 3 is a review of design of pollution control policies. Since this research is not a pure economic theory study, this literature review examines the theory but more attention is given to modeling, empirical estimation, and policy implications. Section 4 covers the literature on modeling joint products. The last section is a summary of the chapter.

2.2 Economic Theory of Pollution

Economists noticed that omission of the pollutants from economic activities, which include production and consumption, was misleading and violated the assumptions which underlie traditional economics and that lead to a general equilibrium. Economic theory on pollution consists of the definition of externalities and adjusted general equilibrium conditions. These are the topic of this section.

2.2.1 The Definition of Externality and Its Classification

When economists observed effects that were out of the scope of a firm's profit maximizing decision-making process, they gave the effects a very board term, externality (Meade 1952; Mishan 1971; Cornes and Sandler 1996; Buchana and Stubblebine 1962; Freeman

2003; Baumol and Oates 1988). For example, the SO₂ and NO_x from electricity plants pollute air and adversely cause air borne diseases when regulation of the emissions is absent. This pollution effect is external to power plants but internal to society. The key factor that determines an externality is that an agent generates an output or result but does not pay for it. Pollution is a waste that is discharged into the environment from human based production and consumption activities and is one form of an externality.

Economists have explored the theoretical definition of an externality from a normative point of view and have made great efforts to define the term precisely. Some enumerate the phenomena of externalities (Scitovsky 1954; Mishan 1971); some define it either as the source or consequence of market failure (Cornes and Sandler 1996; Mishan 1971); some define it by example (Meade 1952; Tietenburg 1998); and others define it at a very abstract/purely theoretical level (Buchana and Stubblebine 1962; Freeman 2003; Baumol and Oates 1988). These definitions characterize different externalities in different economic systems, e.g., competitive and noncompetitive economic systems (Meade 1952; Scitovsky 1954), explore the different general equilibrium or partial equilibrium contexts and possible results when externalities are included (Meade 1952; Buchanan and Stubblebine 1962; Hazilla and Kopp 1990), or define externality in policy oriented (Baumol and Oates 1988) or theorem oriented approaches (Arrow 1970; Cornes and Sandler 1996), etc. Even so, there has been no single universally accepted definition of externality. In general, the intention has been to define externality from theoretical concepts to practical purposes at different levels or from different angles to serve different kinds of issues.

Here, I present a general picture of an externality and pinpoint the definition used for this study. First, an externality is a spillover effect of economic activity of an individual from a

consumption activity or a firm from a production process on other individuals, firms, or society (Buchanan and Stubblebine 1962). Second, an externality can be either good (an external economy) or bad (an external diseconomy). When economists define externality, they observe that the externality can be positive or negative (Mishan 1971; Mead 1952; Scitovsky 1954). This is the root of all externality classifications. Meade (1952) gave two examples of good externalities, an apple farmer provides food for bees and a forest creates a more productive climate for the wheat farmer. These are positive externalities. Environmental pollution is one of the bad examples of externalities in economics. The third and key element is that there is no compensation for a positive externality, no costs to polluters for a negative externality. The beekeeper gets bee food from an apple farmer but does not pay for it; neither does the wheat farmer pay the forest owner. This is because the externality, from the point of view of a producer or a consumer, is a side- or spill-over effect that one production process or consumption activity generates and which impacts others. The good or positive externality brings benefits to others. In reality, economists or policy makers do not give much attention to good externalities. The focus is on the negative externalities, e.g., air pollution, water pollution, toxic waste pollution, etc., because these obviously cause public health problems or have other harmful effects. Coal-burning electricity plants pollute air and may cause global warming. Such detrimental side-effects might have been generated by any human being's activities on the earth, but became more common as economic activities accelerated. These effects were not a major problem for society for a long time and polluting firms freely used the natural environment. However, industrialization in western economies was intensive and worsened environmental quality, especially after World War II. Mostly, the intensified pollution greatly exceeded the assimilative capacity of nature due to population increases and expansion of economic development.³ Of

³ This is because nature's intrinsic assimilation capacity largely absorbed the adverse effects before industrialization.

course, the pollution problem in developing countries is severe and will become worse as these countries attempt to reduce the economic gap with the developed nations. Scitovsky (1954) addresses the differences in externalities between developed and undeveloped nations. But this is beyond the scope of this study. The externalities in this study refer those in industrialized countries or in competitive economies.

The fourth aspect of the externality definition is the source that generates the externality, i.e., whether the externality is generated from a production or a consumption activity. Buchanan and Stubblebine (1962) gave a definition of these. A consumption externality exists when “external effects exist in consumption whenever the shape or position of a man’s indifference curve depends on the consumption of other men” (p. 371). The production externality exists when “External effects are present whenever a firm’s production function depends in some way on the amounts of the inputs or outputs of another firm” (p. 371). The externality generated from a production process is different than that from consumption with respect to adverse impacts, disposal strategies, and control policies. Production externalities are widely discussed in the economics literature and are the type of externality dealt with in this study.

The fifth aspect of the externality definition is the theoretical model or justified theory of general equilibrium. Baumol and Oats (1988) gave their definition with two conditions: (1) the externality as a real variable is presented in an individual utility function or a firm’s production function; and (2) the factor representing the externality in either function does not incur any cost for a negative externality or receive any payment for a positive externality. Their classification includes technologic and pecuniary externalities, public and private externalities, Pareto-related externalities, and depletable and undepletable externalities. Baumol and Oats gave a relatively

Then the extent of pollution exceeded nature’s assimilation ability and externalities became a problem for society.

thorough classification for their definition, but did not distinguish between production and consumption externalities.

The sixth point is that an externality is a market failure or the absence of well-defined property rights for air, water, or environmental services (Cornes and Sandler 1996; Baumol and Oates 1988; Pearce and Turner 1990; Tietenberg 1998, 1995; Randall, 1983). This feature has very important implications for economics and policy design. Consider the third feature of an externality, there are no economic transactions between a benefit receiver and provider for a positive externality or pollution victims and polluter for a negative externality. Economists call the former an economy due to externality and the latter as a diseconomy due to an externality. These two situations are both due to lack of markets to trade or value the externalities. Therefore, from a social production perspective a process with a positive externality is under produced while negative externalities are characterized by overproduction. The economic consequences are that resource allocations are not efficient compared to a perfect market.

In general, whatever definition of externality is given and whatever the type under which the externality is classified, it serves one common purpose – that is, the externality cannot be ignored and solutions must be found for the problem. A detailed and thorough theoretical discussion of externalities is beyond the scope of this study. I only intend to define the concept for this specific study. The concept used is the diseconomy of externalities generated in a production process. The definition for the current study can be properly rephrased as a working definition. That is, an externality is the effect of a by-product of the production process that is external to the firm and their profit-making decision process, but internal to society.

2.2.2 Theories of Externalities

The definitions of an externality discussed above provide the basic building blocks for the theory of externalities. The theory of externalities follows the same general framework as conventional economics, but a justification is necessary to construct a new general equilibrium theory. In conventional economics, a general equilibrium is the core of the economic analysis (Varian 1992), where all the markets are cleared given that all markets of products and services are perfectly competitive. For a general equilibrium, there are three conditions that must hold. That is, the marginal rates of substitution of inputs equal the respective input price ratios for producers; the marginal rate of substitution for any two consumption goods is equal to their respective price ratios; and producer's marginal rates of product transformation between any two products must equal the consumers' marginal rates of substitution between the two consumption goods. If either of the first two conditions holds, the situation is a partial equilibrium. Theoretically, when all of these three conditions are met, a general equilibrium is achieved. It also means that the allocation of all resources is efficient in the Pareto sense.

Since social welfare is based on the welfare of individuals, it normally implies Pareto efficiency: "(1) each individual is the best judge of his own welfare; (2) the welfare of society depends on the individual welfare of its citizens; and (3) if the welfare of one individual increases and the welfare of no one decrease the welfare of society increases" (Mäler 1985, p.7). The assumptions of perfect competition imply that the resulting allocation of resources is Pareto efficient. That efficiency result may no longer hold if there is a violation of the perfect competition assumptions such as the existence of externalities. When any externalities exist the general equilibrium model must be modified to accommodate this change. The common approach to show this is to point out that when the previously ignored pollutant from either a

consumption or production process is added to the basket of consumption (consumer) or production (firm) activities, the additional marginal conditions for pollutants change the landscape of traditional economics and, thus, general equilibrium.

Economists have attempted to modify general equilibrium and welfare economics to incorporate externalities (Mäler 1985; Mishan 1961, 1971; Gowdy and O'Hara 1995; and Cornes and Sandler 1996). There are three modified general equilibrium theories when the externality is considered in the general equilibrium model: Samuelson conditions for a public good, Nash-equilibrium, and Lindahl-equilibrium for nonmarket goods (Cornes and Sandler 1996; Mäler 1985). These theories take public goods into the equilibrium framework and present different solutions for handling market failure. For simplicity, there is assumed to be one private good, one pure public good, and two individuals that purchase these two goods. Brief discussions of the three equilibriums are given in the following paragraphs.

The Samuelson condition, in addition to the aforementioned three conditions for general equilibrium, adds an optimal condition for a pure public good when an externality is present. Optimality for a pure public good⁴ requires that the summation of marginal rates of substitution between the private good and the pure public good for each individual in the economy equals the marginal rate of transformation between the private good and the pure public good for the economy. This condition is derived by maximizing the utility of any individual, subject to the constancy of the utility levels of the rest of community, the economy's transformation function, and the private good's production-distribution constraint.

If two individuals make decisions on the contribution to the public good independently, a Nash-equilibrium results (Cornes and Sandler 1996). That is, each individual chooses an

⁴ A public good, by definition, is available to all in a region or a community when it is made. A public good is distinguished by the technical nature of the good, not by the type of organization making it available. Therefore, environmental quality is essentially a public good.

optimizing level subject to the constraint that his or her counterpart's choice is at an optimizing level. Each agent chooses his or her public and private goods allocation, subject to a resource or budget constraint, while taking the other individual's public good contribution level as given at a best-response level, assuming that they are rational players. Since one believes his or her optimal choice will not influence the other's choice that holds the best-response level, the free rider problem exists in a Nash-equilibrium. Strictly speaking a Nash-equilibrium is not Pareto optimal because neither individual accounts for the well-being of the other or attempts to gain at the expense of the other. Cornes and Sandler (1996) point out that the free rider is not completely free for most public goods and easy riding is a more appropriate term.

Assuming one private good and one pure public good and two individuals, the Lindahl-equilibrium uses an auctioneer who calls out the tax shares for the public good, and the two individuals respond with their utility-maximizing public good quantities. Each individual maximizes his or her utility by taking the tax share as given. The auctioneer will arrange a new tax share unless the two agree on the same amount of tax share of the public good. When both opt for the same public good provision level based on a set of tax shares, a Lindahl-equilibrium has been reached. A Lindahl-equilibrium creates a pseudo market equilibrium by finding a general equilibrium price vector capable of clearing private markets. When the process succeeds the Lindahl-equilibrium is a Pareto optimum. A Lindahl-equilibrium is associated with two fundamental theorems of welfare economics for a pure public good economy. The first theorem states that a Lindahl-equilibrium is Pareto-optimal (Cones and Sandler 1996; Mäler 1985), and the second indicates that lump-sum redistributions can sustain a Pareto optimum as a Lindahl-equilibrium (Cornes and Sandler 1996). A variant of the Lindahl-equilibrium is Mäler's (1985), where an agency of the government, instead of an auctioneer, determines the tax share. The

agency is responsible for the provision of public good. It assumes that all individuals are utility maximizing and all firms are profit maximizing. The government agency is also profit maximizing. A profit results from selling waste disposal services to individuals and firms or selling pollution rights on an auction market. These services consist of clean air, water, increased productivity due to less pollution, increases in recreational amenities due to clean-ups, etc. The value of these services can be interpreted as a market value if these services are sold on a competitive basis to individuals and firms. These modified general equilibria are Pareto optimal and set up the theoretic basis for policy solutions for pollution problems. Of the three general equilibriums, the Lindahl-equilibrium is the one that is the most closely related to the U.S. SO₂ and NO_x cap-and-trade market model. Additional detail on the U.S. SO₂ and NO_x cap-and-trade market model is given in the following section and in Chapter 5.

2.3 Pollution Control Policies

The previous section discussed the theoretical framework of a general equilibrium when externalities are included. Especially in Lindahl-equilibrium, it is necessary that a government agency be directly involved to determine environmental services and control pollution. Several of the areas that need government provisions and intervention noticed by economists can be dated back at least to Adam Smith and David Hume in the eighteenth century (Pearce and Turner 1990; Cornes and Sandler 1996). These areas include the establishment of a justice system, the enactment and enforcement of laws, protection against invasion, and the provision of schools and other public goods (Pearce and Turner 1990). Environmental services and goods are special public goods. They can benefit individuals and groups, consumers and producers without exclusivity and/or rivalry. Adam Smith in his *Inquiry into the Nature and Causes of the Wealth*

of Nations realized that the pollution problem was one of areas that need government intervention (Swinton 1996; Mallette 1955).

In English history, during the twelfth century the Queen of England left the throne in Nottingham because of heavy smoke. Three hundred years later, the brewers of Westminster switched fuels from coal to wood to protect Queen Elizabeth from the ill effects of coal smoke. By the end of Queen Elizabeth's reign, Parliament prohibited the burning of coal during its sessions (Cornes and Sandler 1996; Swinton 1996; Mallette 1955).

Another important contribution of general equilibrium theory for economists is as a guide to the design of policy solutions for the pollution problem in the economic system, how the government intervenes and in what regulatory form. The role that government can play in pollution reduction may fall into two categories of pollution control policies, command and control (CAC) and incentive-based pollution control policies. This classification is based on whether the policy gives the polluting firms or individuals the inherent incentive to comply with the environmental pollution reduction, while each category is a cluster of pollution control policies. The former has a long history and has dominated environmental pollution control policies in the U.S. and other countries. It relies on standards of various types to bring about the improvement in environmental quality. There are three kinds of standards: ambient, emission, and technology standards (Field and Field 2002). The standards are the thresholds set by law that mandate all individuals or firms to obey and then provides the authority to enforce them. With this approach the government sets up rules or standards as mandatory requirements that polluting firms have to implement. For example, CAC was considered the approach to force electricity plants to install scrubbers in the early stage of policy design to reduce SO₂ pollution.

Why is the command-and-control framework used or favored? The advantages of CAC are explained as a simple and straightforward method for all of parties involved and some positive control by regulators and affected parties (Stavins⁵ 1998, 2003; Tietenberg 1985, 1999, 2000; Field and Field 2002). The difficulties with CAC relate to the information requirements needed to develop and set up appropriate standards of various types to protect human health and the eco-system; to estimate social damages caused by the various pollutants; and to estimate the abatement costs with various levels of pollution as prescribed by the best available technology. For many economists, the CAC approaches are neither socially efficient nor cost-effective in most cases. Incentive-based policies for pollution control have been the preferred alternative policy instruments to CACs. Such policies give polluting firms flexibility to reduce pollution at minimum costs and thus provide incentives for innovation and technical progress. Therefore economists have long advocated incentive-based policies, e.g., pollution taxes, effluent fees, and transferable pollution permits. In the following sections these forms are discussed in more detail.

2.3.1 Tax Regime and Property Regime

The question for economists is how to convince government officials to adopt incentive-based public policies that should be used in pollution control. The consensus among economists as well as some decision-makers and environmentalists is that pollution is the result of the lack of well-defined property rights for air, water, and other environmental goods. When pollution is a severe problem that affects public health, the authority has to intervene to reduce pollution and protect the public interest. Under this logic, the government is the surrogate owner of air, water, and public environmental goods and services. One of the rationales for government intervention

⁵ Stavins has listed the players involved in the process to regulate pollution and favored the CAC approaches. They are the affected firms, environmental advocacy groups, organized labor, legislators, and bureaucrats. Therefore he infers that the reasons that CAC are dominant in U.S. environmental pollution policy are due to political economy factors.

for environmental externalities is to provide incentives for the private sector to internalize the full costs of their actions; this was long thought to be the theoretically correct solution to the externality problem. The primary advocate of this view was Arthur Pigou. In *The Economics of Welfare* (1920), Pigou proposed that the government impose a tax on emissions equal to the cost of the related damages at the efficient level of control after he recognized and described the third-party effects (externalities) of the pollution problem. He considered air and water to fall within the realm of the public domain.

Pigou advocated the taxation of polluters as a method for bringing the polluter's marginal cost in line with the social marginal cost of production. By increasing the cost of production, the government can both force the producer to internalize the social damage of the production process and obtain the resources necessary to compensate the victims of the pollution. On the other hand, if an activity has beneficial third-party effects, a state subsidy can increase the social dividend by increasing the level of the activity.

Pigou was concerned with the potential divergence of social marginal product and private marginal product because it revealed a departure from optimal investment behavior. He described the optimal allocation of resources as that that equates the marginal return across opportunities. Because investors are liable to ignore returns to those other than themselves, "There might still be scope for State action designed to increase the magnitude of the national dividend and augment economic welfare," Pigou wrote (1920, p.141). Furthermore, he also pointed out, "in any industry, where there is reason to believe that the free play of self-interest will cause an amount of resources to be invested of the national dividend, there is a prima facie case for public intervention" (p.331).

In response to Pigou's tax approach, Coase (1960) focused on the ability of free-market transactions to remedy the effects of externalities. Because Pigou's argument relied in part on a well-functioning price mechanism to allow the state to affect outcomes through taxation, it stands to reason that the price mechanism should work to remedy the external effects of all transactions. Coase demonstrated that if one were to make the assumptions that markets worked flawlessly and information flowed freely, then government intervention would be unnecessary to internalize external effects. Coase gave an example of how the optimal solution could be reached between a grain farmer and a cattle rancher. The grain farm has an open field that abuts the cattle ranch's grazing pasture. With the incidence of a cow straying into the corn field, the question is to determine who should compensate whom and the efficiency that would result in the exchange. If the rancher has the property right, the farmer should pay the rancher to restrain the cattle if it is cheaper to do so than building a fence; if the farmer has the property right, the rancher would either pay the farmer or build a fence, whichever is cheaper. Coase's theorem was that economic efficiency is served if the two parties negotiate a solution in the absence of government intervention and transaction costs regardless of who compensates whom. With established property rights and smoothly operating price mechanisms, there is no need to tax either of the parties. He also carefully pointed out that this result rested heavily on the assumptions that all agents could freely negotiate with all other agents and no costs were incurred in making a transaction. Coase's work was criticized by many free-market advocates in that negotiation is infeasible when more parties are involved in air or water pollution cases, and that transaction costs would be unavoidable. However, it is fair to say that Coase demonstrated a very important foundation for environmental economics and public policy related to pollution control. Well-defined property rights are more important than advocating an elimination of

government involvement in the economy. The definition of property rights is a form of State intervention in the market place for those public goods and services, e.g., air and water.

Randall (1983) gives a clarification to Coase's theorem. He notes that two very important characteristics of a good or service are rivalry and exclusivity. Rivalry refers to the degree to which one individual's consumption of a good affects the ability of others to consume it and exclusivity refers to the ability of a producer to limit consumption of the good by others once it has been produced. While air pollution is non-rival in consumption, government rules can change air pollution availability as a means for producers to dispose of waste. By placing restrictions or by establishing property rights for air, the government makes air pollution an exclusive good rather than a non-exclusive good. Randall also clarifies the importance of the distributional aspects of property rights and the role transaction costs play in the distribution of benefits.

For a long time governments in the western hemisphere hesitated to use taxes or its variant, fees, on emissions of pollutants as Pigou proposed (Pearce and Turner 1990). In reality, effluent fees on water pollution in European countries are more popular than in the U.S. because Europeans tend to believe that polluters should pay. These charges can reduce pollution from industries, but effluent charges may not be based on calculations of social cost and, thus, may not be cost effective (Tietenberg 1997; Field and Field 2002). The difficulties with efficiently enforcing standards for clean air or water are multi-fold but mainly lie in two obstacles. The first is that technology rapidly changes. Efficient tax or fees developed by a regulatory agency for one specified industry require constant adjustment in a regional and/or dynamic sense based on technological advances. The second is how to obtain information at the firm or industry level on abatement costs and technology given that these are confidential business data that producers do

not want to provide to the agency. Enforcement issues to ensure compliance with the mandated pollution reductions also exist.

2.3.2 Transferable Market Permits

Despite long debate between command and control and taxes, many economists have long advocated market mechanisms to create a pollutant market in which transferable pollution permits are allowed to be traded. The most appealing advantages of the transferable market permit over unit taxes on pollutants are: (1) flexibility for polluting firms to have choices to reduce pollution, (2) lower demand for information than needed for the authority to decide the unit tax rate or discharge fee, and (3) gains in efficiency of pollution control that can be achieved through market trading (Tietenberg 1985). Then what system of transferable market permit should be designed for the pollution control market? Is the permit price or the total permit set by the regulatory agency for the pollutant on the market? Weitzman (1974) offered insights into the choice by examining the occasions when policy benefits from the use of a price tool as opposed to a quantity tool. He concluded that the information the government possesses determines which policy tool is most effective. Tietenberg (1974) first took up the problem of designing an effective transferable pollution permit for air pollution. He favored “air-rights” and argued for the supremacy of an “air-rights” market, which he found preferable to a taxation or a command-and-control approach. Collinge and Oats (1982) developed a system called rental emission permits (REP) which would have more flexibility than the fixed unit tax. Rent in REP is a designated increase sequentially corresponding to different ranges of pollution levels by the administration. This differential rent system provides a supply curve of pollution permits (the shape is similar to other goods with a positive slope) to confront the polluting firms that have various pollution abatement costs. When the marginal rent of emission permit equals the

marginal abatement cost for each individual polluting firm, efficiency of pollution reduction is a result. Compared to the taxation approach, the demand for information on the total social damage and the firm's abatement costs for the administering agency is modest.

If there were well-defined property rights for water, air, and environment resources there would have been a well-functioning market for them. This thought naturally led to the solution to establish such a market for environmental goods or services. Crocker (1966) proposed the idea of the government setting a cap on aggregate emissions and letting the market determine the emission price and the degree of abatement at individual facilities, rather than having the government set the price through an emission fee. Dales (1968) popularized the idea. He proposed a market mechanism to tackle the pollution problem. His proposal is based on the development of the Coase theorem. The essential spirit of the Coase theorem is that two parties are involved in the pollution problem and they would bargain to reach a Pareto optimum if the property rights were defined. The condition for this Pareto optimum is the assignment of property rights. That is, either the polluter has the right to pollute or the victim of the pollution has the right to avoid the pollution. Because there is no market for the pollution, the property right has to be assigned by a third party. This third party can be the government agency that provides the appropriate property rights. Then the market will allocate the cost of pollution reduction efficiently. This approach offered regulators a tool to achieve a given level of pollution abatement at least cost for polluters in the aggregate. Dales (1968), in his *Property, Pollution, and Prices*, points out that the property regime that defines who has a right to the environment drastically influences the marginal costs and marginal benefits of any project. Furthermore, he offered a policy solution: a regulatory agency creates property rights for units of pollution. Under his proposal the market forces could allocate the costs of pollution efficiency

between polluters and those harmed by pollution if one could assign property rights to units of pollution. Montgomery (1972) rigorously demonstrated that for any given level of emissions, Dales' market would efficiently allocate allowances among polluters. He showed that if the number of allowances limited the aggregate level of pollution, polluters would have to incorporate the cost of pollution into their production function. This would ensure that polluters who could reduce emissions at a low marginal cost would do so either in order to sell residual allowances or to avoid having to purchase allowances.

Montgomery offered two systems of property rights for pollution that could be the underpinning of a market for pollution reduction. His first and preferred offering was a system of pollution rights. In his pollution rights market, Montgomery described a system in which polluters trade licenses based on the effect their emissions have on a set of monitoring sites. Total emissions landing at any monitoring site is a linear combination of emissions from all sources. His second offering was a less complicated system of emission rights. The transferable emission rights entitled the holder to emit a specified pollutant at a certain rate. The benefit of such a system of rights is that it is easier to monitor and administer. The shortcoming of such a system of rights is that it risks allowing polluters in a particular area to increase emissions beyond a level that is locally desirable. The regulatory agency can place some restrictions on trading flows among possible "hot-spots." Montgomery proved that a market equilibrium that reduces the ambient concentration or emissions of pollutants at least cost to polluting industries exists.

These theoretical preponderances provide a sound and logical outline for what the economy should be and what ought to be done. It is often referred as normative analysis. Normative analyses give the basis for value judgments and guidance for policy making. Under

this guidance, environmental economics examines each specific pollution issue in the specific field or industry. This brief review provides an outline of the general equilibrium conditions when pollution presents a problem in the economic system that requires special treatment in theory. It is a natural starting place for further consideration of practical policies and solutions to pollution problems.

2.3.3 Pollution Permits from Theory to Reality: SO₂ and NO_x Allowance Markets

For economists the basic components for a pollutant market include the creation of pollution rights for polluters by the authority, the total amount of pollution reduction or emissions of a specific pollutant or a set of pollution permit prices, and an initial distribution of the pollution permits. The economic players in this special market are the demand for emission/pollution rights by polluting firms and the supply of such emission/pollution rights by a regulatory agency.

In practice, the first application of emission trading was designed by economists and policy analysts in the EPA's Regulatory Reform group in 1975-76 (Burtraw et al. 2005; Tietenberg 1985, 1999). This application is also known as offset policy or emission reduction credits (Field and Field 2002). By 1976 the regions that were initially designated as nonattainment regions obviously could not meet the ambient air quality standards by the deadlines mandated by the Clean Air Amendments. The CAA would prevent new firms from entering these regions to worsen air quality. EPA developed a system of emission offsets to solve the conflicts between improving the air quality in a region and promoting economic development. The existing polluting firms could obtain emission credits certified by local authorities if they reduced their emissions sufficiently. Then, new firms could buy emission credits from the existing sources when entering the region. The total emissions would not exceed

the previous level before new firms' operations. Therefore, "offsetting emissions increases with reductions elsewhere" (Burtraw et al. 2005). The results were that new sources would enter the nonattainment regions with sufficient emission reduction credits (120% of their emissions level required of which 20% would be retired) and lower the regional emissions. The variations of offset policy include "bubble", "banking", and "netting" (Tietenberg 1985). Successful programs utilizing the offset policy were the lead phaseout program, reduction of ozone-depleting chemicals, and Los Angeles Regional Clean Air Incentive Market (Tietenberg 1999). These programs provided encouragement for authorities to move forward in using market mechanisms for efficient and effective pollution control. It also came from change in the political arena – the congress and the administrative branch – from those resistant to market mechanisms that can help solve social problems to those favoring such approaches (Stavins 1998, 2003).

Title IV of the 1990 U.S. Clean Air Act Amendments (CAAA) created the world's first and largest pollution permit market, the SO₂ allowance market. It targeted coal-fired power plants that are major contributors of SO₂, NO_x, and particulate matter that form acid rain. The reduction of SO₂ from these power plants was to be in two phases. The first phase (1995-1999) had a goal of reducing SO₂ emissions by 10 million tons per year. It was a long process to move from a general decision on a policy strategy to the design of an actual system of marketable permits to the development and implementation of both the final policy and the functioning market. Before the SO₂ allowance market was initiated, the offset policy and other market-based policies for pollution control were sporadic and regional or pollutant specific.

There are several unique features that the SO₂ allowance market possesses. First is the nature of tradable emission rights. Since the air is a common property resource, the government's intervention represents society's welfare and benefits accrue from limiting the use

of its environmental services. The permits issued by the authority to the polluting firms are the legal limits to use air as a dumpster but are not private property rights to the air. Title IV of 1990 U.S. Clean Air Act Amendments makes no ambiguity: “An allowance under this title is a limited authorization to emit sulfur dioxide.... Such allowance does not constitute a property right.” Economists consider tradable pollution permits as “secure property rights to protect the incentive to invest in pollution control equipment” (Tietenberg 1999, 2002). In practice, this means that administrators are expected to recognize the security needed to protect control investments by not arbitrarily confiscating rights. The authorities, however, do not give up their ability to change control requirements as the need arises. Second, the initial permits for Phase I are based on the average heat input of the historical base period, 1985-1987, times an emission rate as yearly aggregated emissions. This calculation differs from the emission reduction credits in offset policy. The allowance is source-based and measured in discrete terms (one-time entitlement) while the credit in offset policy is technology-based and a continuing entitlement to a pollutant flow.⁶ Once one unit of emission is discharged, the allowance is surrendered. Third, the allowance allocation gives more flexibility compared to emission reduction credits. The polluting firm can reduce the emission temporarily or permanently, while the reduction in offset policy is permanent. The initial permits are equal to the target emission cap that is maximally allowed for each power plant to emit in a specific year. In other words, for each unit of SO₂ emitted the plant must have a one unit permit. Without sufficient permits, the plant must internalize emissions within the company, buy permits from other plants, adopt pollution reduction technology, or pay a fine. Fourth, the allowance calculation and allocation mechanisms facilitate aggregate pollution control by the authority. The total number of permits

⁶ Tietenberg (1999, 2002) called them a credit denomination. ERCs are measured in terms of a pollutant flow, e.g., tons per year while allowances are in terms of tons for a pollutant.

issued by the authority for a specific year is at the control of the regulatory agency. Therefore, the agency can decrease the number of permits to reach the goal of emissions reduction over time. This is referred to as the cap-and-trade in the SO₂ allowance program. The allowance market represents a shift of pollution control policy from price to quantity in pollution control policy.

2.4 Pollution Control Modeling

The modeling presented in this section focuses on the pollution-generating firm. It includes a discussion of both theoretical and empirical modeling including a brief discussion of the distance function approach.

2.4.1 Theoretical Modeling

Pollution control modeling is discussed conceptually in Section 2.2 where the economic theory of externalities is reviewed. Each general equilibrium theory has had its model laid out. A general equilibrium model starts with the utility function. The theoretical foundation for pollution control policy mainly lies with including externalities in the general equilibrium framework. In the three justified general equilibrium models discussed in Section 2.2, environmental pollution as a component is included. The equilibrium conditions for the pollution component are discussed in addition to the traditional general equilibrium conditions. These conditions have one thing in common compared to the conditions in a traditional general equilibrium: one or a vector of public goods – pollutants – appears in the utility function for consumers and the production function for producers. The optimal condition is that the marginal price of the product equals the marginal cost of production or consumption. The problem is that the pollutant does not have either direct market price or cost. In Lindahl-equilibrium, the price is assumed to be set by a government agency and the cost is willingness-to-pay by the consumer or

producer. The clearance for the pollutant is when these two are equal. The question that arises is how the government agency decides the price.

A widely used approach in theoretical models with externalities is a damage function. When a pollution problem is present, the individual's welfare and thus social welfare are affected. Theoretically, economists proposed the social damage function to measure welfare change caused by pollution (Cornes and Sandler 1996; Pearce and Turner 1990; Field and Field 2002). When the cost of social damage is included in the general equilibrium model with externalities, a new optimal solution can be found.

The damage function in environmental economics is an exogenous function in terms of the socially optimal solution for pollution control. It accounts for all of damages or impairments to the natural or common property resources. The damage function may consist of the costs of degradation of air or water qualities, limited beneficial and recreational uses, diseases of humans and animals, and deaths caused by pollution. The damage function is an aggregated function for all of economic and social welfare losses. In most cases, the damage function is only a conceptual model and difficult to specify or form. In some cases, the damage function is a surrogate for benefit losses caused by pollution. Freeman (2003) calls it a naïve model⁷ even though his view is in the context of valuing the environmental services. Pearce and Turner (1990) consider it a virtual model.

There also is a marginal damage function that establishes a relationship between the quantity of a pollutant and the damage that pollutant causes (Field and Field 2002). The quantity of pollution represents the level of pollution while the damage represents the marginal cost that corresponds to each level of the pollution. Therefore, a Pigovian tax set in accordance with the

⁷ Freeman characterizes the damage function approach as naïve and reasons that responses or behavioral changes to adverse environmental effects from consumers or producers can rule out the damage (2003, p.27).

marginal damage function provides an optimal solution (Pearce and Turner 1990). Field and Field (2002) give two definitions for a damage function: an emission damage function and an ambient damage function. The emission damage function measures the quantity of a residual emitted from a source or a group of sources and the resulting damage while the ambient damage function measures the relationship between the concentration of particular pollutants in the ambient environment and the resulting damages. The same difficulty arises due to quantitative estimates on the magnitude of damage for one pollutant or several pollutants. The damage function is not appropriate for a polluting industry when the industry's production activity and its pollution control instruments are incorporated into the theoretical model. First, the modeling of the production technology does not take into account the fact that the generation of pollutants is a by-product of the production process if the pollution caused by the firm is external to the production decisions about production. The second is that the polluting firm has an option, a trade-off between the product and the pollutant. An exogenously imposed tax or damage function cannot reflect this trade-off.

2.4.2 Pollution Control Modeling of the Firm

A theoretical general equilibrium model includes consumer market equilibrium, producer market equilibrium, and equilibrium between these two markets. Most empirical analyses, however, are based on partial equilibrium or models of particular aspects of an economy with the rest of the economic relationships assumed to hold. That is the approach taken here. This discussion focuses on a model of a polluting firm.

Models of production with explicit consideration of pollution modeling can be theoretical or empirical. Such model serve as tools to design pollution control policy and examine the effects of different policies after they are enforced in a specific firm or industry. Mishan (1969),

Mäler (1985), and Baumol and Oats (1988) presented different theoretical models of potential policy designs and analyses.

The firm is assumed to be profit maximizing while producing pollution that has an adverse impact on the individual and society. The firm must reduce pollution based on specified regulatory constraints. In the absence such constraints, the firm's decisions concern production costs of the normal inputs but ignores the cost of disposing of the pollutant(s), the by-product of the production process. The issue is how to treat the pollutant within the production process of the model. There are three ways to include pollutant in the production function: as an input, as an output, or as an intermediate product.

The pollutant can be treated as an intermediate product within the firm. An intermediate product is a by-product that comes out of a main production process and is used as an input to another or secondary production process that neutralizes the pollutant and reduces pollution to the environment (Mishan 1969; Ethridge 1981). A system that treats pollutants as intermediate products in a firm is called an integrated production system or vertically linked system (Ethridge 1973; Uimonen 1992). The aim is to internalize the pollution; the problem is that some processes cannot absorb all of the pollutants, or the secondary process generates other pollutant(s). In this type of production model there can be one or more than one intermediate product. For more than two processes or two outputs, a Leontief-technology is usually assumed. This means that inputs enter the production processes in a linear way and that joint outputs occur in fixed proportions to the main product. For simplicity, two processes in production are assumed. The two processes are constrained by appropriate conditions. For example, an input constraint is one where the total amount of each input in the firm must equal the summation of the inputs used in the two processes. The constraint of an intermediate input is imposed on the

interrelationship between the two processes. The intermediate product is used as an input into the second process and may be only a fraction of the pollutant coming out of the first process (Baumgärtner and Jöst 2000). The constraint on total emissions of the pollutant from both processes is considered in some cases (Baumgärtner and Jöst 2000) where the pollutant cannot be completely internalized. This is, some pollutant may be generated from a secondary production process when the pollutant from a main production process is used. In this last constraint, the damage function is introduced to measure the impact on the quality of the environment.

An alternative approach to treat pollutants as inputs directly in a production model (Shephard 1970, 1974; Färe 1988; Färe, Grosskopf, and Lovell 1994; and Färe and Primont 1995). This model treats the pollutant associated with a specific production process as either an input or a vector of inputs. The pollutant as input in a production process is treated as a cost incurred just as are other inputs used in the production process when pollutant has to be disposed of at a cost to meet external constraints.

A third alternative is to treat the pollutant as an output generated by the production process (Shephard 1970, 1974; Färe 1988; Pittman 1983; Färe, Grosskopf, and Lovell 1994; and Färe and Primont 1995). The sign of the input price of a pollutant is assumed positive while an output price of pollutants can be positive (Hetemäki 1996; Mishan 1969) or negative (Shephard 1970, 1974; Färe 1988; Pittman 1983; Färe, Grosskopf, and Lovell 1994; Färe and Primont 1995). For the intermediate product, the price for pollutant as one output in the main production is positive but is negative as the input in secondary process (Uimonen 1992). Uimonen imposed a constraint that the sum of the value of the marginal productivities for a pollutant must be zero in two production processes.

Another approach is to model production and pollution jointly (Mishan 1969). Mishan (1969) discussed joint products in private and collective goods without externalities and with externalities, respectively. The collective goods he defined are similar to Samuelson's public goods but not completely pure as one of two polar cases.⁸ The collective goods externality is defined as a bad side-effect, e.g., when a dam provides electricity and prevents flood, it damages the fish habitat. Without an externality, a private good and a collective good possess the same marginal conditions. With an externality, the marginal condition for the private good is the marginal value of the product equal to the marginal private cost plus the marginal public cost of the product. For jointly produced collective goods, the marginal condition with or without the externality is the same. Assume that for private good jointly produced with collective goods, the cost is the sum of marginal private costs of all private goods jointly produced plus the sum of all individual willingness to pay for the collective goods jointly produced. This analysis gives a conceptual model of joint production of private and public goods. The discussion to this point far is theoretical but an explicit model of production and joint externality is needed to evaluate the U.S. market approach to reduce pollutant emissions that cause acid rain from power plants. The distance function approach provides an answer (Shephard 1970, 1974; Färe 1988; Färe, Grosskopf, and Lovell 1994; Färe and Primont 1995).

2.4.3 Distance Function Approach

The distance function approach includes a family of production models that can be considered as two sub-families – input distance functions and output distance functions. The input distance function treats the pollutant as an input measure in the model while the pollutant is treated as an output in the output distance function. The distance in either function characterizes

⁸ Two polar cases are complete private goods and complete public goods and each is at one of ends of the line if one horizontal line is used to characterize public nature of goods. There are goods that are between the two polar cases.

the firm's performance relative to the production frontier under the specified technology and input set or output set. The production frontier is the minimum combination of inputs for a given output level for the input distance function, or the maximum output given a set of inputs for the output distance function. The production frontier represents the same efficiency as an optimal solution in production economics. In these approaches, there is a dual function associated with each, respectively. For the input distance function approach, the dual function is the cost function. For the output distance function, the dual function is either the revenue function or profit function. When the dual function is either minimized or maximized, the shadow price for either the bad input (in the input distance function) or bad output (in the output distance function) is estimated. The distance function is a promising approach to incorporate environmental "bads" into the firm production model. There are several advantages compared to other models that target the pollutant in the firm's production decisions. First, it directly models each production process without the complication of treating the pollutant as an output in one process and an input in the other process. Second, the technology for a specific production process determines the estimate of the price of the environmental "bads" since, in the distance function approach, a given technology is mapped by the relationship between the input set and output set. In the input distance function "the input correspondence maps output vector into subsets of input vectors," while the output correspondence maps the input vectors into subsets of output vectors in the output distance function (Färe 1989). Duality theory links the production function to the economic models. Shephard (1953, 1970, and 1974) initially developed the duality theory that underlies the distance function approach and established the relationships between the desired output and undesirable output through duality theory when environmental bads are also produced

in the production process. His theoretic work has been extended and applied to the empirical work by Färe (1988, 1990, 1995, 1998, and 2000).

The distance (either input or output) function essentially estimates an empirical production frontier and evaluates each firm's or plant's performance relative to this estimated frontier. Then, through the duality theorem and the appropriate economic model, the undesirable input or output price can be derived or estimated. This is the most attractive property that this approach possesses for production modeling with externalities. In this research the output distance function approach is employed, more details are discussed in the next chapter.

The socially optimal price for emissions reduction is equal to the opportunity cost. The output distance function can estimate this opportunity cost of pollution abatement in percentage terms as an elasticity or in dollars as an absolute shadow price. The estimation of abatement cost provides an indication of the potential effectiveness of the proposed penalties for failing to meet the new clean air standards.

2.5 Summary

In this chapter, a systematic literature review of production externalities starts with a broad definition of externalities and a working definition. The theory of externalities presents Samuelsson's conditions, the Nash-equilibrium, and Lindahl-equilibrium. The Lindahl-equilibrium includes government intervention in the general equilibrium and assumes that a government agency is profit maximizing when it distributes pollution permits to polluters. Among the pollution control policies are command and control, pollution tax or effluent fee, and marketable pollution permit approaches. The 1990 Clean Air Act Amendments enabled a SO₂ allowance market to become reality. The model for the pollution producing firm is an output distance function that provides a tool to evaluate the performance of abatement effectiveness

under the SO₂ allowance market. The next two chapters provide additional detail for the output distance function approach.

Chapter 3. Output Distance Function and Its Dual-Revenue Function

3.1 Introduction

When a production process produces multi-outputs, especially some undesirable outputs, and is regulated by environmental law, the production model becomes complicated. Economic theory states that an efficient allocation of social resources is achieved in such a way that the firm generating pollutants, e.g., water or air pollutants, must internalize the pollution damage to consumers or other producers to account for the full social costs of production. Generally, the government either steps in to impose a tax on the industry for the social damage or sets up stringent environmental standards (command and control) for the discharged pollutants. Both of these popular policy instruments for pollution control have drawbacks in practice.

Environmental economists model production behavior by explicitly including the environmental “bads” in the production process in order to understand the effects of pollution controls. Normally there are two ways to model environmental “bads”: one is to treat pollutants from the production as a kind of input. The reasoning behind this approach is that the firm has to dispose of the “bads” at some cost and this has the same effect as if the firm “purchased” a disposal input. The drawbacks for this modeling approach are two. First, the pollutants are not inputs, but outputs generated from the same production process that produces the desirable output(s). Second, trade-offs between desirable and undesirable outputs can not be explicitly expressed.

Another way is to model multiple outputs and, thus, to directly include the undesirable outputs. This is the approach used in this study. The advantages of this approach are threefold. First, the production process model reflects the production technology. Given the inputs used, all feasible combinations of outputs are determined. This set of feasible outputs is called the

production requirement set. Details are given in the next section of this chapter. Second, the substitution or trade-off between desirable and undesirable outputs can be explicitly measured. This measure incorporates costs related to disposing of or reducing undesirable outputs to meet environmental regulations or potential environmental regulations. More importantly, this approach provides a means to derive the shadow price of undesirable outputs without requiring explicit abatement cost data, information that is difficult to obtain. The abatement cost may not be reliable even though sometime the data are available.

It may be possible for the firm or policy makers to obtain plant-specific opportunity or abatement costs for the specific pollutant when facing potential environmental regulations. In that case, the shadow price can be used to evaluate the efficiency of pollution control measures. This information is especially useful when there is no market or no well-established market for the pollutant. It can also be used when there is no regulation in place for some undesirable outputs (see Fare et al. 1993).

In this chapter, section 2 presents the production technology requirement set and the properties of the output requirement set. Section 3 introduces the output distance function concept and discusses the properties of the output distance function. Section 4 covers the dual to the distance function, the revenue function, and discusses the duality relationships. Section 5 explains how the virtual prices of the outputs are derived from the revenue function. Section 6 presents the equilibrium model in terms of the output distance function; and Section 7 concludes the chapter.

3.2 Production Technology Requirement Set

The fundamental concepts that underlie the output distance function approach were laid out by Shephard (1953, 1970) and developed and extended by Färe (1988) and Färe et al. (1994,

1995). This section follows Färe's framework. A production technology is represented by a given input vector, $\mathbf{x} = \{x_1, x_2, \dots, x_N\} \in \mathbf{R}_+^N$, which is transformed into a collection of feasible output sets, $\mathbf{y} = \{y_1, y_2, \dots, y_M\} \in \mathbf{R}_+^M$. That is, the technology representation maps a given input vector into an output space. It is denoted as:

$$(3.2.1) \quad \mathbf{T} = \{(\mathbf{x}, \mathbf{y}) : \mathbf{x} \text{ can produce } \mathbf{y}\}$$

or

$$(3.2.2) \quad p(\mathbf{x}) = \{\mathbf{y} \in \mathbf{R}_+^M : \mathbf{x} \text{ can produce } \mathbf{y}\}$$

(3.2.1) is called the technology set while (3.2.2) is called the output requirement set. Both contain the collection of all output vectors, $(\mathbf{y} \in \mathbf{R}_+^M)$ that are obtainable from the input vector, $\mathbf{x} \in \mathbf{R}_+^N$. The output requirement set is illustrated in figure 3.1 for a two-output case.

Figure 3.1 The output requirement set, $P(\mathbf{x})$

The output requirement set possesses a number of desirable properties to ensure that the functions defined in the next section have desirable properties. The following axioms for the output requirement set, proposed by Shephard (1970), are also called maintained axioms (Färe, 1988):

- P.1 (a) $P(\mathbf{0})=\mathbf{0}$ (b) $\mathbf{y} \notin P(\mathbf{0}), \mathbf{y} \geq \mathbf{0}$.
- P.2 $P(\mathbf{x}) = \mathbf{0}_M$, for all $\mathbf{x} \in \mathbf{R}_+^N$.
- P.3 $P(\mathbf{x}) \subseteq P(\mathbf{x}')$, if $\mathbf{x}' \geq \mathbf{x}$, for all $\mathbf{x}, \mathbf{x}' \in \mathbf{R}_+^N$.
- P.4 (a) weak disposability of outputs
 $\mathbf{y} \in P(\mathbf{x}) \Rightarrow \theta \mathbf{y} \in P(\mathbf{x}), \text{ for all } \mathbf{x} \in \mathbf{R}_+^N, 0 \leq \theta \leq 1.$
(b) strong disposability of outputs
 $\mathbf{y} \in P(\mathbf{x}) \Rightarrow \mathbf{y}' \in P(\mathbf{x}), \text{ for all } \mathbf{y} \geq \mathbf{y}', \text{ for all } \mathbf{x} \in \mathbf{R}_+^N$
- P.5 $P(\mathbf{x})$ is a closed set, for all $\mathbf{x} \in \mathbf{R}_+^N$.
- P.6 $P(\mathbf{x})$ is a bounded set, for all $\mathbf{x} \in \mathbf{R}_+^N$.
- P.7 $P(\mathbf{x})$ is convex, for all $\mathbf{x} \in \mathbf{R}_+^N$.

Axiom P.1(a) states that a null output vector results from a null input vector, or no free lunch. P.1 (b) says a semipositive output vector cannot be produced without employing some positive amount of inputs.

P.2 says that inaction in production is possible given an input vector, $\mathbf{x}$. P.3 imposes strong disposability of inputs in the production process. Axiom P.4 (a) imposes weak disposability on outputs. It says that if $\mathbf{x}$ can produce $\mathbf{y}$ then $\mathbf{x}$ can produce any proportional reduction of $\mathbf{y}$. Weak disposability allows for the possibility that one or more of the outputs is bad. For example, if electricity is produced by burning coal, sulfur dioxide, nitrate oxide, carbon oxide and other outputs are also generated. The weak disposability implies that a 10% reduction in sulfur dioxide is possible if there is a 10% reduction in electricity generation, holding the input vector constant. P.4 (b) defines the strong disposability of outputs. In other words, the output can be disposed of without incurring any extra cost. The strong disposability only applies to desirable outputs (i.e., where the prices are positive).

The output set, $P(\mathbf{x})$, contains all vectors of desirable outputs on or below the boundary (production possibilities curve). The slope of the production possibilities curve for $P(\mathbf{x})$ is the marginal rate of transformation between two outputs. The marginal rate of transformation

represents the amount of one good that must be given up when an additional unit of the other good is produced, holding inputs fixed. The output set depicts the production technology.

Weak disposability and strong disposability are shown in the figure 3.2.

Figure 3.2 Weak vs. Strong Disposability of Outputs

In order to show strong and weak disposability, the output set is constructed as piece-wise linear with one desirable output and one undesirable output. From P.4 (a), weak disposability requires both outputs decrease when one undesirable output is present. The region OB represents the positive slope of production on the boundary of $P(x)$. When production moves from E to F, the undesirable output moves Point 2 to Point 1 while the desirable output also is reduced from Point 4 to Point 3. Therefore, the pollution reduction requires the concurrent reduction of the good output. It is no longer the case that some quantity of a good output must be sacrificed for the gain of another good. In words, when more of the desirable output is produced, more of undesirable output must also be produced. This area of production between DC is a non-economic region.

Several other regions are also shown in figure 3.2. The region OABO represents the strong disposability of desirable output. The movement from B to A does not affect production of the desirable output, while the undesirable output is reduced. The region of BC is noneconomic and has negative slope. It means that the pollution increases while the desirable output has to decrease in this region. This represents a trade-off between desirable and undesirable outputs when environmental regulation is imposed on polluting firms.

In reality, environmental regulations prevent the free disposal of environmental “bads” so this study limits the interest to the positively sloped region on the boundary of $P(\mathbf{x})$. The relationship between P.4(a) and P.4(b) is that P.4(a) implies P.4(b). Weak disposability can apply to all outputs. Weak disposability also points out that desirable outputs and undesirable outputs are jointly produced. Färe et al.(1992, 1997) call this property the nulljointness of desirable outputs and undesirable outputs. If production of undesirable output goes to zero, the production of desirable outputs must also go to zero. Using electricity production as an example, if electricity is nulljoint with pollution, then the only feasible way to reduce pollution to zero is to reduce production of electricity to zero as well.

P.5, the closed set assumption, imposes the requirement that the output set $P(\mathbf{x})$ be closed. Graphically, the boundary of $P(\mathbf{x})$ is the production possibilities frontier in the output space $\mathbf{R}_+^M$. Alternatively, suppose there is a sequence of output vectors, $\mathbf{y}^n, n = 1, 2, \dots$, such that $\lim_{n \rightarrow \infty} \mathbf{y}^n = \mathbf{y}^0$, then for every such sequence, if x can produce $\mathbf{y}^n$ for all n , i.e., if $\mathbf{y}^n \in P(\mathbf{x})$ for all n then x can produce $\mathbf{y}^0$. This axiom allows us to define an output isoquant as a subset of the boundary of the output set $P(\mathbf{x})$.

P.6 says the output set is finite because the amount of inputs is finite ($\mathbf{x} \in \mathbf{R}_+^N$). The economic meaning simply is that the scarcity of resources implies the scarcity of outputs. P.5 and P.6 together imply that the output set is compact.

P.7 imposes convexity on the output set, $P(\mathbf{x})$. If $\mathbf{y}$ and $\mathbf{y}'$ are elements of the output set, $\mathbf{y} \in P(\mathbf{x})$ and $\mathbf{y}' \in P(\mathbf{x})$, then any convex combination of these points, $[\theta \mathbf{y} + (1-\theta)\mathbf{y}']$, is also an element of the output set where θ denotes a fraction between 0 and 1 ($0 \leq \theta \leq 1$). This axiom is valid for time divisible technologies (Shephard, 1970). Thus, convexity can be interpreted as if production of outputs $\mathbf{y}$ and $\mathbf{y}'$ is feasible from a given set of inputs, then those inputs can be used to produce output $\mathbf{y}$ some fraction of the time and output $\mathbf{y}'$ the remainder of the time.

3.3 Output Distance Function

A production technology is represented by the output correspondence $P(\mathbf{x})$ in the previous section with the assumed properties. It provides a tool to model multi-outputs and multi-inputs. Now we are ready to define the output distance function. First consider and describe intuitive description of the output distance function. Consider Figure 3.3 where the boundary of the output set $P(\mathbf{x})$ represents the production frontier and observed production at point A is inside the production frontier. The distance function measures how far away from the frontier an observed production point is, i.e., OA/OB . This ratio is the same as Farrell (1957) called technical efficiency or Debreu (1951) referred to as the coefficient of resource utilization. If we use θ as the value of the distance function, D_o , i.e., $\theta = D_o(\cdot)$, the distance function seeks to find the minimum distance and maximum scalar value ($1/\theta$) to expand the feasible output of the frontier, given the inputs, $\mathbf{x}$. As shown in the figure, $\mathbf{y}^0/\theta$ is on the production frontier.

Figure 3.3 The Output Set and Output Distance Function

Following the discussion of the output set, $P(\mathbf{x})$, the definition of the output distance function is:

$$(3.3.1) \quad D_o(\mathbf{x}, \mathbf{y}) = \min_{\theta} \{ \theta : (\mathbf{x}, \mathbf{y}/\theta) \in P(\mathbf{x}) \}, \mathbf{x} \in \mathbf{R}_+^N, \mathbf{y} \in \mathbf{R}_+^M.$$

This definition can be interpreted as finding a minimum value of θ such that the scalar $1/\theta$ can project the output to the production frontier. This definition of the output distance function characterizes the firm's technology in output space.

The output distance function can also be defined in terms of the production function, $F(\mathbf{x})$. This production function depicts the maximum feasible output for a given level of inputs and underlying technology. Therefore, the distance function can be given by

$$(3.3.2) \quad D_o(\mathbf{x}, \mathbf{y}) = \mathbf{y}/F(\mathbf{x}).$$

In figure 3.3, $D_o(\mathbf{x}^0, \mathbf{y}^0) = \mathbf{y}^0/F(\mathbf{x}^0)$ and $F(\mathbf{x}^0) = \mathbf{y}^0/D_o(\mathbf{x}^0, \mathbf{y}^0)$.

So far we have considered the output as desirable in the discussion of the output distance function presented. What happens to the output distance function when some outputs are undesirable? Assume at least one output is undesirable. There are two different cases for the output distance function.

First, assume both of the outputs can be scaled by θ . Following Färe, Grosskopf, and Lovell (1994, p, 218) the output distance function is defined as:

$$(3.3.3) \quad D_o = \min \{ \theta : (\theta \mathbf{x}, \theta^{-1} \mathbf{y}_g, \theta \mathbf{y}_b) \in P(\mathbf{x}) \}, \quad 0 \leq \theta \leq 1.$$

Thus, the output distance function says we find a minimum value for the output distance function such that θ contracts the input vector and undesirable outputs while expanding the desirable output at $1/\theta$. The treatment of the undesirable output and desirable output is asymmetric (see Figure 3.4).

Figure 3.4 The scale of desirable output and undesirable output

For the second case, assume that the undesirable output is fixed and only the desirable output is increased. Output is at point A with the undesirable output at its fixed level, y_b^0 , and desirable output at y_g^a . The desirable output is expanded by a scalar value $(1/\theta)$ to achieve the projected output at B. The value of the scalar that projects the desirable output to the frontier, $1/\theta$, is equal to y_g^b/y_g^a as shown in figure 3.5.

Figure 3.5 The scale of desirable output when undesirable output fixed

Consider these two cases. For the first case, simultaneously expanding the desirable output while contracting the undesirable output and input vectors gives several advantages. First, it directly includes the environmental “bads” in the model as outputs instead of treating them as inputs. One reason for this is that the desirable output cannot be increased when this input is increased in the model if the environmental “bads” are treated as inputs. Second, the good outputs and bad outputs are jointly produced as discussed in the Section 2.2. They may have the same type of disposability when environmental regulation is absent. Third, the inputs can be modified in different ways. This can be the case in the production of electricity by

burning coal. The high sulfur content of coal can be substituted for by using low sulfur coal so that both the input of sulfur content from the coal and sulfur dioxide emissions are reduced while the production electricity might be expanded. Overall this model enables us to model the inputs, desirable outputs, and undesirable outputs together.

A modification of this model is needed when environmental law requires the firm control pollution and does not allow the firm to freely dispose of the environmental “bads.” This is when weak disposability is employed for the outputs. Figure 3.2 shows the strong and weak disposability of outputs. The technology with strong disposability is represented by output set $P^s(x)$ and the area $0ABC0$. This assumes that both outputs can be freely disposed of and, in particular, that the amount of undesirable output $0y_1$ can be freely disposed of. The technology with weak disposability is $P^w(x, y_1)$ and area $0BCD$, a reduction of undesirable output must require a reduction of desirable output. This relationship is shown on the ray $0B$.

For the second case, the fixed amount of the undesirable output has two implications. Economically, the pollution does not need to be completely eliminated. Second, the fixed amount of the undesirable output might be set by environmental regulation such as sulfur dioxide emissions set at 2.5 pounds per mmBtu for Phase I and 1.2 pounds per mmBtu for Phase II. Under this regulation annual aggregate emissions of SO_2 is determined for each firm, the firm can expand the production feasibly on the frontier without incurring additional abatement cost if it can hold SO_2 emissions constant.

The properties of the output distance function under the assumed axioms of the output set are summarized (Färe 1988; Färe and Primond 1995) as:

$$D.1 \text{ (a) } D_o(x, 0) = 0 \text{ for all } x \in \mathbf{R}_+^N, \text{ (b) } D_o(0, y) = +\infty \text{ for all } y \geq 0.$$

$$D.2 \text{ } D_o(x, \mu y) = \mu D_o(x, y) \text{ for all } y \in \mathbf{R}_+^N, y \in \mathbf{R}_+^M, \text{ for all } \mu > 0.$$

- D.3 $D_o(\mathbf{x}, \theta \mathbf{y}) \leq D_o(\mathbf{x}, \mathbf{y}), 0 \leq \theta \leq 1$, for all $(\mathbf{x}, \mathbf{y}) \in \mathbf{R}_+^{M+N}$.
- D.3.S $D_o(\mathbf{x}, \mathbf{y}) \geq D_o(\mathbf{x}, \mathbf{y}')$, $\mathbf{y} \geq \mathbf{y}'$ for all $\mathbf{x} \in \mathbf{R}_+^N$.
- D.4 $D_o(\mathbf{x}, \mathbf{y})$ is lower semi-continuous on $\mathbf{R}_+^{N+M}$.
- D.5 If $D_o(\mathbf{x}, \mathbf{y}) \leq 1$ and $\mathbf{y} \geq 0$, then for all $\theta \geq 0, \exists \lambda_\theta$ such that $D_o(\lambda_\theta \mathbf{x}, \mathbf{y}) \leq 1/\theta$.
- D.6 $D_o(\mathbf{x}, \mathbf{y})$ is convex on $\mathbf{R}_+^M$, for all $\mathbf{x} \in \mathbf{R}_+^N$.
- D.7 $D_o(\mathbf{x}, \mathbf{y})$ is quasi-convex on $\mathbf{R}_+^N$, for all $\mathbf{y} \in \mathbf{R}_+^M$.

Proofs of these properties are included in Shephard (1970, p. 208) and Färe (1988, pp. 31-33). Because these properties have a one to one relationship with those of the output set, these properties can be summarized as follows:

D.1(a) is valid if P.1(a) is imposed; no production is taken given the inputs. D.1(b) follows P.1(b); there is “no free lunch”. In this case, the value of the output distance function is set to $+\infty$. Therefore D.1 defines the value of distance function in the range, $[0, +\infty]$ but in this study, we restrict the value to $[0, 1]$. Intuitively, we can see this from the figures 3.3, and 3.4.

D.2 states that the output distance function is homogeneous of degree one in outputs.

3.4 Revenue Function

In the context of output distance functions, the revenue function is the dual. Let $\mathbf{r} = (r_1, \dots, r_M)$ be associated with outputs $\mathbf{y} = (y_1, \dots, y_M)$ for all $\mathbf{r} \in \mathbf{R}_+^M$ and $\mathbf{y} \in P(\mathbf{x})$. The output prices are restricted to be nonnegative. The revenue function is given by:

$$(3.4.1) \quad R(\mathbf{x}, \mathbf{r}) = \max_{\mathbf{y}} \{\mathbf{r} \cdot \mathbf{y} : \mathbf{y} \in P(\mathbf{x})\}.$$

The maximum revenue, R , exists only if the properties of the output correspondence, P.1, P.3, and P.4 hold. These assumptions guarantee that $\mathbf{r} \cdot \mathbf{y}$ is continuous.

The revenue function has the following properties (Färe 1988; Färe and Primond 1995; Färe et al. 1993):

- R.1 $R(0, \mathbf{r}) = 0$ for all $\mathbf{r} \in \mathbf{R}_+^M$.
- R.2 $R(\mathbf{x}, \lambda \mathbf{r}) = \lambda R(\mathbf{x}, \mathbf{r})$ for all $\mathbf{x} \in \mathbf{R}_+^N, \mathbf{r} \in \mathbf{R}_+^M$.

R.3 $R(\lambda \mathbf{x}, \mathbf{r}) \geq R(\mathbf{x}, \mathbf{r})$, $\lambda \geq 1$, for all $\mathbf{x} \in \mathbf{R}_+^N$, $\mathbf{r} \in \mathbf{R}_+^M$

R.3.S $R(\mathbf{x}, \mathbf{r}) \geq R(\mathbf{x}', \mathbf{r})$ $\} \mathbf{x} \geq \mathbf{x}'$, $\mathbf{x} \in \mathbf{R}_+^N$, $\mathbf{r} \in \mathbf{R}_+^M$.

R.4 $R(\lambda \mathbf{x}, \mathbf{r}) \rightarrow \infty$ as $\mathbf{r} \rightarrow +\infty$ if $R(\mathbf{x}, \mathbf{r}) > 0$.

R.5 $R(\mathbf{x}, \mathbf{r})$ is upper semi-continuous in $\mathbf{x}$, for all $\mathbf{r} \in \mathbf{R}_+^M$.

R.6 $R(\mathbf{x}, \mathbf{r})$ is convex in $\mathbf{x}$, for all $\mathbf{x} \in \mathbf{R}_+^N$, $\mathbf{r} \in \mathbf{R}_+^M$.

R.7 $R(\mathbf{x}, \mathbf{r})$ is nonnegative and nondecreasing in prices, for all $\mathbf{x} \in \mathbf{R}_+^N$, $\mathbf{r} \in \mathbf{R}_+^M$

R.8 $R(\mathbf{x}, \mathbf{r})$ is convex and continuous in prices, for all $\mathbf{x} \in \mathbf{R}_+^N$, $\mathbf{r} \in \mathbf{R}_+^M$.

The above properties follow the interpretations of the output set in Section 2.2. R.2 says it is homogeneous degree of one in output prices. R.3 is the weak disposability of inputs and R.3.S is strong disposability of inputs. These properties were proven by Shephard (1970, p. 229) and Färe (1988, pp. 92-95).

The discussions in Sections 3.2, 3.3, and this section show that revenue function properties imply properties for the output set and equivalent properties of the output distance function.

3.5 Duality between the Revenue Function and Output Distance Function

Following the Shephard (1953, 1970) and Färe (1988), recall from Section 2.3 that the output distance function is limited to $0 \leq D_o(\mathbf{x}, \mathbf{y}) \leq 1$ for an output correspondence $P(\mathbf{x})$ given the input vector. The duality between the output distance function and the revenue function is established through the output set. It is:

$$(3.5.1) \quad \mathbf{y} \in P(\mathbf{r}) \Leftrightarrow D_o(\mathbf{r}, \mathbf{y}) \leq 1.$$

This statement is proven in Färe and Primont (1995, pp. 15-16). It says both the output requirement set and the distance function characterize the firm's production technology. It is possible to define either the output distance function or revenue function. Therefore, the revenue function can also be considered a distance function:

$$(3.5.2) \quad R(\mathbf{x}, \mathbf{r}) = \max_y \{ \mathbf{r}\mathbf{y} : D_o(\mathbf{x}, \mathbf{y}) \leq 1 \}, \quad \mathbf{x} \in \mathbf{R}_+^N, \mathbf{r} \in \mathbf{R}_+^M.$$

The revenue function characterizes the firm's technology in quantity space.

The distance function is dual to the revenue function and can be defined in terms of the revenue function:

$$(3.5.3) \quad D_o(\mathbf{x}, \mathbf{y}) = \sup_r \{ \mathbf{r}\mathbf{y} : R(\mathbf{x}, \mathbf{r}) \leq 1 \}, \quad \mathbf{x} \in \mathbf{R}_+^N, \mathbf{y} \in \mathbf{R}_+^M.$$

The proof of (3.5.3) is given in Färe (1995, p. 50).

Equations (3.5.2) and (3.5.3) are dual to each other and reflect the relationship between the revenue function and the output distance function. In words, (3.5.2) says that if the revenue function is derived from the output distance function by maximizing all feasible output vectors, then the output distance function can be recovered from the revenue function. (3.5.3) says that if we start with a revenue function, we can derive the output distance function.

3.6 The Derived Shadow Price

The revenue maximization function is given by Färe et al. (1993):

$$(3.6.1) \quad RM(\mathbf{x}, \mathbf{r}) = \{ \mathbf{y} \in P(\mathbf{x}) : \mathbf{r}\mathbf{y} = R(\mathbf{x}, \mathbf{r}) \}.$$

where $R(\mathbf{x}, \mathbf{r})$ is a given revenue. This definition gives the maximum revenue when $\mathbf{r}\mathbf{y}$ is maximized equal to $R(\mathbf{x}, \mathbf{r})$ while the output set $P(\mathbf{x})$ is convex.

Maximizing the revenue function subject to the output distance function is a Lagrangian problem:

$$(3.6.2) \quad \Lambda(\mathbf{y}, \lambda) = \mathbf{r}\mathbf{y} + \lambda(D_o(\mathbf{x}, \mathbf{y}) - 1).$$

The first order condition for (3.6.2) is:

$$(3.6.3) \quad \begin{array}{ll} \text{(i)} & \mathbf{r} = \lambda \nabla_y D_o(\mathbf{x}, \mathbf{y}) \\ \text{(ii)} & D_o(\mathbf{x}, \mathbf{y}) = 1 \end{array}.$$

From (3.6.2) and (3.6.3), get:

$$(3.6.4) \quad \begin{aligned} \mathbf{r}\mathbf{y} &= \lambda \nabla_{\mathbf{y}} D_o(\mathbf{x}, \mathbf{y}) \mathbf{y} \\ &= \lambda D_o(\mathbf{x}, \mathbf{y}) \end{aligned}$$

Then,

$$(3.6.5) \quad \begin{aligned} \mathbf{r} \mathbf{y}(\mathbf{x}, \mathbf{r}) &= \lambda \\ \text{or} \quad R(\mathbf{x}, \mathbf{r}) &= \lambda. \end{aligned}$$

where $R(\mathbf{x}, \mathbf{r})$ is the maximum revenue with parameter $\mathbf{x}$ and $\mathbf{r}$. Equation (3.6.4) uses homogeneity in outputs to get the result. Through (3.6.3) (ii), (3.6.4) becomes (3.6.5), which says that at the optimum, the maximum revenue is equal to the Lagrangian multiplier.

Substituting (3.6.5) into (3.6.3) (i) gives:

$$(3.6.6) \quad \mathbf{r} = R(\mathbf{x}, \mathbf{r}) \nabla_{\mathbf{y}} D_o(\mathbf{x}, \mathbf{y}).$$

Here $\mathbf{r}$ is the shadow price vector for the output prices. Now let $\mathbf{r}^*(\mathbf{x}, \mathbf{r})$ be the maximizing output price vector, and use (3.5.3):

$$(3.6.7) \quad D_o(\mathbf{x}, \mathbf{y}) = \mathbf{r}^*(\mathbf{x}, \mathbf{r}) \mathbf{y}.$$

Applying Shephard's dual lemma to (3.6.7), yields:

$$(3.6.8) \quad \nabla_{\mathbf{y}} D_o(\mathbf{x}, \mathbf{y}) = \mathbf{r}^*(\mathbf{x}, \mathbf{r}).$$

Substituting (3.6.7) into (3.6.6) gives:

$$(3.6.9) \quad \mathbf{r} = R(\mathbf{x}, \mathbf{r}) \mathbf{r}^*(\mathbf{x}, \mathbf{r}).$$

(3.6.9) implies that $\mathbf{r}^*(\mathbf{x}, \mathbf{r})$ is the revenue deflated or normalized price vector. In (3.6.9) the undeflated shadow price $\mathbf{r}$ can be computed. If $R(\mathbf{x}, \mathbf{r})$ is known, the shadow price with respect to the specific output can be computed. However, $R(\mathbf{x}, \mathbf{r})$ depends on the shadow price vector, $\mathbf{r}$, which is the vector of unknown shadow prices. For more detailed reference see Färe (1988); Färe and Primont (1995); Färe et al. (1993); and Färe, Grosskopf, and Lovell (1994).

According to Färe (1993), one assumption must be made to calculate the undeflated shadow price. That is, one output price must be equal to its observed market price. Taking the m^{th} output, let its market price equal to its shadow price, r_m^o and (3.6.9) becomes:

$$(3.6.10) \quad R(x,y) = \frac{r_m^o}{r_{m'}^*}.$$

Combining (3.6.8), (3.6.9), and (3.6.10), for all $m' \neq m$, absolute shadow price:

$$(3.6.11) \quad \begin{aligned} r_{m'} &= R \cdot r^*(x, y) \\ &= R \cdot \frac{\partial D_o(x,y)}{\partial y_{m'}} \\ &= r_m^o \cdot \frac{\partial D_o(x,y)/\partial y_{m'}}{\partial D_o(x,y)/\partial y_m} \end{aligned}$$

Or

$$(3.6.12) \quad \frac{r_{m'}}{r_m^o} = \frac{\partial D_o(x,y)/\partial y_{m'}}{\partial D_o(x,y)/\partial y_m}.$$

(3.6.12) is the relative shadow price for two outputs and also shows the point where the price ratio of two outputs is equal to their marginal rate of transformation. The marginal rate of transformation of two outputs is depicted as the corresponding ratio of two distance function derivatives.

3.7 Equilibrium Model

This section presents the general equilibrium model in terms of the output distance function and the revenue function (Färe and Grosskopf, 1998).

In the production market, we know that the relative prices for two outputs in (3.6.12) are the ratio of two derivatives of the output distance function. If we assume these two outputs are produced by two different firms in competitive markets, (3.6.12) is the equilibrium condition for producers; the price ratio is equal to the marginal rate of the production transformation.

In the consumer goods market, we construct a consumer's utility function subject to the output distance function as:

$$(3.7.1) \quad \begin{aligned} &\text{Max } U(\mathbf{y}) \\ &\text{s.t. } D_o(\mathbf{x}, \mathbf{y}) \leq 1 \end{aligned}$$

where $\mathbf{y}$ is a vector of consumer goods produced by firms.

The utility maximization problem is the Lagrangian problem.

$$(3.7.2) \quad \Lambda(\mathbf{y}, \lambda) = u(\mathbf{y}) + \lambda(D_o(\mathbf{x}, \mathbf{y}) - 1) .$$

The first order conditions for (3.7.1) are:

$$(3.7.3) \quad \begin{aligned} (i) \quad &\nabla_y U(\mathbf{y}) = \lambda D_o(\mathbf{x}, \mathbf{y}) \\ (ii) \quad &D_o(\mathbf{x}, \mathbf{y}) = 1 \end{aligned}$$

Together with (3.6.12), we get the equilibrium conditions for both the production and consumer markets as:

$$(3.7.4) \quad \frac{\partial U(\mathbf{y})/\partial y_{m'}}{\partial U(\mathbf{y})/\partial y_m} = \frac{r_{m'}}{r_m} = \frac{\partial D_o(\mathbf{x}, \mathbf{y})/\partial y_{m'}}{\partial D_o(\mathbf{x}, \mathbf{y})/\partial y_m}$$

for all m and m' .

(3.7.4) can be interpreted as that, in equilibrium, the marginal rate of substitution of consumer goods is equal to marginal rate of production transformation through the market clearing prices. On the other hand, these shadow prices can be computed either from the producer or consumer model. These equilibriums only hold for competitive markets. This discussion provides a link to general equilibrium theory in terms of the distance function approach.

3.8 Summary

This chapter provides an outline of the theoretic model used for this study. The model characterizes the production technology of the firm. The technology is represented by an output

set, output requirement set, or technology set. For a specific production situation, the outputs are determined given the input set. The output distance function is defined over the output set to represent the specific technology and measure technical efficiency. The dual to the output distance function is the revenue function. The revenue function can be defined either by the output set or distance function, while the distance function is defined in terms of the revenue function. The duality between the output distance function and the revenue function provides a tool to derive the shadow prices of outputs. Finally the equilibrium model is presented in terms of the output distance function.

This model differs from traditional production modeling. It departs from single output production modeling and directly includes multiple outputs and multiple inputs. It is also different from conventional approaches to consumer theory or the utility theory to approach.

Chapter 4. Subvector Distance Function via Undesirable Outputs

4.1 Introduction

The previous chapter presented a model that characterizes a multi-output and multi-input production technology. This theoretical model can be used to analyze the production performance of the firm, measure its allocation efficiency, and derive the virtual prices of outputs. For this study, the focus is on the last of these and extends the model to consider some environmental “bads” produced in the production process and derives their shadow prices. For this purpose the output vector can be partitioned into good output and bad output subvectors that are treated asymmetrically in the model.

Färe, Grosskopf and Lovell (1994) use a subvector output distance function to analyze situations in which a subset of outputs are subject to scaling while other outputs are restricted or fixed. McFadden (1978) and Diewert (1981) considered the general case of production in restricted or regulated contexts. Turner (1994) uses an axiomatic approach to establish the properties of the subvector output distance and the revenue functions, the duality of the two functions, and then to derive the shadow prices for undesirable outputs. Following Turner’s approach, the subvector output set is defined in the Section 2, the subvector output distance function in the Section 3, and the subvector revenue function and the derived shadow prices of undesirable outputs in Section 4. In the case of the electric utility industry, the derived shadow prices of the undesirable outputs are used as the opportunity costs for the firm’s pollution control cost or the loss of the revenue under Title IV of the 1990 CAAA. They are also used as a tool to evaluate the performance of the electric plants in complying with the Phase I requirements from Title IV of the 1990 CAAA. In Section 5, the specific functional form for the distance function

and estimation methods are presented. Section 6 gives a brief comparison on output distance function and data envelopment analysis. The last section is the summary for the chapter.

4.2 The Restricted Output Requirement Sets

When the outputs are not all desirable, let the output vector $\mathbf{y}$ be partitioned as two subvectors, $\mathbf{y}_g$ and $\mathbf{y}_b$. Subvector $\mathbf{y}_g$ represents the desirable outputs and subvector $\mathbf{y}_b$ the environmental “bads.” The output space R_+^M is also partitioned as $\mathbf{y}_g = (y_{g1}, \dots, y_{gm'}) \in R_+^G$ and $\mathbf{y}_b = (y_{bm'+1}, \dots, y_{bm}) \in R_+^B$, two sub-output spaces. The input vector is defined the same as in the previous chapter (Färe, Grosskopf, and Lovell 1994; Färe and Primont 1995; and Turner 1994).

If we define undesirable outputs to be a fixed level as required by environmental regulations, e.g., the emission of sulfur dioxide is 2.5 pounds per mmBtu in Phase I and 1.25 pounds per mmBtu in Phase II, we can define RP as the restricted output set:

$$(4.2.1) \quad RP(\mathbf{x}, \bar{\mathbf{y}}_b) = \{\mathbf{y}_g : (\mathbf{y}_g, \bar{\mathbf{y}}_b) \in P(\mathbf{x})\}, \text{ for all } \mathbf{x} \in R_+^N, \bar{\mathbf{y}}_b \in R_+^B$$

From the definition, the restricted output set is defined as the set of desirable outputs, $\mathbf{y}_g$, producible given inputs and fixed undesirable outputs. This fully characterizes the firm's feasible technology. This definition differs from the general definition of output sets for two practical reasons. The first is that it does not require that environmental regulation force pollution to zero. The Earth has a certain assimilative ability to dilute or absorb pollutants and to restore balance in the ecosystem. The permitted level of pollution set by environmental regulations aims at a safety standard to protect human and animal life or specific ecosystems. Secondly, it is not economically efficient to reduce pollution to zero. It may be very costly because of the diminishing return rule for abatement costs to reach zero pollution. The economically efficient point of pollution reduction is where the marginal abatement cost is equal

to the marginal social benefit from pollution reduction. In most cases, the marginal social benefit is not easily observable; the allowable level is chosen to be both politically feasible and environmentally beneficial. Thus, a cost effectiveness approach is often used when pollution reductions are externally set.

The restricted output set $RP(\mathbf{x}, \bar{y}_b)$ also implies that the undesirable outputs cannot be disposed of freely. For example, electric utilities must take special measures to reduce emissions of SO_2 and NO_x to meet the requirements of Title IV of the 1990 CAAA in two Phases. The restricted output set is illustrated in figure 4.1.

Figure 4.1 The Restricted Output Requirement Set

Assuming y_b is an undesirable output and y_g is a desirable output in Figure 4.1, the region, $OABO$, is the unrestricted output set while the region, $OAA'\bar{y}_bO$ is the restricted output set, and $\bar{y}_b$ is the fixed emission level of SO_2 or NO_x for electric plants. The restricted output region, $OAA'\bar{y}_bO$, is of interest for this study. This is when the pollution level is at or below the level $\bar{y}_b$ and the slope of the production frontier curve is nonnegative, which implies the

undesirable output cannot be disposed of without incurring costs. In other words, the firm has to divert resources to control pollutants at the expense of reducing good output.

We can define the output set in terms of the restricted output set because both represent the firm's technology.

$$(4.2.2) \quad P(\mathbf{x}) = \{(\mathbf{y}_g, \mathbf{y}_b) : \mathbf{y}_g \in RP(\mathbf{x}, \bar{\mathbf{y}}_b)\}, \text{ for all } \mathbf{x} \in \mathbf{R}_+^N, \mathbf{y}_b \in \mathbf{R}_+^M$$

(4.2.1) and (4.2.2) are equivalent to

$$(4.2.3) \quad \mathbf{y}_g \in RP(\mathbf{x}, \bar{\mathbf{y}}_b) \Leftrightarrow (\mathbf{y}_g, \bar{\mathbf{y}}_b) \in P(\mathbf{x})$$

that means we can define that output set as the set of good and bad output vectors such that the good output vector is an element of the restricted output set or that the restricted output set is the set of the good output subvector, such that good and bad output subvectors are the elements of the output set, given the input vector and fixed level of undesirable outputs. Equation (4.2.3) shows the relationship needed to derive the properties for the restricted output set, $RP(\mathbf{x}, \bar{\mathbf{y}}_b)$, from the properties of the output set, $P(\mathbf{x})$. The properties for the restricted output set are summarized by Turner (1995); for the proofs of the properties, see Shephard (1970); or Färe (1988):

- RP.1 (a) $RP(0, \bar{\mathbf{y}}_b) = 0$ (b) $\mathbf{y}_g \notin RP(0, \bar{\mathbf{y}}_b), \mathbf{y}_g \geq 0$.
- RP.2 (a) $RP(\mathbf{x}, 0) = 0$ (b) $\mathbf{y}_g \notin RP(\mathbf{x}, 0), \mathbf{y}_g \geq 0$.
- RP.3 $RP(\mathbf{x}, \bar{\mathbf{y}}_b) \subseteq RP(\mathbf{x}', \bar{\mathbf{y}}_b)$, for all $\mathbf{x}, \mathbf{x}' \in \mathbf{R}_+^N$.
- RP.4 If $\mathbf{y}'_g \leq \mathbf{y}_g$ and $\mathbf{y}_g \in RP(\mathbf{x}, \bar{\mathbf{y}}_b)$, then $\mathbf{y}'_g \in RP(\mathbf{x}, \bar{\mathbf{y}}_b)$.
- RP.5 $RP(\mathbf{x}, \bar{\mathbf{y}}_b)$ is upper semi-continuous on $\mathbf{x}$, i.e. if $[\mathbf{x}^l \rightarrow \mathbf{x}^0, \bar{\mathbf{y}}_b^l \rightarrow \bar{\mathbf{y}}_b^0]$ and $\mathbf{y}_g^l \in RP(\mathbf{x}, \bar{\mathbf{y}}_b)$, for all l , then $\mathbf{y}_g^0 \in RP(\mathbf{x}, \bar{\mathbf{y}}_b)$.
- RP.6 $RP(\mathbf{x}, \bar{\mathbf{y}}_b)$ is convex for all $\mathbf{x} \in \mathbf{R}_+^N$ and $\bar{\mathbf{y}}_b \in \mathbf{R}_+^B$.

The interpretations of the properties of the restricted output set, except for RP. 2, are similar to those of in $P(\mathbf{x})$ in Section 3. 2. RP. 2 represents the relationship between the desirable

and the undesirable output, the nulljointness. If bad output is zero the good output is also zero (Turner 1994).

4.3 The Subvector Distance Function

The subvector output distance function is defined on the restricted output set (Turner 1994):

$$(4.3.1) \quad \begin{aligned} SD(\mathbf{x}, \mathbf{y}_g, \bar{\mathbf{y}}_b) &= \min\{\theta: (\mathbf{y}_g/\theta \in RP(\mathbf{x})\}, \\ \mathbf{x} \in \mathbf{R}_+^N, \mathbf{y}_g &\in \mathbf{R}_+^G, \bar{\mathbf{y}}_b \in \mathbf{R}_+^B. \end{aligned}$$

The subvector distance function, (4.3.1) is interpreted as the desired output scaled by the maximum scalar, $\left(\frac{1}{\theta}\right)$, on the production frontier while the undesirable output is fixed and not scaled, given the inputs. This function is defined as the minimum value θ or maximum scalar value $\left(\frac{1}{\theta}\right)$ to feasibly expand the desirable output, holding the undesirable outputs and inputs fixed.

Alternatively, the subvector output distance function can be given in terms of the output correspondence set:

$$(4.3.2) \quad \begin{aligned} SD(\mathbf{x}, \mathbf{y}_g, \bar{\mathbf{y}}_b) &= \min\{\theta: \left(\frac{1}{\theta}, \bar{\mathbf{y}}_b\right) \in P(\mathbf{x})\} \\ \mathbf{x} \in \mathbf{R}_+^N, \mathbf{y}_g &\in \mathbf{R}_+^G, \bar{\mathbf{y}}_b \in \mathbf{R}_+^B. \end{aligned}$$

The properties of the subvector distance function inherit its properties from the restricted output requirement set (Turner 1994). They are:

- SD.1* (a) $SD(\mathbf{x}, 0, \bar{\mathbf{y}}_b) = 0$, for all $\mathbf{x} \in \mathbf{R}_+^N, \bar{\mathbf{y}}_b \in \mathbf{R}_+^B$;
 (b) $SD(\mathbf{x}, \mathbf{y}_g, 0) = 0$, for all $\mathbf{x} \in \mathbf{R}_+^N, \mathbf{y}_g \in \mathbf{R}_+^G$;
 (c) $SD(0, \mathbf{y}_g, \bar{\mathbf{y}}_b) = +\infty$, for all $\mathbf{y}_g \in \mathbf{R}_+^G, \bar{\mathbf{y}}_b \in \mathbf{R}_+^B$;
 (d) $0 < SD(\mathbf{x}, \mathbf{y}_g, \bar{\mathbf{y}}_b) < +\infty$, for all $\mathbf{x} \in \mathbf{R}_+^N, \mathbf{y}_g \in \mathbf{R}_+^G, \bar{\mathbf{y}}_b \in \mathbf{R}_+^B$.
SD.2 $SD(\mathbf{x}, \lambda \mathbf{y}_g, \bar{\mathbf{y}}_b) = \lambda SD(\mathbf{x}, \mathbf{y}_g, \bar{\mathbf{y}}_b)$, for all $\mathbf{x} \in \mathbf{R}_+^N, \bar{\mathbf{y}}_b \in \mathbf{R}_+^B$.
SD.3 $SD(\mathbf{x}, \mathbf{y}_{g1} + \mathbf{y}_{g2}, \bar{\mathbf{y}}_b) \leq SD(\mathbf{x}, \mathbf{y}_{g1}, \bar{\mathbf{y}}_b) + SD(\mathbf{x}, \mathbf{y}_{g2}, \bar{\mathbf{y}}_b)$, for all $\mathbf{x} \in \mathbf{R}_+^N$,
 $\mathbf{y}_{g1}, \mathbf{y}_{g2} \in \mathbf{R}_+^G, \bar{\mathbf{y}}_b \in \mathbf{R}_+^B$.

- SD.4* $SD(\mathbf{x}, \mathbf{y}_g, \bar{\mathbf{y}}_b) \leq SD(\mathbf{x}, \mathbf{y}'_g, \bar{\mathbf{y}}_b)$, if $\mathbf{y}_g \leq \mathbf{y}'_g$, for all $\mathbf{x} \in \mathbf{R}^N_+$, $\bar{\mathbf{y}}_b \in \mathbf{R}^B_+$.
- SD.5* $SD(\mathbf{x}, \mathbf{y}_g, \bar{\mathbf{y}}_b)$ is convex in $\mathbf{y}_g \in \mathbf{R}^G_+$, for all $\mathbf{x} \in \mathbf{R}^N_+$, $\bar{\mathbf{y}}_b \in \mathbf{R}^B_+$.
- SD.6* $SD(\mathbf{x}, \mathbf{y}_g, \bar{\mathbf{y}}_b)$ is continuous in $\mathbf{y}_g \in \mathbf{R}^G_+$, for all $\mathbf{x} \in \mathbf{R}^N_+$, $\bar{\mathbf{y}}_b \in \mathbf{R}^B_+$.
- SD.7* $SD(\mathbf{x}', \mathbf{y}_g, \bar{\mathbf{y}}_b) \geq SD(\mathbf{x}, \mathbf{y}_g, \bar{\mathbf{y}}_b)$, if $\mathbf{x} \geq \mathbf{x}'$, for all $\mathbf{y}_g \in \mathbf{R}^G_+$, $\bar{\mathbf{y}}_b \in \mathbf{R}^B_+$.
- SD.8* $SD(\mathbf{x}, \lambda \mathbf{y}_g, \bar{\mathbf{y}}_b)$ is lower semicontinuous on $\mathbf{x} \in \mathbf{R}^N_+$, for all $\mathbf{y}_g \in \mathbf{R}^G_+$, $\bar{\mathbf{y}}_b \in \mathbf{R}^B_+$.

These properties are presented by Turner (1994); for proofs see Shephard (1970, p. 208) or Färe (1988) with modifications in terms of subvectors.

The subvector distance function is in the range of values, (0, 1), for this study. It can be proven by the definition of the restricted output set. The important property of the subvector distance function is that the desirable outputs can be expanded while the undesirable outputs are fixed. The question here is, is this property characterized in the production process? It can be motivated by installation of a scrubber in an electric plant (unit). When the scrubber is installed in the plant, SO₂ emissions are reduced. If a fixed emission level is required by environmental law, this needs to be imposed by an additional constraint on the production process.

4.4 The Subvector Revenue Function

As the dual to the subvector distance function, the subvector revenue function is defined by partitioning the output price vector into two subvectors, $\mathbf{r}_g = (r_{g1}, \dots, r_{gm'}) \in \mathbf{R}^G_{++}$ and

$\mathbf{r}_b = (r_{b1}, \dots, r_{bm''}) \in \mathbf{R}^B_+$ where $\mathbf{r}_g$ is the strictly positive price subvector for desirable outputs, and $\mathbf{r}_b$ is a nonpositive price subvector for undesirable outputs, i.e., the prices for the desirable outputs are strictly positive while the prices for undesirable outputs are negative or zero. In most cases, undesirable outputs do not have market prices so shadow prices are computed as approximations to market prices. Since Title IV of the CAAA of 1990 establishes an allowance trading market for SO₂, the derived shadow prices can be an evaluation tool for the firm. A

comparison of the market trading price to the shadow price can help identify cost effective approaches to pollution control – meeting the restriction or buying permits.

If the undesirable output price is negative, pollution control is not free as discussed in the previous chapter. This follows from the weak disposability restriction imposed on the distance and revenue functions. If the undesirable output price is zero, it may imply that the environmental regulation is not binding or has been reduced as a consequences of other pollution controls. That is, if the production process generates several pollutants, this effect might exist, e.g., electricity production creates multiple pollutants, SO₂, NO_x, and CO₂. Pollution controls for SO₂ might have reduced the emissions of NO_x or CO₂.

Now the subvector revenue function is defined as (Turner, 1994):

$$(4.4.1) \quad \begin{aligned} SR(\mathbf{x}, \mathbf{r}_g, \bar{\mathbf{y}}_b) &= \max_{\mathbf{y}_g} \{ \mathbf{r}_g \cdot \mathbf{y}_g : \mathbf{y}_g \in RP(\mathbf{x}, \bar{\mathbf{y}}_b) \}, \\ \text{for all } \mathbf{x} &\in \mathbf{R}_+^N, \mathbf{r}_g \in \mathbf{R}_{++}^G, \bar{\mathbf{y}}_b \in \mathbf{R}_+^B \end{aligned}$$

(4.4.1) defines the subvector revenue in terms of the restricted output requirement set using a general form, $P(\mathbf{x})$, (Färe, Grosskopf and Lovell 1994):

$$(4.4.2) \quad \begin{aligned} SR(\mathbf{x}, \mathbf{r}_g, \bar{\mathbf{y}}_b) &= \max_{\mathbf{y}_g} \{ \mathbf{r}_g \cdot \mathbf{y}_g : (\mathbf{y}_g, \bar{\mathbf{y}}_b) \in P(\mathbf{x}) \}, \\ \text{for all } \mathbf{x} &\in \mathbf{R}_+^N, \mathbf{r}_g \in \mathbf{R}_{++}^G, \bar{\mathbf{y}}_b \in \mathbf{R}_+^B \end{aligned}$$

The subvector revenue function is the maximum variable revenue that can be achieved given the level of inputs and fixed amount of the undesirable outputs. The properties of the subvector revenue function have properties similar to the revenue function. For details see Turner (1995) and for the proofs see Shephard (1970, 229-230). These properties indicate that the subvector revenue function characterizes the firm's technology and inherits the parent's

technology.⁹ The duality between the subvector output distance function and the subvector revenue function is given by

$$(4.4.3) \quad \begin{aligned} \text{SR}(\mathbf{x}, \mathbf{r}_g, \bar{\mathbf{y}}_b) &= \max_{\mathbf{y}_g} \{ \mathbf{r}_g \cdot \mathbf{y}_g : \text{SD}(\mathbf{x}, \mathbf{y}_g, \bar{\mathbf{y}}_b) \leq 1 \}, \\ \text{for all } \mathbf{x} &\in \mathbf{R}_+^N, \mathbf{r}_g \in \mathbf{R}_{++}^G, \bar{\mathbf{y}}_b \in \mathbf{R}_+^B. \end{aligned}$$

This duality can be presented and proven by the relationship (Turner, 1995) from (2. 5. 1)

$$(4.4.4) \quad \mathbf{y}_g \in \text{RP}(\mathbf{x}, \bar{\mathbf{y}}_b) \Leftrightarrow \text{SD}(\mathbf{x}, \mathbf{y}_g, \bar{\mathbf{y}}_b) \leq 1$$

4.5. The Absolute Shadow Price for the Undesirable Output

There are two ways to derive the absolute shadow prices for undesirable outputs. Both are presented here, first the total revenue approach, then the duality approach. Define the total revenue function including both desirable and undesirable outputs as:

$$(4.5.1) \quad \begin{aligned} \text{TR}(\mathbf{x}, \mathbf{r}_g, \mathbf{r}_b) &= \max_{\mathbf{y}_g} \{ (\mathbf{r}_g \cdot \mathbf{y}_g + \mathbf{r}_b \cdot \mathbf{y}_b) : (\mathbf{y}_g, \mathbf{y}_b) \in P(\mathbf{x}) \}, \\ \text{for all } \mathbf{x} &\in \mathbf{R}_+^N, \mathbf{y}_g \in \mathbf{R}_+^G, \mathbf{y}_b \in \mathbf{R}_+^B. \end{aligned}$$

The output vector is partitioned into a good output subvector and bad output subvector, $\mathbf{y} \rightarrow (\mathbf{y}_g, \mathbf{y}_b)$, and the output price vector into two corresponding subvectors, $\mathbf{r} \rightarrow (\mathbf{r}_g, \mathbf{r}_b)$, where $\mathbf{r}_b \leq 0$. Total revenue is maximized over the desirable outputs, $\mathbf{y}_g$, at given inputs and undesirable outputs.

The Lagrangian problem that maximizes feasible revenue is:

$$(4.5.2) \quad L = \mathbf{r}_g \cdot \mathbf{y}_g + \mathbf{r}_b \cdot \mathbf{y}_b + \lambda(\text{SD}(\mathbf{x}, \mathbf{y}_g, \mathbf{y}_b) - 1)$$

where $\mathbf{r}_g$ and $\mathbf{r}_b$ are the absolute shadow prices of the desirable and undesirable outputs.

⁹ Parent's technology refers to the output requirement set before the partition into two subvectors, the desirable output subvector, $\mathbf{r}_g$, and undesirable output subvector, $\mathbf{r}_b$.

Assuming that the subvector output distance function is differentiable, we derive absolute shadow prices of both desirable and undesirable outputs. The first order conditions of (4.5.2) are:

$$(4.5.3) \quad \begin{aligned} (i) \quad \mathbf{r}_g &= -\lambda \nabla_{y_g} SD(\mathbf{x}, \mathbf{y}_g, \mathbf{y}_b) \\ (ii) \quad \mathbf{r}_b &= -\lambda \nabla_{y_b} SD(\mathbf{x}, \mathbf{y}_g, \mathbf{y}_b) \\ (iii) \quad SD(\mathbf{x}, \mathbf{y}_g, \mathbf{y}_b) &= 1. \end{aligned}$$

solving (i) and (ii) in (4.5.3) for λ gives:

$$(4.5.4) \quad -\lambda = \frac{\mathbf{r}_g}{\nabla_{y_g} SD(\mathbf{x}, \mathbf{y}_g, \mathbf{y}_b)} = \frac{\mathbf{r}_b}{\nabla_{y_b} SD(\mathbf{x}, \mathbf{y}_g, \mathbf{y}_b)}$$

where λ is a vector whose elements correspond to the values associated with a particular output, y_g or y_b . Solve (4.5.4) for $\mathbf{r}_b$, the shadow prices of the undesirable output:

$$(4.5.5) \quad \mathbf{r}_b = \mathbf{r}_g \frac{\nabla_{y_b} SD(\mathbf{x}, \mathbf{y}_g, \mathbf{y}_b)}{\nabla_{y_g} SD(\mathbf{x}, \mathbf{y}_g, \mathbf{y}_b)}.$$

Note that the ratio, $\frac{\nabla_{y_b} SD(\mathbf{x}, \mathbf{y}_g, \mathbf{y}_b)}{\nabla_{y_g} SD(\mathbf{x}, \mathbf{y}_g, \mathbf{y}_b)}$ is the marginal rate of transformation between the

desirable output and undesirable output, the slope of the production frontier, at the point on the frontier determined by the solution of the subvector distance function.

Now assume that the shadow price of desirable output, $\mathbf{r}_g$, is its observable market price, $\mathbf{r}_g^o$, as in (3. 6). Calculate the absolute shadow prices for undesirable outputs from (4.5.5) as:

$$(4.5.5.a) \quad \mathbf{r}_b = \mathbf{r}_g^o \frac{\nabla_{y_b} SD(\mathbf{x}, \mathbf{y}_g, \mathbf{y}_b)}{\nabla_{y_g} SD(\mathbf{x}, \mathbf{y}_g, \mathbf{y}_b)}.$$

4.6 Specification of a Production Frontier for the Output Distance Function

4.6.1 Choice of Output Distance Function

Now consider the specific functional form to capture the firm's production technology required by the output distance function from a given set of observations. The choices for

empirical work must come from available models that deal with production that generate environmental bads and choices of estimation methods for distance function approaches.

The choices for functional form include the Cobb-Douglas function, constant elasticity function, and the translog production function. The criteria for the choice of production frontier in empirical work include (1) the functional form exhibits good behavior globally, and (2) the functional form has sufficient flexibility to reflect complex economic phenomena. The former property often exists in simple production frontier functions, e.g., the Cobb-Douglas and Constant Elasticity production frontiers. These functions satisfy certain regularity conditions globally but lack the flexibility needed to model complex or sophisticated production technologies. The Cobb-Douglas production frontier imposes a unitary elasticity of substitution and transformation (Christensen, Jorgenson, and Lau 1973; Denny and May 1977). This property is more restrictive when some output is an externality (Pittman 1983). The second criterion requires that the function be able to model complex production technology (e.g., the translog production function). Its very flexibility, however, prevents globally good behavior (Guilkey, Lovell, and Sickles 1983). However, the translog production function is a local second-order approximation to a general form (Christensen, Jorgenson and Lau 1973).

Among these choices, the translog production frontier is most often chosen. Compared to Cobb-Douglas and Constant Elasticity production functions, a translog production function has several favorable characteristics for applied analysis. First, it can model a multi-output and multi-input production frontier while the Cobb-Douglas and Constant Elasticity production functions are restricted to a single output (Christensen, Jorgenson and Lau 1973). Pittman (1979, 1981) modeled two outputs (one good output, paper, and one bad output, water pollution) with five inputs in his research on 30 Wisconsin and Michigan paper mills using a profit

maximization approach with a translog production function. He incorporated pollution control into his model as a constraint. The bad output, water pollution, is actually treated as an input in his model, not an output. Such treatment has a direct flaw, as he pointed out, that a truly ‘general’ joint output production function would be of the form $f(y_1, y_2, x_1, \dots, x_i) = 0$, where y_1 as good output, y_2 as a bad output, and $x_1, \dots, x_i$ as inputs), which was not used in his study (Pittman 1981, p5). The general joint output production function he meant is the production frontier function. Färe, Grosskopf, Lovell and Yaisawarng (1993) used the same data set as in Pittman’s research but modeled five outputs (one good output, paper, and decomposed four water pollutants for discharged wastewater from paper mills). Swinton and Coggings (1996) and Swinton (1998) modeled electricity plants with two outputs (electricity and SO_2) and four inputs (the formerly cited research for Wisconsin plants in 1996) and five inputs (the latter research for Wisconsin, Illinois, and Minnesota in 1998). Hetemäki (1996) in her dissertation used the translog production function frontier for her model. These studies chose the translog production frontier over other production function forms for flexibility to model multiple outputs and because it does not impose unity of elasticity of substitution or transformation on either input-input, output-output, or input-output relationships.

Second, the translog function allows the inclusion of undesirable outputs in the model. This favorable feature is self-explanatory from the previous feature because the Cobb-Douglas or Constant Elasticity production functions are restricted to a single output (Pittman 1979).

Third, the translog does not impose constant elasticity of substitution and transformation on inputs and outputs; for more than one product or two input factors in the production, the “constancy of elasticity is highly restrictive” (Christensen, Jorgenson and Lau 1973). Cobb-Douglas or constant elasticity functions require constant elasticity.

Finally, when the restrictions imposed on the production function are based on economic theory and the restriction imposed by the specific functional forms may be incorrect, the translog function should be applied in terms of the absence of correct *a priori* information on the specific functional form (Christensen, Jorgenson and Lau 1973). Therefore, the translog function is a more suitable, flexible functional form that provides “a local second-order approximation to any production frontier” and “permit a greater variety of substitution and transformation patterns than frontier based on constant elasticities of substitution and transformation.” (Christensen, Jorgenson, and Lau 1973).

Empirical estimation methods used in distance function estimation include mathematical programming and econometric methods. Each method has its advantages and disadvantages. Econometric methods for the distance function approach takes measurement and other errors into account when empirical estimation is performed. They also allow for statistical inferences, which is a favorable characteristic when compared with mathematical programming (Hetemäki 1994a, b, 1995a, b, 1996; Groskopf and Hayes 1997; Hadley 1998). Hetemäki applied econometric methods to the output distance function for her Finnish paper mill data (1994a, 1994b; 1995a, 1995b; 1996). She uses a panel data set and specifies a two-factor random effects model that allows for constant terms that are randomly distributed across cross-sectional plants and time. She employs strong disposability for all outputs and does not constrain the price of the undesirable output to be negative (1994a, b). Her estimates of absolute shadow prices¹⁰ on all outputs are positive, indicating that increasing pollution would add to revenue, and are typically small for each plant. She attributes this finding to increased productivity and/or modernization

¹⁰ Absolute shadow prices are used to distinguish them from the relative prices that are the ratio of two output prices for the derivation of the shadow price of one output.

caused by firms taking measures to satisfy environmental regulations. Specifically, it implies that the paper mill recycle the waste water to reuse in the plant.

A basic problem, however, with this estimation method is that the distance measure as a dependent variable is not observable even though it takes values from zero to one ($0 \leq D \leq 1$). If one sets the distance value to 1 (that is, every observation is assumed to lie on the production frontier), then all the dependent variable values are invariant, an intercept term can not be estimated, and the OLS estimate is biased (Hetemäki 1994a, b; 1995a, b; 1996). If the distance function is estimated in logarithm form, then all distance measures are zero (e.g., $D = \log 1 = 0$) for those on the production frontier. The residuals are one sided. Lovell et al. (1990), Grosskopf et al. (1996) propose normalizing the dependent variable by one of the outputs in the model by using the property that the output distance function is homogeneous of degree +1 in outputs. Thus, for each observation used in estimating the distance function, a value that is unique to that observation can be used to multiply all output values on the right-hand side and the value of the distance function on the left-hand side. But the choice is arbitrary and different estimated results may be obtained when a different output value is used to normalize in estimation process.

The second criticism for econometric estimation is the assumption that all outputs are weakly disposable. It means that the desirable output cannot be freely taken by anyone and would seem to have important implications for the positive absolute shadow prices of some pollutants, calculated as the ratio of the dual values of pulp and the pollution outputs. Also, Hetemäki maximizes the output distance function over all outputs, good and bad. It is questionable what the appropriate maximization problem is when some outputs are undesirable. The last problem for her studies is that the error measures for the distance function following the definition are one sided, either 1 or less than 1, or either 0 or less than 0 if the values are taken in

logarithms. The fourth disadvantage is that the estimates from the econometric method cannot give efficiency measures or productivity changes. Thus, the econometric model estimation is not appealing, at least to date.

The empirical model for the output distance function approach that has been most commonly used is mathematical programming. Empirical research includes Färe et al. (1989, 1993); Yaisawrng (1989); Turner (1995); Hetemäki, (1996); Coggings and Swinton (1996); and Swinton (1998, 2002, 2004). Programming approaches can be further classified as either nonparametric and parametric programming. Nonparametric programming is simply to set up the optimization problem under a set of constraints without specifying a functional form. This method is the same as special linear programming used in activity analysis or data envelopment analysis. What is used in activity analysis is a piece-wise linear programming algorithm that estimates a performance efficiency frontier given the observed data set. Applications of this type of linear programming estimation can be seen in Färe et al. (1989); Yaisawrang and Klein (1994); Färe, Grosskopf, and Lovell (1994); Shaik (1998); Tyteca (1997); Yaisawrng (1989); Färe and Primont (1995); and Turner (1995).

Estimation with nonparametric linear programming for a distance function can measure production efficiency. The first such study was Färe, Grosskopf and Lovell (1985) and the book by Färe, Grosskopf, and Lovell (1994). In the book they give a number of numerical examples of different types of linear programming computations for distance functions. Färe et al. (1989), Yaisawrang and Klein (1994), Yaisawrang (1989), Hakuni (1994), and Brannlund et al. (1995) are examples of this approach using the weak disposability assumption to compute the impact of environmental regulations on production efficiency. These studies are based on the idea that one

computes the linear programming problem and, thereby, production efficiency under two sets of efficiency scores, which is then interpreted as the measure of pollution control or regulation.

The more popular parametric mathematical programming approach employed for distance function estimation is the translog function. The translog function was first applied to shadow price estimation for pollutants by Pittman (1981). He specified the firm's production function as a transcendental function and incorporated environmental regulations as constraints directly in the function. After the estimation of the translog function as revenue maximization, the shadow prices for pollutants are derived as Lagrange coefficients. The output distance function adopting the translog function form was first used by Färe et al. (1993). Färe et al. adopted the nonlinear programming estimation method proposed by Aigner and Chu (1968) to estimate the translog output distance function. The study showed the estimates of shadow prices for four undesirable outputs (BOD, TSS, PART, and SOX¹¹) for Wisconsin paper mills. Work on parametric mathematical programming is also used in Coggings and Swinton (1996), Swinton (1998, 2002, 2004), and Hetemäki (1994a, b; 1995a, b). The translog function has desirable properties, including homogeneity of degree one in outputs, symmetry for second order cross products between inputs and outputs, and allows nonnegative prices for desirable outputs, and nonpositive prices for undesirable outputs. These properties will be covered in more detail in the following section.

4.6.2 Translog Production Frontier Function

The general translog production frontier was first proposed by Christensen, Jorgenson and Lau (1973). They called it a transcendental logarithmic production frontier and its dual, the price frontier. This production frontier provides the flexibility to estimate multi-output and multi-

¹¹ BOD represents biological oxygen demand, TSS total suspended solids, PART particulate, and SOX sulfur oxides.

input production technologies for a wide variety of production processes. It also possesses desirable properties on equality, normalization, and symmetry in parameters. The tradeoff for using a translog production frontier instead of the Cobb-Douglas production frontier is that it may satisfy the desired regularity conditions over a range of observations that contain or intersect the set of sample observations even though it is not globally well behaved. The translog production frontier takes the following form:

$$\begin{aligned}
 \ln(F(x, y) + 1) = & \alpha_0 + \sum_{i=1}^M \alpha_i \ln y_i + \sum_{j=1}^N \beta_j \ln x_j + \frac{1}{2} \sum_{i=1}^M \sum_{i'=1}^M \alpha_{ii'} \ln y_i \ln y_{i'} \\
 & + \frac{1}{2} \sum_{j=1}^N \sum_{j'=1}^N \beta_{jj'} \ln x_j \ln x_{j'} + \frac{1}{2} \sum_{j=1}^N \sum_{i=1}^M \gamma_{ji} \ln x_j \ln y_i
 \end{aligned}$$

(4.6.1)

$$\begin{aligned}
 \text{(i)} \quad & \sum_{i=1}^M \alpha_i = 1; \\
 \text{(ii)} \quad & \sum_{i=1}^M \sum_{i'=1}^M \alpha_{ii'} = 0; \\
 \text{(iii)} \quad & \sum_{j=1}^N \sum_{i=1}^M \gamma_{ji} = 0; \\
 \text{(iv)} \quad & \alpha_{ii'} = \alpha_{i'i}, \text{ and } \beta_{jj'} = \beta_{j'j} \text{ for } i \neq i' \text{ and } j \neq j'.
 \end{aligned}$$

In (4.6.1), $\ln(F(x, y) + 1)$ is the logarithm of the production frontier plus one, when the production function is frontier $F(x, y) = 0$. The unity term avoids the logarithm of zero problem. $\ln(F(x, y) + 1) = 0$ if the logarithm production function is a frontier point. In equation (4.6.1), x and y are the input and output vector, respectively, for a specific production process. The properties of a translog production frontier are (4.6.1(i)-(iv)). (4.6.1(i)) implies homogeneous degree of one in output, and (4.6.1(ii)-(iii)) impose the homogeneous of degree zero restriction on the second-order output terms and cross interactive terms between outputs and inputs, respectively, while (4.6.1(iv)) requires symmetry of both second-order output and input terms.

When the output distance function approach is applied, it not only measures a single firm's production frontier, but a set of production firms used to construct an industry production

frontier. Each firm included in the data set is placed either on or inside the industry frontier. Production efficiency can be measured or compared in this context. This is also called a data envelopment analysis in the operations research and management fields. In Shephard and Färe's theoretical framework, the output distance function approach provides an analytic instrument to focus on the undesirable output generated through the good output. Therefore, the subvector distance function laid out here can be written as:

$$\begin{aligned}
 \ln SD_o(x, y_g, y_b) = & \alpha_0 + \sum_{g=1}^{M'} \alpha_g \ln y_g + \sum_{b=M'+1}^M \alpha_b \ln y_b + \sum_{n=1}^N \beta_n \ln x_n \\
 & + \frac{1}{2} \sum_{g=1}^{M'} \sum_{g'=1}^{M'} \alpha_{gg'} \ln y_g \ln y_{g'} + \frac{1}{2} \sum_{b=M'+1}^M \sum_{b'=M'+1}^M \alpha_{bb'} \ln y_b \ln y_{b'} \\
 & + \frac{1}{2} \sum_{n=1}^N \sum_{n'=1}^N \beta_{nn'} \ln x_n \ln x_{n'} + \frac{1}{2} \sum_{n=1}^N \sum_{g=1}^{M'} \gamma_{ng} \ln x_n \ln y_g \\
 & + \frac{1}{2} \sum_{n=1}^N \sum_{b=M'+1}^M \gamma_{nb} \ln x_n \ln y_b
 \end{aligned}
 \tag{4.6.2}$$

- (i) $\ln SD_o(x, y_g, y_b) < 0$;
- (ii) $\sum_{g=1}^{M'} \alpha_g + \sum_{b=M'+1}^M \alpha_b = 1$;
- (iii) $\sum_{g=1}^{M'} \sum_{g'=1}^{M'} \alpha_{gg'} + \sum_{b=M'+1}^M \sum_{b'=M'+1}^M \alpha_{bb'} + \sum_{g=1}^{M'} \sum_{b=M'+1}^M \alpha_{gb} = 0$;
- (iv) $\sum_{n=1}^N \sum_{g=1}^{M'} \gamma_{ng} + \sum_{n=1}^N \sum_{b=M'+1}^M \gamma_{nb} = 0$;
- (v) $\alpha_{gg''} = \alpha_{g'g}$, $\alpha_{bb''} = \alpha_{b'b}$, $\alpha_{gb} = \alpha_{g'b}$, and $\beta_{nn'} = \beta_{n'n}$
for $g \neq g'$ and $b \neq b'$, and $n \neq n'$.

where $0 < SD_o(x, y_g, y_b) \leq 1$, because it takes the logarithm, instead of $0 \leq SD_o(x, y_g, y_b) \leq 1$, the domain subvector output distance function.

The empirical estimation model can be further specified as:

$$\begin{aligned}
(4.6.2) \quad & \min \sum_{k=1}^K [\ln 1 - \ln SD_o(x^k, y_g^k, y_b^k)] \\
& (i) \quad \ln SD_o(x^k, y_g^k, y_b^k) \leq 0, \quad k = 1, \dots, K, \\
& (ii) \quad \frac{\partial \ln SD_o(x^k, y_g^k, y_b^k)}{\partial \ln y_g^k} \geq 0, \quad g = 1, \dots, m', \\
& (iii) \quad \frac{\partial \ln SD_o(x^k, y_g^k, y_b^k)}{\partial \ln y_b^k} \leq 0, \quad b = m' + 1, \dots, m,
\end{aligned}$$

where $k=1, \dots, K$ indexes individual observations and $\ln SD_o(x, y_g, y_b)$ is the explicit functional form as in (4.6.2). The objective function minimizes the sum of the deviations of individual observations from the frontier of the technology. Since the distance function takes a value of less than or equal to one, the natural logarithm of $SD_o(x^k, y_g^k, y_b^k)$ is less than or equal to zero.

The condition (4.6.3. i) sets the value range for the natural logarithmic output distance function. (4.6.3. ii) imposes strong disposability on the desirable output, while (4.6.3. iii) imposes weak disposability on undesirable outputs. Equations (4.6.2) and (4.6.3) together are the empirical model for this study. Efficiency in this study is a relative efficiency as the shadow price of pollutant is evaluated.

The computation of (4.6.2) and (4.6.3) provides the parameters for an empirical industrial output distance function (given the observations in the data set). The parameters are used to compute each firm's output distance score in (4.6.2). The estimates of the shadow values for each undesirable output are then calculated. This provides measures of the output transformation rate, the marginal transformation rate of two outputs, e.g., between electricity and SO_2 , electricity and NO_x , electricity and CO_2 . These rates are calculated as

$(\partial D_o / \partial y_1) / (\partial D_o / \partial y_2) = \partial y_2 / \partial y_1$. The economic interpretation for the shadow values may be opportunity costs for abatement options, the forgone revenue for the firm under environmental regulation, or the firm's individual abatement costs. The marginal rate of transformation is

directly interpreted as the sacrifice of the desirable output in order to meet the environmental regulation.

4.6.3 Comparison and Connections between Output Distance Function and Data Envelopment Analysis

It is worthwhile to discuss a concept which is very closely related to the distance function, data envelopment analysis (DEA). There are interesting relationships between the two. The distance function approach is rooted in Shephard's activity/productivity analysis (Shephard 1970). The terms activity analysis, productivity analysis, and distance function analysis are interchangeable. Data envelopment analysis model was developed by Charnes, Cooper, and Rhodes (CCR) in 1978. DEA means that given inputs, the analysis uses the observed data to maximize an approximate envelop curve (equivalent to the production frontier in this study), then measure the difference between each observed activity/point and the estimated envelop curve. The concept is very similar to the output distance function approach, but productivity analysis and DEA were long considered different approaches. Hetemäki (1996, p. 30) compares the two and concludes that the output distance function approach is superior to DEA. In her words: "...distance functions are firmly based on neoclassical production theory, whereas no such theory lies behind the DEA." Thus, in using DEA, one does not define the production technology. Moreover, there is no parametric functional representation of DEA. While her claim may be true on theoretical grounds, the methods are often identical in practice. This latter connection is identified by Färe and Grosskopf (2002) where they prove the link between DEA and the distance function¹².

¹² Färe and Grosskopf called it CRC instead of DEA and distance function in their work. CRC represents Charnes, Cooper and Rhodes (1978) and they termed data envelopment analysis while Shephard (1970) introduced the distance function approach. In this article they prove the connection between DEA and the input distance function,

Approximate DEA curve are piece-wise linear. Thus, the common estimating method of DEA is linear programming, a nonparametric method. Since DEA is originally and widely used in the management field and operations research, many think they are the same as the distance function in estimating the production frontier and efficiency as production activity analysis (Seiford and Thrall 1990; Charnes, Cooper, and Seiford 1985). The connection was first pointed out by Grosskopf (1986) for the input output distance function. The relationship includes, first, that the two approaches have a theoretical relationship through duality. DEA measures Farrell's production efficiency using linear programming and its dual is a cost function, while the input distance function is the reciprocal of Farrell's efficiency measure (see Chapter 3, Sections 2 and 3) and the cost function is dual to the distance function.¹³ Second, the regularity conditions stated in distance function are also met by DEA (Grosskopf, 1986).¹⁴ Third, the empirical formulations of both approaches are related. In theory, Shephard uses linear programming to prove the existence of the derived output price from the cost function as the dual. DEA models form the linear programming model following Shephard's cost function (even though they don't make the direct connection) and give the dual to the cost function, output pricing model, which determines a shadow price vector for outputs and inputs. The latter structure is similar to the DEA input oriented dual model. Their conclusion is that the "two approaches coincide" (p. 41) by appropriate normalization of Shephard's output price model.

As for the two approaches, from the discussions above several differences are obvious.

First, DEA and the distance function were developed in different fields of application. The

but the same relationship should exist between output distance function and DEA as well. This may require further study.

¹³ As they point out "It is of interest to note that Shephard never formulated a linear programming model for directly estimating the input distance function. Nor did Farrell formulate his efficiency measure as a linear programming problem in his 1957 article." P.43.

¹⁴ The regularity conditions are (1) the technology is a closed set; (2) outputs cannot be produced without inputs; (3) free or strong disposability of both inputs and outputs if they both are desirable; and (4) the input requirement set is convex for each output vector.

former started by representing Farrell's efficiency measure while the latter started as a cost function. Second, the applications, at least at the early stage, were different; the former employed in public services and activity/management evaluations or decision-making units (especially for service sections, bank, school, hospital and governmental agencies) while the latter laid the foundation for measuring efficiency and deriving the shadow prices for environmental bads. Third, the difference following the second point is that all outputs and inputs in DEA are assumed to be strictly positive while the outputs or inputs are not subject to these constraints in the distance function.¹⁵ However, both approaches can use the same linear programming techniques to reach the analytic/managerial goal.

4.7 Summary

This chapter is presented as a bridge between the theoretical model and an empirical application. The output set is partitioned into two subvectors corresponding to the desirable outputs and the environmental bads as are the revenue functions and the set of price vectors.

¹⁵ The conditions in the distance function are (1) each output is at least produced by one decision making unit (DMU); (2) Each DMU produces at least one output; (3) each input is used by at least DMU; and (4) each DMU uses at least one input. These conditions allow some zeros in DMUs.

Chapter 5. Empirical Estimates and Interpretation

5.1 Introduction

This chapter applies the output distance function to coal-fired electricity production to measure the shadow prices of selected by-products, SO_2 , NO_x , and CO_2 . As Färe et al. (1993, p. 375) state “... shadow prices reflect the impact of regulations faced by the firms, and so they can be used to assess the effectiveness of existing regulation. They could be used by firms to determine whether emission trading is worthwhile under the Clean Air Act of 1990.” The choice of the empirical model, the translog production function, is discussed. A description of the data for 16 coal fired electricity plants in West Virginia for the 1995-2000 time period and other variables used in the analysis follows. The estimation results and interpretation are given in the final section of the chapter.

5.2 The Variables and Data Used in the Analysis

5.2.1 Variables

The electricity sector is a major source of emissions of several air pollutants including sulfur dioxide (SO_2) which contributes to acid rain and fine particulate concentrations in the atmosphere, nitrogen oxides (NO_x) which contribute to both of these pollution problems and to ground-level ozone, mercury which is a toxic substance linked to neurological and other health problems, and carbon dioxide (CO_2) which contributes to global warming. The electricity sector contributes roughly 68 percent of national SO_2 emissions, 22 percent of NO_x , 40 percent of mercury, and 40 percent of CO_2 . The effects of the emissions of SO_2 and NO_x are particularly strong in the northeast which is downwind of a large number of coal-fired generators located in the Mid-Atlantic states and the Ohio Valley (Burtraw et al. 2005; EPA 2005).

Electricity is the only desirable output considered; choices for undesirable outputs include SO₂, NO_x, CO₂, and Mercury. In several empirical studies SO₂ is the only bad output chosen (Swinton 1994, 1998, 2002, and 2004). However, SO₂, NO_x, and CO₂, a subvector of undesirable outputs, were chosen for analysis in this study. There are two reasons for doing so. First, the contributions of NO_x emissions to acid rain were addressed for the first time in Title IV of 1990 CAAA. Title IV requires the reduction on NO_x from existing sources including coal-fired boilers. The requirements specify emission rate limitations based on emissions per unit of heat content of the coal input. The emission reduction approach for NO_x sets up a trading scheme for NO_x of the same type used for the SO₂ reduction calculations. Second, the U.S. Department of Energy (USDOE) has proposed strategies for reducing multiple emissions from power plants including SO₂, NO_x, and CO₂. This strategy recognizes that pollutants are generated from the same process, electricity production from coal, and can be jointly reduced in the long run. The proposal suggests that the reduction of the multiple emissions is a more attractive alternative than the separate sets of SO₂ and NO_x emission reductions as required in the 1990 CAAA (EIA 2000).¹⁶ Electricity, SO₂, NO_x, and CO₂ are the four outputs analyzed in this study. Electricity is measured in kilowatts hour per year while SO₂, NO_x, and CO₂ are in tons per year.

The vector of inputs includes coal (broken into heat and sulfur as a function of coal quality), labor, and capital. The heat input is used as a uniform measure for the energy input, calculated from coal used, and measured in millions of British thermal units (mmBtu). Heat was also used as a base measure to assign allowances to each coal-generating power plant as required

¹⁶ EIA: Analysis of Strategies for Reducing Multiple Emissions from Power Plants: Sulfur Dioxide, Nitrogen Oxides, and Carbon Dioxide. This analysis was requested by the Subcommittee on National Economic Growth, Natural Resources, and Regulatory Affairs of the U.S. House Committee of Government Reform. It examined the potential costs of various multiple emissions reduction from electric power plants.

by the 1990 CAAA. Sulfur is calculated from the sulfur content of the coal used and measured in tons. Labor is in annual hours based on the number of full-time employees times 2000 hours per year. Capital is represented by production capital and deflated by the 1997 GDP price index. Electricity prices are based on delivered quantities deflated to 1997 dollars; prices are plant averages.

5.2.2 Data

This study uses data on 16 coal-fired electricity generating power plants operated by public investor-owned utilities and cooperatives in West Virginia. Of the 16 plants, six are on the Phase I list,¹⁷ four plants voluntarily participated in Phase I as either substitute or compensating units, and six plants are Phase 2 plants. For details about these plants and their respective generating units, see Appendix A. The electricity industry is regulated under various laws and required to report inputs and outputs to FERC (Federal Energy Regulatory Commission). Therefore, these data are available to regulators and the public in paper and in electronic format through the FERC website. FERC's Form 1 is an annual report required of each power plant and contains the power plant's annual inputs, production capital, and labor utilized, while Form 423 has production cost data and quality of fuels used at the unit-level including the content of heat and sulfur in each coal used by each boiler unit on an annual basis. Because different coals have various content of heat and sulfur, the coal-boiler (unit-level) operator reports each purchase of coal with its respective contents of heat and sulfur. Therefore, the data in Form 423 were aggregated to the plant level on an annual basis to be compatible with the data in Form 1. The heat content is the major factor input in the production of electricity and

¹⁷ The Phase I list is commonly known as the Table A list, the boiler units on the list include the dirtiest units as assigned by Congress and they were required to meet the emission cap of Phase I. Thus, it is more accurate to say that the Table A list is the dirtiest boiler units. I refer to the units as plants because of some data availability only at the plant level.

sulfur is the primary measure of a bad input factor. Form 1 also provides output data including the total annual electricity generated by each electric plant and the price of electricity (at the sales meter).¹⁸ The data from Form 1 and Form 423 were downloaded from the FERC website, extracted by the applicable software utilities for the 1995-1999 period, and summarized to provide the format described in the previous section. Electricity prices are deflated to 1997 dollars. To develop estimates of undesirable outputs, SO₂, NO_x, and CO₂ emissions data were collected and compiled from the US EPA acid rain market program website. Descriptive statistics of the inputs and outputs for the 16 WV plants participating in Phase I for the five year study period are included in Table 5.1.

Table 5.1 Descriptive Summary of Data (observations=80)

Variable	Unit	MEAN	STD	MIN	MAX
Electricity	Kwh/year (millions)	4,973	4,215	117	17,655
SO ₂	Tons/year	43,720	38,585	1,270	165,458
NO _x	Tons/year	20,461	15,632	479	71,025
CO ₂	Tons/year	6,124,259	4,961,101	156,007	19,853,965
Heat	mmBtu/year	58,802,391	47,150,431	1,520,546	17,560,5985
Sulfur	Tons/year	41,558	52,044	14	198,824
Labor	Hours/year	308,333	183,556	82,000	966,000
Capital	1997 Dollars	292,990,938	280,766,169	5,212,304	1,528,098,254
Price	Cents/kWh	6.64044	2.27046	4.21000	10.80000

5.3 Empirical Results

The major goal of the empirical study is to employ the output distance function approach laid out in Chapter 4 to estimate the shadow prices of undesirable outputs as an evaluation tool defined by the specific production technology. These estimates can serve several purposes in the pollution reduction setting, as Färe et al. (1993) outlined. The estimates can be used as a tool by power plants operators to self-evaluate their estimated abatement costs; they can also be used to

¹⁸ Electricity prices are based on the delivered quantities. These prices are plant averages, weighted by quantities delivered to each ratepayer classification.

evaluate the impacts of environmental regulations on a firm's production and to examine the performance of SO₂ and NO_x allowance markets. The estimation method presented in chapter 4 is implemented and the estimations are carried out using the constrained optimization programming package (version 2.0.7) in GAUSS (version 7).¹⁹

5.3.1 Estimated Distance Function

The empirical estimation approach to the output distance function and the development of estimates of appropriate shadow values can be described in as a series of specific steps. The implementation of these steps as a GAUSS application and the output obtained is included as Appendix E and F, respectively.

The first step in the empirical application is to estimate the parameters of the distance function (Equation 4.6.3) using all (80 – 16 plants x 5 years)) observations of the four outputs (one good, three bad) and four inputs related to electricity production and subject to the constraints imposed by the choice of the translog production function in (4.6.3). The four outputs are electricity, SO₂, NO_x, and CO₂ and the four inputs are heat, sulfur, labor, and capital. The translog production function imposes four constraints on the estimation: homogeneous of degree one in output, homogeneous of degree zero in second-order output terms and cross interactive terms between output and inputs, respectively; and symmetry of second-order output and output and input terms, respectively. See Section 4.6 of the dissertation for details. In this case, there are 57 total terms to be estimated for the translog production function, 56 parameters and one constant.

The second step is to calculate the values for the output distance function based on the parameter estimates obtained from the first step for each observation, i.e., a value of the distance

¹⁹ I sincerely give my thanks to Dr. Swinton for generously providing his program code and cheerful attitude.

function is calculated for each plant for each year. The third step is to calculate the shadow price for the undesirable outputs. T from the derivative of output distance function with respect to one of the undesirable outputs given inputs, outputs, and the price of electricity.

The parameter estimates obtained are presented in Appendix C. The empirical output distance functions are calculated based on the estimated parameters. Table 5.2 lists each plant's output distance function estimates for each year during the Phase I time period, 1995-1999. The values of the distance function estimates provides estimates of the relative production efficiency for each plant. Relative efficiency means that the production frontier is fitted to the data set collected for this study. The frontier represents the best operating results observed; the results would most likely be different if data for other time periods were used in the estimation procedures.

Table 5.2 Distance Function Estimates by Plant by Year

Plant	1995	1996	1997	1998	1999
1	0.7961	0.9037	0.8907	0.9064	0.9588
2	0.9975	0.8740	0.7962	0.8708	0.9049
3	0.7749	0.6430	0.6367	0.7127	0.7374
4	0.9098	0.8839	0.8377	0.8131	0.8247
5	0.8148	0.7796	0.8489	0.8326	0.8609
6	0.8720	1.0000	0.9380	0.9885	1.0000
7	0.7985	0.9587	0.9987	0.9647	0.9853
8	0.3767	1.0000	0.8472	0.9108	0.8990
9	0.7502	0.6737	0.6678	0.6292	0.6569
10	0.8826	0.4568	0.5137	0.4917	0.5666
11	1.0000	0.6160	0.6548	0.6561	0.6662
12	0.9669	0.9234	0.8560	0.9130	0.8801
13	0.7359	0.4700	0.4687	0.4694	0.4678
14	0.7751	0.9996	0.8569	0.7372	0.7257
15	1.0000	0.7054	0.7576	0.6964	0.5771
16	1.0000	0.9537	0.9810	0.8776	1.0000

A distance value of one indicates a plant operating at the production frontier (technically efficient), while values less than one are inside the frontier and indicate inefficient operations for the specified time period. As noted, the efficiency estimates would likely be different for different data.²⁰ The efficiency measure is equivalent to the inverse of Farrell's radial efficiency measure (Farrell 1957). The values in Table 5.2 provide a comparison among plants for a given year or changes across time for a given plant. For example, there are five points that lie on the production frontier in Table 5.2. Plants 2, 11, 15, and 16 operated on the production frontier for 1995 while Plants 6 and 8 did so for 1996 and Plants 6 and 16 for 1999. There were no frontier points for the years of 1997 and 1998. Several plants operated near the frontier as shown in the table. Values of the output distance functions less than 1 indicate the extent of inefficiency; one minus the output distance function times the potential output on the frontier is the required increase in production to be efficient. Take for example, the lowest value for Plant 16 in 1995 of 0.3767, which indicates that the plant would have to increase its current electricity production by 62% of potential output to reach production efficiency. The overall weighted average (weighted by each plant's electricity production) of the output distance functions across firms and time periods is 0.8391. The electricity production for all plants in this sample must be increased by about 16%, on average, of potential output if all plants are to operate on the frontier of the production possibility set (a total output increase of about 20% of current levels).

Possible explanations for fluctuations in estimated distance function values for a given plant in Phase I primarily relate to operating efficiency reflected in inputs, i.e., heat or/and

²⁰ Swinton (p.234, 2004) gives an explanation about relative efficiency. He states that if all of the plants are somewhere below the production frontier then the estimated distance function value provides relative measures of efficiency. Because all of the plants face some state regulation it is unlikely that any of the observations are on the production frontier. This explanation is not accurate because, if all of plants face the regulation all of them should respond to the regulation and make decisions on their production choices. Some may operate efficiently while others may not. The empirical fitting of the output distance function can reflect these plants' responses from the data set. The relative efficiency is an empirical concept from the data envelope analysis approach.

output, i.e., electricity fluctuations²¹. Much of this will relate to long term operations and scheduled maintenance decisions. Some variation may also be due to the panel data used in the study which includes 16 plants in the first phase of five years. Another reason may be that only a limited range of factors are explicitly included in the model; others are ignored. For example, plant age and capacity affect efficiency but are not explicitly considered. Although each plant consists of two or more generating units, FERC Form 1 only provides plant level data, e.g., year originally constructed and date last unit installed. It is not possible to obtain this data at the generating unit level. Appendix D lists basic information (capacity, year of the earliest generating units built, and the year of latest generating unit installed) for the plants considered in this study.

5.3.2 Shadow Values of Undesirable Outputs

Estimation of the output distance function is not the primary purpose of this study. The focus is to derive shadow prices of undesirable outputs from coal-generating power plants through the slope of the production possibility frontier. The slope of the production frontier curve in traditional production economics is the rate of substitution between two desirable (normal) outputs or production transformation given the input vector. The slope of the production frontier here reflects the trade off between the desirable output and the undesirable output. Assume the price of the desirable output is known (given by market price). The shadow value of the undesirable output is then the ratio of the derivative of $D(\mathbf{x}, \mathbf{u})$ with respect to one of the specified undesirable outputs and the electricity output times the price of electricity as described in equation (3.6.11). The shadow values for the three undesirable outputs, SO_2 , NO_x ,

²¹ An attempt to plot heat and electricity against estimated distance function value for each plant in Phase I did not reveal any pattern of relationship.

and CO₂, are calculated. The shadow values of CO₂ are much lower than those of SO₂ and NO_x and may deserve further analysis in the future. Here the analytical focus is on the shadow values of SO₂ and NO_x.

5.3.2.1 Shadow Values of SO₂

Shadow prices of SO₂ reported in Table 5.3 vary greatly from plant to plant. Overall the shadow values range from nearly zero (virtually unconstrained negative outputs) to \$7,426 per ton. The lowest shadow values, Plant 4 for all years except 1995, range from \$0.01 to \$10.04 while the highest values for Plant 11 range from \$2486 to \$7426. These shadow prices can be viewed as estimates of the virtual abatement cost for each plant. This empirical work attempts to evaluate the performance of the power plants, especially those listed in Table 1 for Phase I of the 1990 CAAA.

Of the total 41 units in 16 plants, 14 units in six plants were listed in Table 1. Since the data used in the study can not be separated at the unit level, plants that have Table I unit(s) are indicated as Table I plants, i.e., plants 4, 6, 9, 10, 11, and 12. Of these, two plants, 11 and 13, have implemented SO₂ emission control measures. Plants 7, 8, 13, and 14 are substitution plants in Phase I and only Plant 13 has taken control measures. Plants 11 and 13 use wet line flue gas desulfurization (scrubbers) and Plant 12 uses wet limestone. Plant 11 has three units; all have installed scrubbers. Details of plant status in Phase I are included as Appendix B. From plant-year unit estimations of shadow prices for SO₂ (each entry in Table 5.3), the lowest estimated shadow prices of SO₂ for the 1995 to 1999 period are for Plant 4 and seem low while the highest are for Plant 11 and are unexpectedly high. The estimated shadow values the other plants are in the range of reasonable values.

Table 5.3 SO₂ Shadow Prices Per Ton by Plant and Year

Plant	1995	1996	1997	1998	1999
1 ^c	-135.65	-442.51	-467.77	-468.29	-259.80
2 ^c	-189.56	-571.36	-462.56	-550.46	-316.40
3 ^c	-60.22	-71.83	-205.21	-273.32	-159.10
4 ^a	-0.0066	-2.02	-5.33	-5.13	-10.04
5 ^c	-117.68	-395.60	-478.62	-450.97	-238.64
6 ^a	-165.42	-224.70	-239.98	-260.80	-278.59
7 ^b	-227.92	-751.77	-790.47	-772.72	-390.63
8 ^b	-0.9156	-95.50	-121.13	-114.23	-61.24
9 ^a	-0.0002	-90.17	-59.99	-68.67	-58.19
10 ^a	-6.6028	-46.55	-50.37	-56.54	-39.08
11 ^a	-2486.43	-3182.70	-7425.89	-7146.36	-5042.32
12 ^a	-129.57	-78.31	-200.07	-187.20	-175.33
13 ^b	-116.07	-318.33	-238.67	-236.30	-177.88
14 ^b	0.0001	-87.91	-100.64	-72.03	-152.67
15 ^c	-41.83	-185.87	-206.27	-100.01	-162.67
16 ^c	-41.59	-227.20	-120.96	-130.58	-191.39
Average	-119.18	-261.07	-297.77	-303.66	-204.60

Note:

^a indicates Table 1 units;

^b Substitution units in Phase I;

^c Phase II units.

Differences in SO₂ shadow prices among plants can be explained if a plant installs the scrubber (formally scrubber is the nickname for flu-gas desulfurization equipment to reduce SO₂ emissions). If a scrubber is installed in the boiler unit, the abatement cost is reflected in a much higher shadow price than if scrubbers are not installed. Although there are different types of scrubber technologies, in all cases the installation of a scrubber represents a large capital investment. Plant 11 (Harrison) has three units; all of three units have scrubbers installed, while Plant 4 (Kammer) with the lowest average shadow price for SO₂ did not install scrubbers for its three units even though all three units were listed in Table 1 for Phase I. Plant 4 has the lowest abatement cost. Conversely, it has the highest SO₂ emission rates among the 16 plants ranging

from 5.50 to 5.086 lb per mmBtu. Kammer was allocated 54,127 allowances²² while its 1995 emissions were 122,193 tons and, thus, short by 68,066 allowance units. The plant opted for the second option, buy enough allowances to fill the shortage gap between the allocation of allowances and generated SO₂. This is discussed in more detail in Section 5.4.

The last row of Table 5.3 shows the weighted average yearly shadow values for WV plants. Note also that, in most cases, the shadow prices for 1995 are lower than for other years.

5.3.2.2 Shadow Values of NO_x

The shadow prices for NO_x reported in Table 5.4 provide estimates of the marginal abatement cost for each ton of NO_x removed by plant each year. Each plant can use this information as an evaluation tool as an approximate abatement cost for each year. For this study each entry in Table 5.4 represents an observation as a plant-year unit. The shadow values of NO_x vary from \$0 (Plant 10 and 14 in year of 1995, Plant 16 in year of 1998) to \$818.5 (Plant 8 in year of 1996). When compared to the estimates of shadow values of SO₂, the shadow values of NO_x overall are much lower. The highest shadow price is \$818.5 for NO_x while the highest is \$7426 for SO₂. The annual average shadow values of NO_x across plants (last row of Table 5.4) are lower than those of SO₂ (last row of Table 5.3).

²² Each allowance represents one ton of SO₂ gas. The calculation of SO₂ allowance for each plant in operation in 1985 is based on the average heat input of the plant for the years of 1985, 1986, and 1987.

Table 5.4 Estimated NO_x Shadow Prices by Plant and Year of 1995-1999

Plant name	Plant	1995	1996	1997	1998	1999
Amos, John E	1 ^a	-171.52	-364.20*	-310.75*	-472.74*	-239.58*
Clinch River	2	-41.99	-118.04	-92.96	-108.92	-106.03
Glen Lyn	3 ^a	-132.45	0.0001	-261.19*	-310.37*	-138.68
Kammer	4	-0.0001	-3.26	-1.83	-2.97	-27.09
Kanawha River	5	-21.29	-80.92	-82.55	-74.04	-54.85
Mitchell	6 ^a	-244.47*	-95.51	-261.61*	-253.63*	-233.72*
Mountaineer	7 ^a	-222.04	-738.90*	-722.87*	-673.78*	-315.86*
Phil Sporn	8	-404.06*	-818.45*	-112.93	-161.36	-116.21
Albright	9 ^a	-76.72	-314.74*	-217.42	-151.51	-155.01
Ft Martin	10	0.0001	-38.60	-29.39	-48.03	-24.42
Harrison	11 ^a	-0.2719	-96.00	-46.14	-52.41	-29.62
Mt. Storm	12 ^b	-91.59	-142.36	-85.98	-175.58	-176.18
Pleasants	13 ^a	-28.53	-141.03	-79.74	-106.93	-76.10
Rivesville	14 ^a	0.0000	-91.98	-47.81	-21.44	-58.39
Willow Island	15	-3.54	-38.76	-41.95	-0.00001	-39.51
R. Paul Smith	16 ^a	-99.40	-360.42*	-167.34	-125.28	-240.68*
	Average	-110.06	-227.87	-145.06	-184.10	-125.72

Note: ^a indicates Phase 1 units with dry-bottom wall-fired boiler;

^b Plants with tangentially fired boiler in Phase I;

* indicates the abatement cost per ton of NO_x is higher than the average abatement cost \$227 for all of Phase I units reported by US EPA.

It is possible to examine potential relationships in the shadow values of SO₂ and NO_x. Regulators and economists try to understand correlations to minimize total abatement cost when several pollutants are reduced simultaneously (EIA 2000). This is also a motivation of this study to include multiple pollutants into the output distance function. The annual average shadow values for NO_x (last row in Table 5.4) are lower than those for SO₂ (last row in Table 5.3). As reported in Appendix A, the data collected for this study show that the control/abatement technology for these two air pollutants is different. For SO₂ emission control the plant can install “scrubbers” while for NO_x control power plants change coal burning technology by installing low-NO_x burners. In Phase I two types of boilers are targeted by NO_x emission limits. Another

control measure for SO₂ is to switch from high sulfur coal to low sulfur coal to reduce emissions; this measure was not observed in West Virginia power plants during the study period.

The regulatory requirements for reduction of NO_x emissions are more complicated than for SO₂ emission reductions. NO_x is regulated under two provisions of the 1990 Clean Air Amendments Act, Title IV and Title I. A key component of the acid rain provisions outlined in Title IV is a two million ton per year reduction of NO_x emissions from coal-fired boilers.

Unlike the SO₂ cap-and-trade program, the reduction of NO_x is also required in Title I of the 1990 CAAA. Title I targets NO_x emissions to control ozone problems while Title IV deals with stationary NO_x emissions reduction, Title I is for non-stationary source NO_x emissions that are mostly from off- and on-road vehicles. The two provisions in the 1990 CAAA resulted in two major programs, different except for Southern California's Regional Clean Air Incentive Market. They are the Ozone Transport Commission (OTC) NO_x Budget Program under Title I and NO_x State Implementation Plan (SIP) Call Program under Title IV. The OTC NO_x Budget Program was created by Congress to develop a regional strategy to enable the Northeast corridor (see Footnote 22) to achieve compliance with the ozone standard. The states that belong to the commission cooperated in the development of emission rate standards for NO_x and volatile organic compounds (VOC) from point sources (as well as harmonizing compliance strategies for mobile sources). The OTC NO_x Budget Program originally had three phases: Phase I was the preexisting emissions rate standards required by Title I of the 1990 CAAA, Phase II marked the beginning of the cap-and-trade policy and was to run from 1999 to 2002, and the third phase was to begin in 2003. By 2003, the emission cap would represent an approximate 70% reduction from the five-month summer emissions of 490,000 tons in 1990 by the affected sources. The

third phase has been replaced by the NO_x SIP Call Program. The states²³ included in the NO_x OTC budget program represented only a portion of the eastern United States affected significantly by transboundary movements of NO_x. In late 1997, under Section 110 of the 1990 CAAA, EPA exercised its authority to require states to impose restrictions on electricity generators and industrial sources of NO_x emissions to help downwind states comply with ozone standards. The rule is known as the NO_x SIP Call, because it called on states to revise their state implementation plans that outline their strategies for complying with federal ambient air standards. The NO_x SIP Call assigns each state a summertime NO_x emission budget for large point sources. These programs of SIP Call and OTC Budget Program incorporate the cap-to-trade to reduce NO_x emissions to be implemented in 1999, 2003, or later. The results are varied and complex and are not discussed further.

The reduction of NO_x required by Title IV of the 1990 CAAA was implemented through the Acid Rain Program. The goal of the Acid Rain Program is to reduce two million tons of NO_x from 1980 emission levels from coal-fired power plants.²⁴ Approximately 90 percent of total stationary NO_x emissions in 1980 came from coal-fired electric utility power plants. As with the SO₂ emission reduction requirements, the NO_x program was implemented in two phases; Phase I began in 1996, one year later than the beginning year of the SO₂ Phase I.

However, the NO_x program does not "cap" NO_x emissions as the SO₂ program does, nor does it

²³ These states are CT, DC, DE, MA, MD, ME, NH, NJ, NY, PA, RI, and VT.

²⁴ Title IV specifies a two-part strategy to reduce emissions from coal-fired electric power plants. The first stage of the program, promulgated April 13, 1995, will reduce annual NO_x emissions in the United States by over 400,000 tons per year between 1996 and 1999 (Phase I), and by approximately 1.17 million tons per year beginning in the year 2000 (Phase II). These reductions are achieved by coal-fired dry bottom wall-fired boilers and tangentially fired boilers (Group 1). The total annual cost of this regulation to the electric utility industry is estimated at \$267 million, resulting in an overall cost-effectiveness of \$227 per ton of NO_x removed.

initially utilize an allowance trading system. The program directly targets two sets of boilers to meet the NO_x emission limits: dry-bottom wall-fired boilers and tangentially fired boilers (which were already targeted for Phase I SO₂ reductions). Dry-bottom wall-fired boilers were required to meet a limit of 0.50 lbs of NO_x per mmBtu averaged over the year, while tangentially fired boilers had to achieve a limitation of 0.45 lbs of NO_x per mmBtu, again averaged over the year. Plants 1, 3, 6, 7, 9, 11, 13, 14, and 16 are dry-bottom wall-fired while only Plant 12 is tangentially fired. For the former type of plant, seven have taken NO_x control measures by using low NO_x burner technology; Plants 14 and 16 are exceptions. Plant 12 uses low NO_x-close-coupled overfire air (OFA) technology.

The estimated shadow values for NO_x for dry-bottom wall-fired plants that have also taken pollution control are higher than those of plants are not under the regulation of NO_x Phase I. The exceptions are for Plant 16 in the NO_x Phase I which did not adopt control measure and Plant 8 which was not required to adopt by the regulation. Plant 12 has higher shadow values than those that are not regulated but lower than those of dry-bottom wall-fired plants.

5.3.2.3 Shadow Values of CO₂

Reduction of CO₂ is not required in Title IV of 1990 CAAA but a subject included because of the increased interest in global warming effects. The estimated shadow values of CO₂ for the WV power plants are reported in Table 5.5.

Table 5.5 Estimated CO₂ Shadow Prices by Plant and Year of 1995-1999

Plant name	Plant	1995	1996	1997	1998	1999
Amos, John E	1	-4.3744	-8.6254	-7.5715	-10.7583	-5.4953
Clinch River	2	-1.4458	-3.2505	-2.6281	-3.0229	-2.6138
Glen Lyn	3	-3.0632	0.0000	-5.4538	-6.5992	-2.9688
Kammer	4	-0.0237	-0.0853	-0.0298	-0.0013	-0.4718
Kanawha River	5	-0.8760	-2.2105	-2.3310	-2.0932	-1.4024
Mitchell	6	-5.2633	-1.6201	-5.7477	-5.6057	-5.1317
Mountaineer	7	-5.2777	-16.1026	-15.9160	-14.6777	-6.8046
Phil Sporn	8	-10.4311	-20.5380	-3.0560	-4.0906	-2.6503
Albright	9	-1.3564	-5.3572	-3.5972	-2.1624	-2.6617
Ft Martin	10	0.0000	-0.3997	-0.3718	-0.7266	-0.2970
Harrison	11	-0.0003	-1.6137	-0.6515	-0.7775	-0.3734
Mt. Storm	12	-1.9722	-3.0119	-1.6384	-3.7264	-3.6432
Pleasants	13	-0.0001	-0.8522	-0.1422	-0.7542	-0.3552
Rivesville	14	0.0000	-1.3024	-0.4127	-0.2738	-0.7897
Willow Island	15	-0.2955	-0.7802	-0.9868	-0.0001	-0.6454
R. Paul Smith	16	-1.9977	-6.3271	-2.9589	-1.8491	-4.0286
Average		-2.5537	-4.7460	-3.4717	-4.2562	-2.7230

Compared to the shadow values of SO₂ and NO_x, the shadow values of CO₂ are low.

There are two reasons to explain the values. First, CO₂ emission reduction is not required by Title IV of 1990 CAAA, so the abatement technology is not in place for WV power plants and not reflected in the data. The estimated shadow values of CO₂ can still be good indicator for WV power plants to self evaluate their virtual abatement cost for CO₂ if they are required to make small reductions in CO₂ under the current production technology and emission control conditions.

5.3.2.3 Phase I Average Shadow Values of SO₂, NO_x, and CO₂

The preceding sections discuss the shadow values of SO₂, NO_x, and CO₂ in terms of plant-year units under Phase I for West Virginia plants. This section turns to the five-year

averages of the output distance function, shadow prices of SO₂ and NO_x, and emission levels of SO₂ and NO_x for each plant (see Table 5.6).

The five-year average output distance values vary from 0.4 (Plant 13) to 1.0 (Plant 16) and with an overall mean of 0.7944. These averages are weighted by the five-year average electricity output.

The five-year average shadow values for SO₂ range from \$4.50 per ton (Plant 4) to \$5058.77 per ton (Plant 11). The average emission rate between these two plants exhibits an inverse relationship. Plant 11 has the lowest emission rate (0.128 lb per mmBtu) while Plant 4 has the highest five-year emission rate (5.51 lb per mmBtu), far beyond the 2.5 lb per mmBtu cap for Phase I. All plants, except Plant 4, have emission rates below the cap. The overall mean shadow value of SO₂ is \$239.81.

The shadow prices of NO_x for plants vary from \$0 to \$818.45. Generally, there is again an inverse relationship between shadow values and emission rates, i.e., the lower the average emission rate for a given plant, the higher the shadow prices of NO_x. The emission rate for NO_x, however, is complex. As noted, emission reductions of NO_x in Phase I target two types of boilers, dry bottom wall-fired (DB) boilers and tangentially fired boilers. The emission limit for dry bottom wall-fired boilers is 0.45 lb per mmBtu while it is 0.50 lb per mmBtu for tangentially fired boilers. Table I plants,²⁵ as indicated by “a,” except Plant 12 are of the DB type. Detailed information is listed in Appendix B. The emission rates for Plants 4, 6, 9, 10, and 11 should be 0.45 lb per mmBtu since they use the same burner technology, while Plant 12 should be 0.5 lb per mmBtu. Plant 16’s emissions were less than the cap while other plants

²⁵ Table 1 plants are accurate but approximate while Table 1 units are designated by Title IV of 1990 CAAA. Because the estimation is based on plant data, the analysis can only be reported in terms of plants, not units.

exceeded the Phase I cap. The inverse relationship between shadow values and emissions rates (high shadow values correspond with low emission rates, and vice versa) was also reported in Swinton's studies (Coggins and Swinton 1996, Swinton 1998, 2002, 2004).

Table 5.6 Estimated Phase I Mean Shadow Prices; Emissions of SO₂, NO_x, and CO₂; and Output Distance Function by Plant

Plant name	Plant	Distance	Shadow Price (\$/ton)			Mean Emission (lb/mmbtu)		
			SO ₂	NO _x	CO ₂	SO ₂	NO _x	CO ₂
Amos, John E	1 ^c	0. 85	-355.26	-362.36	-7.37	1.30	0.51	151.57
Clinch River	2 ^c	0. 89	-418.38	-389.01	-2.59	1.19	1.19	183.29
Glen Lyn	3 ^c	0. 71	-154.19	-168.56	-3.62	1.62	0.46	190.01
Kammer	4 ^a	0. 97	-4.50	-4.50	-0.12	5.51	1.41	212.98
Kanawha River	5 ^c	0. 82	-337.84	-319.02	-1.79	1.276	0.74	119.21
Mitchell	6 ^a	0. 94	-233.97	-249.74	-4.68	1.32	0.48	196.67
Mountaineer	7 ^b	0. 96	-587.71	-586.55	-11.77	1.09	0.43	156.29
Phil Sporn	8 ^b	0. 73	-78.66	-159.08	-8.15	2.27	1.03	200.96
Albright	9 ^a	0. 74	-55.35	-70.73	-3.03	2.44	0.55	229.76
Ft Martin	10 ^a	0. 35	-39.88	-38.57	-0.36	2.43	0.76	170.11
Harrison	11 ^a	0. 47	-5058.77	-4563.13	-0.68	0.13	0.51	196.86
Mt. Storm	12 ^a	0. 93	-154.10	-146.50	-2.80	1.991	0.75	199.51
Pleasants	13 ^b	0. 40	-217.47	-199.95	-0.42	1.08	0.43	228.08
Rivesville	14 ^b	0. 78	-83.07	-83.07	-0.55	1.58	0.59	176.14
Willow Island	15 ^c	0. 90	-139.42	-131.80	-0.54	1.99	0.87	180.28
R. Paul Smith	16 ^c	1	-142.74	-154.12	-3.44	1.49	0.35	154.96
Average		0. 7944	-239.81	-168.91	-3.84			

^a indicates Table 1 units;

^b Substitution and compensation units in Phase I;

^c Phase II units.

5.3.2.4 Comparison with Other Studies

EPA declared the allowance trading policy a success when the Phase I trading of SO₂ allowance was concluded at the end of 1999. A comparison can now be made between the performance of WV plants and the EPA annual spot auction results. An interesting comparison is the relationship of the abatement cost of WV plants to auction clearing prices and to the estimated shadow prices of SO₂ for all of Table I units (Swinton 2004). From Table 5.7, for the

first year of Phase I, the average estimated shadow prices for WV plants were lower than the clearing prices in the allowance market while for the remaining four years, the shadow prices for WV plants were higher than the clearing prices.

Table 5.7 Comparisons of WV Plants to EPA Annual Spot Auction Results and Table 1 Units of SO₂

Auction year	Allowances sold	Successful bids	Clearing price ¹	WV avg. shadow value	Table 1 units avg. price ²
1995	50600	46	\$130.00	\$119.18	\$132.00
1996	150000	47	\$66.05	\$261.07	\$68.14
1997	150000	23	\$106.75	\$297.76	\$110.36
1998	150000	21	\$115.01	\$303.66	\$116.96
1999	150010	27	\$200.55	\$204.60	\$207.03

¹ Source: EPA website <http://www.epa.gov/airmarkets/emissions/index.html>

² Source: Swinton (2004): Phase I Completed: An Empirical Assessment of the 1990 CAAA. Environmental and Resource Economics 27: 227–246, 2004

Next, compare the average shadow values of WV plants to those of all of the 110 Table I units estimated by Swinton (2004). The same pattern emerges. These differences can guide WV plants in achieving economic gains, either by participating in the allowance market or adopting alternative abatement technologies. A third comparison between market clearing prices in the allowance market with estimated abatement costs of Table I units shows the convergence.

5.4 Evaluation and Interpretation for WV Power Plants

Based on the estimation results reported, further analysis of the performance of WV power plants in Phase I can consider emission reductions, participation in the allowance market, and cost savings. The evaluations of the emission reduction performances for SO₂ and NO_x for WV power plants in Phase I are considered separately because they fall under different regulatory programs, have different measures for emissions reduction, and require different abatement equipment. The evaluations include emission reductions and economic performance.

5.4.1 Evaluation of SO₂ Reduction Performance

5.4.1.1 Emissions Reductions

The overall national assessment of Phase I SO₂ emissions reductions was considered a success (EPA 2000; Stavins 1998, 2003; Burtraw et al. 2005). Total SO₂ emissions in 1995, the first year of the program, was 11.87 million tons – 25% below 1990 levels and more than 35% below 1980 levels. For affected utilities (the dirtiest 110 plants in the Title IV list plus early reduction or substitute units) emissions were set at 2.5 lb. mmBtu, equivalent to about 6.9 million tons annually in Phase 1. Total emissions from affected units were well below annual allocations throughout the Phase I period. The unused allowances yielded a bank totaling nearly 11.6 million allowances by the end of Phase I (McClellan 2000; Burtraw et al. 2005). The emission reductions of SO₂ and NO_x in WV presented the same pattern. The emission reductions by affected power plants in WV under Title IV of Phase I is presented in Table 5.8.

Table 5.8 Performance Comparison of SO₂ Emission Reductions by WV Plants

	SO ₂ Emissions (Tons)			Number of Units	Emission Reductions	
	1985	1990	1995		(tons)	% change
State	786678	804062	436885	22	349793	-44.5%
S & C Units*	62244	62929	63914	8	1670	2.7%
Table I	724434	741133	372971	14	351463	-48.5%

* S & C units represent substitute and compensation units in Phase I.

5.4.1.2 Participation in the SO₂ Allowance Market

The economic performance of the affected power plants in Phase I has been the focus of numerous studies (Hahn 1989; Joskow et al. 1998; Schmalensee et al. 1998; Carlson et al. 2000;

Burtraw et al. 2005). These studies examined the allowance market trading, participation of the affected electric plants, trading parties, and trading volumes.

Aggregate annual caps on national SO₂ emissions from affected coal-generating electricity units are specified in Title IV of 1990 CAAA. These caps define the number of emissions allowances issued for use in each year. An emission unit is the right to emit one ton of SO₂ into the atmosphere. An affected source covered by the statute must have enough allowances to cover its annual emissions at the end of each year during Phase I. Title IV has also created a pollution permit market for SO₂ with the purpose of giving the affected sources the flexibility to choose the best tools for pollution reduction at the least or less costs. The nature of the allowance market or pollution market is noticeably different and requires clarification. It is obvious that the allowance market is not a common commodity market. There are several features that are different from standard markets. First, the commodity is not a purely well-defined good or service but is one created by the legislature. Second, the maximum amount of the commodity and the issuance are set by the legislature or a designated authority. Third, the distribution of the commodity is decided by the government. In the SO₂ allowance trading case, the initial distribution of the allowance is free as endowments to the polluting firms. Fourth, the commodities final destination is back to the agency that issues them. Therefore, the pollution allowance market, also paraphrased as market-based pollution control policy, is a hybrid market. In practice, such markets are still in their infancy and need time to grow and mature.

To the extent that plants participate, trading is one indicator of whether the allowance market achieves its policy goal – cost savings. Allowance trading includes EPA's annual auction and private transactions where different firms and organizations buy or sell allowances. Because SO₂ allowance trading is the centerpiece of Title IV, several studies have scrutinized SO₂

allowance trading by power plants for the pre-Phase I, Phase I, and the on-going Phase II periods. These studies examined how the market performed and if it resulted in cost savings.

Here participation of WV power plants is examined. The records from EPA auction data show that all WV plants in the Table 1 list started buying allowances in 1993 and 1994, two years before Phase I started. These allowances were for use in 1995, the first year of mandated Phase I compliance. EPA first followed the guidance laid out in Title IV in 1993 and that year held 2.8% of allowances auctioned by the Chicago Board of Trade to help jump-start market exchange.²⁶ This portion of the annual allowance auction was held by EPA through the entire Phase I period. Two types of auctions were administered by EPA, a spot auction and a futures auction. The spot auction sells the current year allowances for use at the end of the same year as the auction is held (the auctions held in 1993 and 1994 for 1995 allowances before Phase I began were also called spot auctions in order to distinguish them from futures auctions). The futures auction includes 6-year and 7-year advance auctions so that the allowances can be first used 6 or 7 years after the year the allowances are purchased.²⁷ All WV power plants, including non-Phase I plants in this study, participated in the 1993 auction, purchasing allowances for the year 2000, which was the first year of Phase II that required all power plants to comply with the SO₂ emissions reduction program. It is notable that all affected plants in WV participated in both spot and future auctions. As for the volume of allowance auctions, the total expenditures for the allowance auction divided by the clearing price of each year are used to approximate the number of allowances traded. The allowances bought among 16 WV power plants ranged from 26 to 550 units (one unit of allowance is one ton of SO₂ emissions).

²⁶ Joskow, Schmalensee, and Bailey (1998) reported the first allowance trades were in May 1992.

²⁷ For more details on allowance auctions and trading see Joskow, Schmalensee, and Bailey (1998)

Private trading is permitted in addition to EPA's annual auction. A firm or broker can offer to sell allowances while other firms and organizations can buy them. An important feature of buying allowances designed in Title IV is to allow non electric-generating organizations to buy allowances, e.g., environmental groups or individuals that may choose to retire the allowances from the market after purchase. In this case, the total allowances available would be reduced which would reduce the total allowed emissions from polluting plants resulting in additional environmental quality improvement. Active participation in the market by WV power plants indicates that they had a positive expectation for allowance trading, even though the evidence from the trading market through EPA's auction showed the transactions to be relatively small at the beginning of the program in 1995. At the national level, the volume of SO₂ allowance trading between economically distinct parties in the first three years of Phase I roughly doubled each year compared to the previous year (Burtraw et al. 2005). The data on private trading show that WV power plants actively took part in private transactions in the market while the trading partners varied from power companies to brokerage companies. A summary of the trading behavior of WV power plants during Phase I is included as Table 5.9. The 1's in Table 5.9 indicate that purchase or sale of allowances occurred in the specified year by a given plant. Since an advance auction exists, the plants' buying or selling allowances for future years of Phase I also are counted as market activities in Table 5.9. Trading activities for Phase II and beyond are excluded. The observed trading patterns of WV plants include both sellers and buyers (Albright and Mitchell, etc.), either buyers (Kammer) or sellers (Harrison), or neither buyers nor sellers (Clinch River, Glen Lyn, Kanawha and Mountaineer). Note that the three plants that did not participate in the market were not covered by Phase I regulations. Therefore, they did not need to respond to the allowance market. The plants covered by Phase I

not only participated in EPA's annual auctions in 1993 and 1994 before Phase I and all five years of Phase I, but also participated in private trading.

Table 5.9 Allowance Transactions by WV Power Plants in Phase I

Year	1994		1995		1996		1997		1998		1999	
	B	S	B	S	B	S	B	S	B	S	B	S
Albright*			1	1	1	1	1	1	1	1	1	
Fort Martin*		1	1	1	1	1	1	1	1	1	1	
Harrison*		1		1		1		1		1		
John E Amos				1	1	1		1		1	1	1
Kammer*			1		1		1		1		1	
Mitchell*	1		1		1	1					1	1
Mount Storm*	1	1	1		1	1	1				1	1
Phil Sporn									1	1		
Pleasants			1	1	1	1						
Rivesville			1		1	1		1	1	1	1	
Willow Island			1		1	1	1	1	1	1	1	
R. Paul Smith			1		1		1		1		1	

* indicates plant is in Table I list of Phase I.

B = buy allowances

S = sell allowances

1 = either selling or buying activity occurred

Source: <http://oaspub.epa.gov/pls/ats/atr> and

<http://www.epa.gov/airmarkets/tracking/ats/transactions.html>

Note: the allowance trading includes EPA's annual auctions and private transactions. The transactions analyzed in this table are private transactions. The year of 1993 did not have any private allowance sales in the market (Joskow, Schmalensee, and Bailey 1998).

Participation in allowance markets includes buying and selling future years allowances.

Clinch River and Glen Lyn did not participate in private transactions in Phase I. Plant R.P.Smith did buy allowances at the yearly auction in 1995, 1996, and 1997, respectively, and used allowances at the end of the same year they bought to cover their emissions. R.P.Smith also bought future allowances in 1998 and 1999 for future years of Phase II and after Phase II²⁸; it

²⁸ US EPA hold two types of SO₂ allowance auction, spot auction and advance auction. EPA held allowance auction starting in 1993 for the first year, 1995, of Phase I and advance auction for the year of 2000. Since 1994, EPA has spot allowance auction and 6- and 7-year advance allowance auctions.

sold in Phase I and sold future allowances for Phase II and after Phase II. This behavior signals the complications in trading, either they really need allowances in different years or they use the transactions to reduce abatement costs. However the firm reacts as a market player in the allowance market and minimizes its abatement cost. On the other hand, Kammer bought allowances in all five years of Phase I to be used for each year in Phase I. Kammer purchased 344,546 total allowances. Kanawha did not buy allowances in Phase I but bought for 2001, 2002, 2003, 2004, and 2005. Harrison, Kanawha and Albright did not buy allowances from private parties in Phase I, only from EPA auctions. Fort Martin sold allowances in four out of six years from 1994 to 1999. Mountaineer sold future allowances beyond Phase I.

The activities of two plants are worth special notice. Large volumes of trading took place at the two extremes. Plant 4, which had the highest emissions rate for SO₂ (5.5 lb per mmBtu), bought allowances in all five years in Phase I totaling 34,356 allowances purchased and the allowances were used each year as designated redemption in Phase I; it did not have any sales of allowances. On the other hand, Plant 11 had the lowest emission rate (0.128 lb per mmBtu) and sold allowances in the Phase I years but did not purchase allowances. Their trading behaviors were rational among the choices faced.

5.4.1.3 Cost Effectiveness and Efficiency

Since the SO₂ allowance market is the centerpiece of Title IV, evaluation criteria to measure the success of the market include cost effectiveness and efficiency compared to command-and-control policy and emission charges. Estimation of cost savings under Title IV have been the focus of many studies at the macro-level since the initial proposal with the debate on SO₂ allowance trading; see Hahn 1989, Burtraw 1995, Schmalensee et al. 1998, Joskow et al. 1998, Lile and Burtraw 1998, Burtraw et al. 2005. The concept of cost effectiveness has several

different meanings in the context of pollution control policy. One is the common sense interpretation that market mechanisms allow trading to set the clearing price resulting in the optimum allocation of resources to control pollution. Another is the cost savings when allowance trading is used in pollution control compared with costs using taxes or the command-and-control approach. The last is the cost savings when the actual observed allowance clearing price is compared to the estimated/expected allowance price before the allowance market. For the last one, the evidence after Phase I came into effect indicated that the early allowance (pre-Phase I) price was too low as expected. Therefore, early studies claimed that the cost saving was much larger than expected. In this study cost effectiveness is based on the first of the two meanings described above using a micro-level analysis. More specifically, the analysis focuses on the plants participating in the allowance market over other alternatives available to help them comply with Title IV requirements.

The empirical results indicated an inverse relationship between the estimated shadow value and the actual emission rate for WV power plants. Several similar studies (Coggins and Swinton 1996; Swinton 1998, 2002, 2004) also show the same relationship. An explanation of the relationship and a plant's response offers some insight into the evaluation of the performance of WV power plants in Phase I.

The estimated shadow values of SO₂ can be used in the analysis in several ways. One can compare the shadow value to the allowance clearing price and then make an evaluation. Swinton (2004) did an analysis based on all Phase I plants. Swinton's assertion about a firm's economic rationale is that a firm should buy (sell) allowances if its shadow value of SO₂ is higher (lower) than the clearing trading price in SO₂ allowance market. Conceptually, this criterion is correct but not the only one used in empirical analysis. For the SO₂ allowance,

trading in Phase I was only one mechanism used to comply with SO₂ emissions requirements for SO₂ while other options, e.g., installation of scrubbers, switching from high sulfur coal to low sulfur coal, or internalizing/averaging emissions, are also available. The decision of a firm to either buy or sell allowances requires that they analyze the alternatives carefully and thoroughly. For example, the Krammer Plant is the highest rate emitter of SO₂ (5.5lb per mmBtu) but has the lowest shadow value of SO₂ (\$4.5 per ton) as reported in Table 5.6 of Section 5.4. This plant bought allowances in all five years of Phase I but, based on Swinton's criterion, the plant should have sold allowances instead. However, if this plant had sold its allowances in the market, its SO₂ emissions would have exceeded the allowed levels and it would have been subject to fines imposed by the law (\$2,000 per ton). For this plant, it not only needed to use all of its allowances to cover its standard emission requirement in Phase I but needed more allowances to cover actual emissions which were higher than the standard emission rate. The other choice for this plant was to install scrubbers for its three units. Why did it choose to buy allowances and not to install scrubbers? To understand this, consider the shadow value of SO₂ of the Harrison Plant. Harrison's shadow value is \$5,058 since Harrison installed scrubbers in all three of its units. Installation of scrubbers for the dirtiest plants was a mandatory requirement in the early stages of the Acid Rain Program. The investment in scrubbers at that time was very high. Once the scrubber is installed, the investment becomes part of the fixed costs of production. It also explains why Harrison (Plant 11) sold allowances each year in all Phase I periods, because it had the lowest emission rate (0.13 lb per mmBtu) among all of plants. Comparing the shadow value of SO₂ in a plant with a scrubber to the clearance price in the allowance market, it is clear that buying allowances is cheaper than installing a scrubber. It is clear that Swinton's criterion alone cannot be used to judge a firm's behavior in the SO₂ allowance market, but that other conditions

have to be considered to make a correct judgment. One caveat is in order. That is, the estimated shadow value can be one of the opportunity costs for abatement but has to be analyzed in context when there are alternative choices to control pollution. As Burturaw (1996, 2005) point out, “There are a variety of mechanisms for compliance under Title IV in addition to allowance trading including intrafirm reallocation of emission allowances, fuel switching and/or blending, installing scrubbers (flue gas desulfurization), retiring plants, repowering plants, energy conservation, reduced utilization and substitution among facilities.” Among these choices, the plant operators tend to choose the cheapest way to meet the environmental regulation. Fuel switching at a national level is estimated to have contributed to cost savings in reducing total SO₂ emissions, but this was mainly in mid-western states when railroad deregulation greatly reduced transportation costs.²⁹ In West Virginia this was not the case; it is cheaper to use local coal. The sulfur content of coal used in WV power plants was unchanged in Phase I. One also needs to be aware of each unit’s age in a plant if a plant decides to install scrubbers or other pollution control equipment.

The overall conclusion of this analysis is that power plants in WV participated in the allowance market and made the best decision among the alternatives available for complying with the requirements mandated by Title IV of 1990 CAAA.

5.4.2 Evaluation of NO_x Reduction Performance

The evaluation of emission reductions of NO_x in affected plants under the Acid Rain Program in Phase I is based on several distinct features that are different from those in the SO₂ program. First, Title IV of the NO_x program establishes standard emission limitations for affected units but does not include the cap-and-trade aspect of the SO₂ program. Title IV of the

²⁹ Fuel switching is that power plants change from high content sulfur coal to low sulfur content coal. This reduces SO₂ and NO_x emissions.

1990 Clean Air Act Amendments required EPA NO_x annual average emission limits (in pounds of NO_x per million British thermal units of fuel consumed, (lb/mmBtu)) for coal-fired electric utility units in two phases. In April 1995, EPA promulgated 40 CFR Part 76 which established NO_x emission limits beginning on January 1, 1996 for Group 1 boilers that were also part of the Phase I SO₂ program. Second, standard emission limitations were established in Phase I for two boiler technologies, dry bottom boilers subject to an NO_x emission limit of 0.50 lb/mmBtu and tangentially-fired boilers subject to an NO_x emission limit of 0.45 lb/mmBtu. The affected units and plants by NO_x emission limitation are listed in Table 5.10. Some plants first were targeted for SO₂ emission reductions as they are included in the Table I list. These same plants were then targeted for NO_x reductions if the boiler is dry-bottom or tangentially fired. For example, Plant 11 is in the Table I list and the boiler is dry-bottom wall-fired, thus is affected by NO_x regulation. Plant 4 is included on Table I list but the boiler is cyclone and not affected by NO_x regulation. Plants 1, 2, 3, 5, 7, 8, and 15 are not in the Table I and neither affected by NO_x even though the boiler is dry bottom.

Table 5.10 WV Power Plant Boiler Type and NO_x Pollution Control in Phase I

Plant	Boiler Type	Phase I	Pollution control	Shadow Value	Mean Emission
1	DB	Not affected	LNB	-362.36	0.5062
2	DVF	Not affected	U	-389.01	1.1939
3	DB	Not affected	U	-168.56	0.4594
4	C	Not affected	U	-4.50	1.4056
5	DVF	Not affected	U	-319.02	0.7373
6	DB	Not affected	LNB	-249.74	0.4834
7	DB	Not affected	LNB	-586.55	0.4245
8	DB	Not affected	U	-159.08	1.0325
9	DB	Affected	LNB	-70.73	0.5479
10	T	Affected	U	-38.57	0.7633
11	DB	Affected	LNB	-4563.13	0.5107
12	T	Affected	LNC1	-146.50	0.7515
13	DB	Affected	LNB	-199.95	0.4336
14	DVF	Affected	U	-83.07	0.588
15	DVF	Not affected	U	-131.80	0.8619
16	DB	Affected	LNC3	-154.12	0.3453
Average				-168.91	

Abbreviation in table

DB = dry bottom wall-fired;

C = cyclone;

CB = cell burner wall-fired;

DVF = dry bottom vertically fired;

T = tangentially fired;

LNB = low NO_x burner technology;

LNC1 = low NO_x -close-coupled OFA;

LNC3 = low NO_x -close coupled and separated OFA;

U = uncontrolled.

Third, one control technology for reducing NO_x emissions is to adopt low NO_x burners.

There are two control technologies adopted by WV affected plants, LNB, LNC1 and LNC3. The emission limitations in the in Acid Rain Program give flexibility to the affected plants. That is, the control approaches have an averaging plan that plants can average emission rates over two or more units to meet an overall emission rate limitation and alternative emission limitation (AEL)

that corresponds to the level that the utility demonstrates is achievable. These options give utilities flexibility in meeting the emission limitations in a cost-effective way and allow for the further development of technologies to reduce the costs of compliance. Phase I for NO_x was from 1996 to 1999, one year later than Phase I for SO₂.

The NO_x emission reductions in Phase I achieved the goal set by EPA (reductions of over 400,000 tons per year between 1996 and 1999 (Phase I)). There were some differences among affected plants between SO₂ and NO_x emission reductions. The affected plants for NO_x were among the group affected by the SO₂ emissions reduction program but the specific effects were determined by boiler type, dry bottom or tangentially fired. They are required to meet two different standard emission limitations based on the type of boiler the plant has. In practice, for the affected plants (the status shown in column 5 in Table 5.10) in WV, four out of seven installed lower NO_x burner equipment to reduce NO_x emissions to meet the standard emission limitations. The average emission rates in affected plants are lower than those in unaffected plants. According to the EPA's estimations, the cost of the NO_x removed was \$227 per ton, the estimations from this study of the five-year average shadow values (weighted by electricity) of NO_x among plants range from \$4.50 to \$4563.13 per ton. Among the affected plants in WV, the cost in plants is lower without control equipment than those of plants that installed the control equipment. The control status is reported in column four of Table 5.10. The costs for uncontrolled plants are from \$4.50 to \$389.00, while the costs for controlled plants from \$70.73 to \$4563.13 per ton of NO_x removed. Further classification of plants as affected and not-affected with control or no-control technology adopted by the estimated shadow value of NO_x shows the same pattern. The shadow values of the uncontrolled and affected plants range from \$38.57 to \$83.07 while for the controlled and affected the range is from \$70.73 to \$4563.13. The costs for

the uncontrolled and unaffected group are from \$4.50 to \$389.00 while for controlled and unaffected plants they from \$249.74 to \$586.55. This relationship is similar to that seen in the analysis of SO₂ shadow values. That is, the higher the emission rate a power plant has, the lower the estimated shadow price of NO_x is.

The five-year average emissions of NO_x are shown in the last column in Table 5.10. The plants emissions can be grouped into dry bottom and tangentially fired boiler for those affected with control technology or those without control technology. Affected plants with dry bottom boilers should meet the emission limitation of 0.45 lb per mmBtu. Among plant's taking control actions, Plants 13 and 16 have averaged emission rate of 0.43 lb and 0.35 lb per mmBtu, respectively, while Plants 9, 11, and 15 are slightly higher than 0.45 lb per mmBtu. Compared to those not affected and uncontrolled plants, 2, 4, and 8, the emission rates are all above 1 lb per mmBtu.

5.5 Summary

This chapter discusses the empirical estimation of shadow values for SO₂, NO_x, and CO₂ for WV power plants in Phase I of the 1990 CAAA. The shadow values of SO₂, NO_x, and CO₂ can be used for self-evaluation as abatement cost for each undesirable output, respectively, regardless there is any environmental regulation imposed on each of these three undesirable outputs. The annual shadow values of the three pollutants for each plant are estimated from 1995 to 1999. Therefore each plant can see their yearly abatement cost for each respective pollutant when one ton of SO₂, NO_x, or CO₂ is removed.

The estimated shadow values of SO₂ and NO_x are used as an evaluation tool to analyze cost effectiveness at the plant level since these two air pollutants emission reduction are required by Title IV of 1990 CAAA. The analyses offered insights for evaluating performances in Phase

I. The empirical evidence reveals an inverse relationship between the shadow values and the corresponding emission rates. This relationship exists for both SO₂ and NO_x. The interpretation for this inverse relationship is that the pollution reduction is costly when firms take control measures, either by installing scrubbers for SO₂ or low NO_x burners. On the other hand, plants with the lower abatement costs have higher emission rates. Another aspect of evaluation is to observe if a plant actively participates in the SO₂ allowance market. In terms of participating in SO₂ allowance markets or taking alternative available control measures to meet environmental regulations, plants operators actively participated in both EPA's auction market and private market for SO₂ allowances. Typically, however, plants installed equipment to meet the NO_x emission limits.

For CO₂ the estimated shadow values are really low and emission rates high. Since there are no regulations directly imposed on CO₂ emission reduction, this study has provided a self-evaluation tool for the plants to look at the virtual abatement cost of CO₂ and the total abatement cost if all of three pollutants were reduced together at current production technology and pollution control technology.

Chapter 6. Summary and Conclusions

6.1 Introduction

The objectives of this dissertation are to provide empirical estimates of the shadow values of SO_2 , NO_x , and CO_2 for WV coal-generating power plants. The estimated shadow value of SO_2 is used to evaluate the performances of these plants in Phase I (1995-1999) in complying with the pollution reduction requirements in the 1990 Clean Air Act Amendments. The shadow values provide insight into plant level decisions and implications for the efficacy of the SO_2 allowance markets. The estimates of shadow values for NO_x are compared to the EPA estimates of average abatement cost in the Acid Rain Program while the estimate for CO_2 is a potential abatement cost for these plants if they were required to reduce (marginally) emissions given the current technology and pollution control measures in their plants. This chapter summarizes the findings of the analysis.

The next section of this final chapter gives a summary of the main results of the study with an emphasis on the key empirical findings in Chapter 5 as they relate to the SO_2 allowance market and findings of previous studies. Section 3 concludes the chapter with suggestions for further research.

6.2 Summary

The first chapter of this dissertation provides an overview of the appropriate regulations and the mandated reductions of emissions by coal-fired power plants under the first and largest pollutant allowance market created by Title IV of the CAAA. Chapter 2 includes a review of the literature on production externalities starting with the definitions of externalities and the theoretical models that provide insight into these issues. The theories presented includes Samuelson's conditions, Nash-equilibrium, and Lindahl-equilibrium. The Lindahl-equilibrium

supports the use of governmental intervention using market mechanisms to control detrimental externalities. Pollution control policies discussed include command and control, pollution tax or effluent fee, and marketable pollution permits. Title IV of the 1990 Clean Air Act Amendments finally made the market mechanisms long advocated and supported by economists a reality with support for a SO₂ allowance market. Title IV also required reduction of NO_x emission from power plants but the emission control approach was markedly different than that for SO₂ (Cap-and-Trade). Plants tend to take a technology based control approach by using low NO_x burners to reduce emissions to meet the NO_x limits.

The approach used to analyze a pollution-producing firm is the output distance function which has several unique advantages for the purpose of this study. First, it models production processes directly and captures the characteristics of a specific production process. Second, input and output data for the production process are sufficient; abatement cost information from each firm is not required. Since abatement cost data is difficult to obtain from firms and may be unreliable even though it is available in some situations, this is a definite advantage. Third, the output distance function approach can explicitly model multiple outputs from a production process. Fourth, explicit imposition of environmental regulations are not required. This approach provides a tool to estimate the shadow values of multiple outputs from the production of electricity by coal-fired power plants. In this study the model includes four outputs, one good output, electricity, and three undesirable outputs, SO₂, NO_x, and CO₂. Based on the estimates obtained, the study evaluates the performance of the abatement effectiveness under the SO₂ allowance market and the evaluation of the NO_x emission reduction in Phase I.

Chapters 3 and 4 present a theoretical and empirical model of the output distance function, respectively. In chapter 3, the theoretic model of output distance function used for this

study is outlined. The model is characterized by the production technology of the firm. The technology is represented by an output set, or output requirement set, or technology set. For a specific production, a given input set for the outputs is determined. The output distance function is defined on the output set to represent the specific technology and also to measure technical efficiency. The dual to the output distance function is the revenue function. The revenue function can be defined either by the output set or distance function while the distance function is defined in terms of the revenue function. The duality of the output distance function and the revenue function provides a tool to derive the shadow prices for the outputs, especially for the “bads,” the SO_2 , NO_x , and CO_2 gases. Finally, the equilibrium model is presented in terms of the output distance function. This model is very different than the traditional production model. It departs from the single output production model by directly modeling multi-outputs. A feature of the output distance function that is especially useful is the ability to directly depict relationships between and among desirable and undesirable outputs when environmental “bads” are included as outputs in the model. Null-jointness of desirable outputs and undesirable outputs demonstrates that (1) the disposal for environmental “bads” is costly because a power plant has to allocate its resources to reduce emission or disposal it; (2) the undesirable output can be reduced but is never reduced to zero.

Chapter 4 presents a bridge between the theoretical model and empirical application. The output set is partitioned into two subvectors corresponding to the desirable outputs and the environmental “bads”, as are the revenue functions and the set of price vectors. The properties of partitioned output distance function and revenue function are derived based on the axioms of unrestricted output sets. These properties are used to establish the duality that connects two functions, to specify a restricted output set, and its duality with the subvector output distance

function. Because the subvector output distance function completely characterizes the production technology, this function is used to derive absolute shadow prices from the unrestricted output price set. The empirical model specified in Chapter 4 is a translog production frontier function. Compared to other empirical models, the translog production frontier function has flexibility and is able to model multiple outputs of a production process. The estimation method is parametric constrained nonlinear programming (Färe et al. 1989; Swinton 1996, 1998, 2002, and 2004).

The estimation was carried out in two steps and discussed in detail in Chapter 5. Data for 16 coal-fired power plants in West Virginia were collected from 1995-1999. The parameters were estimated from observed data and used to derive shadow prices for SO_2 and NO_x . Empirical estimates of the shadow values for SO_2 and NO_x for WV coal-fired electric power-generating plants were developed while estimates for CO_2 were also included in the analysis. The estimated CO_2 shadow prices are low while emission rates are high. Since there are no regulations on CO_2 emission reduction in the Acid Rain Program, the analysis of the estimation for CO_2 offers insights for the power plants to evaluate their abatement cost for CO_2 if CO_2 were required to reduce its emission. The shadow prices for SO_2 , NO_x , and CO_2 in the study are estimated based on observed data and current production technology. If CO_2 is regulated by law and pollution control technology is adopted by the plant, the estimates of shadow values for SO_2 , NO_x and CO_2 would be different from what is estimated in this study. The focus of the analysis of this study is on SO_2 and NO_x and offers insights for evaluating the performance of the power plants during Phase I of the 1990 CAAA. The empirical evidence reveals an inverse relationship between the shadow values and the corresponding emission rates for SO_2 , NO_x , and CO_2 . Evaluations were in terms of participation in the SO_2 allowance market and the choice of

alternative control measures for cost-effectiveness to meet the requirements of environmental regulations. The plants actively participated in both the EPA's auction market and private markets for SO₂ allowances.

The case for NO_x is more complex since pollution reduction is mandated by two different sections of the 1990 CAAA (Title I and Title IV). The focus of this study is Title IV of the 1990 CAAA and promulgated by the USEPA as Acid Rain Program. The compliance with NO_x emission limitations is based on two boiler types of power plants spelled out in Title IV of 1990 CAAA. The plants under regulations by the 1990 CAAA adopted pollution control technologies and had higher estimated abatement costs than the plants that were not regulated in Phase I.

The estimated shadow values of CO₂ are low compared to the shadow values of SO₂ and NO_x, while the emission rates of CO₂ in Phase I are high. Since there is no explicit regulation on CO₂ that are generated and emitted from power plants no detailed analysis is given for CO₂. But the estimated CO₂ shadow values provide information for plant self-evaluation and as so to the decision maker.

6.3 Conclusions

This study examined empirically the performances of WV 16 power plants in Phase I in compliance with the requirements of the 1990 CAAA. The output distance function approach underlies the theoretical framework of the study. The values of the distance function are estimated annually for each plant in Phase I (Table 5.2) and the five-year average for 16 plants. The estimated value of output distance function is the measure of the operating point of each plant from the production frontier estimated by this data set and an efficiency indicator. A value of one for a plant in a given year indicates that the plant operates on the frontier and is empirically efficiency. A plant does not operate at an efficient point if the value is less than one.

The overall weighted average (weighted by each plant's electricity production) of the output distance functions across firms and time periods is 0.8391. The electricity production for all plants in this sample must be increased by about 16% of potential output, on average, if all plants are to operate on the frontier of the production possibility set. The purpose of this study is not to examine the efficiency of each plant production but is its derived shadow values of undesirable outputs.

The three undesirable outputs of SO₂, NO_x, and CO₂ are calculated from the output distance values for each plant annually and overall average of 16 plants in Phase I. The main findings are summarized as follows. The estimated shadow values of SO₂ for all 80 observations (each plant at each year of Phase I) are from nearly zero (virtually unconstrained negative outputs) to \$7,426 per ton. The empirical results showed the shadow prices (opportunity costs of undesirable output for abatement) for SO₂ are higher in plants that installed pollution control scrubbers than those without installation of scrubbers. The highest values for Plant 11 range from \$2486 to \$7426 with its each of three generating units that had installed scrubber while the lowest shadow values, Plant 4, range from \$0.01 to \$10.04 without installation of scrubbers in its three generating units. The estimated five-year average shadow prices for each plant in Phase I (Table 5.6) show Plant four has \$4.05 per ton while Plant 11 \$ 5058.77 per ton for SO₂. These estimated shadow values reflected the capital abatement investment in their respective production capital. These two plants are both in the Table I list. On the other hand the emission rates for these two plants are inversed. Plant 11 has the lowest emission rate of five-year average at 0.13 lb per mmBtu as the contrast Plant 4 at 5.51 lb per mmBtu much higher than the cap set by Title IV for plants in Table I list of Phase I, 2.5 lb per mmBtu.

The annually estimated shadow values of NO_x for each plant of range from \$0 (Plant 10 and 14 in year of 1995, Plant 16 in year of 1998) to \$818.5 per ton (Plant 8 in year of 1996). The relationship of the shadow values between plants with emission control and plants without emission control shows the similar pattern as what has been discussed for SO₂. The target for NO_x emission reduction is on two types of burners, dry-bottom fired and tangentially fired burners, to meet the respective emission limit. The emission limit is 0.50 lb per mmBtu for dry-bottom fired burner and 0.45 lb per mmBtu for tangentially fired burner. The affected plants are required to meet the emission limit by either adopting the low NO_x burner or averaging emission rate at plant level over its all units. The affected plants by NO_x emission limits with the control have higher estimated shadow values than the plants without control. The costs for uncontrolled plants are from \$4.50 to \$389.00, while the costs for controlled plants from \$70.73 to \$4563.13 per ton of NO_x removed. This is similar as what is observed for plants regulated by SO₂ emission cap. Consequently, the emission rates for NO_x in plants that have taken pollution control measures are lower than those that have not adopted the pollution control technology. For dry-bottom fired plants with control technology, Plants 13 and 16 have five-year averaged emission rate of 0.43 lb and 0.35 lb per mmBtu (the emission limit is 0.50 lb per mmBtu), respectively, while without control, Plants 2, 4, and 8, the emission rates are all above 1 lb per mmBtu .

Under newly created SO₂ allowance markets by Title IV of 1990 CAAA, the plants actively participated in the allowance trading, in both the EPA auctions and private markets. The observed participation in allowance market of WV power plants includes both purchases and sales in Phase I. The plants with high emission rates that did not install pollution control equipment heavily traded in both the EPA's allowance auctions and private allowance trading

markets. On the other hand, plants with high shadow values of SO_2 and lower emission rates than the cap set up in Phase I of 1990 CAAA were sellers of allowances. The study reveals the rational behavior for a power plant to either buy or sell its allowance is related to if the plant installs pollution control equipment in WV power plants. Installing pollution control equipment is an abatement investment costly and therefore results in high shadow value of an undesirable output. A plant with the installation of pollution control equipment and resulting in higher abatement cost likely sells its allowances in the market since its emission rate is lower than the required when pollution investment has already incurred. The sale of the allowance in the market is one way to offset the abatement investment. On the other hand a plant without the installation of pollution control equipment the estimated shadow value is much lower than the one with control and has much higher emission rate than the emission cap for SO_2 in Phase I. If the cost of purchase of allowance is lower than their abatement investment it is cost effective to buy allowance. This empirical analysis of this study is different from the criterion stated normally in environmental economic analysis (the firm should sell pollution permit if the abatement cost is lower than the market price, or purchase pollution permit otherwise). That is the elaboration is needed to the observed evidence from each specific case. It is also due to the data collected for this study, the installation of abatement equipment is control measure. The bottom line is that the plants utilized whichever would give then minimum abatement or compliance cost in foreseen available choices: installing pollution reduction technology or trading in the market for SO_2 allowances.

This study attempted to estimate and analyze three nonmarket and undesirable outputs in electricity production process by output distance function approach. It provided the encouraging result and a tool to evaluate the behavior of WV power plants in compliance with the

requirement set by Title IV of 1990 CAAA and participating in SO₂ allowance market. Through the study there are several aspects of this analysis need to be emphasized. First the data that characterize the production process of electricity may need more examination to capture the characteristics of the production as closely as possible. In this study the production capital used but it is aggregation of production investment and abatement investment. If it is possible it can be divided into production capital and abatement investment. The other aspect of the model is to specifically consider if there is any relationship among multiple undesirable outputs, e.g., SO₂ and NO_x, the estimated shadow values of NO_x are lower than those of SO₂. It may need further examining if there is some relationship to be explicitly expressed in the model. Third it is needed to provide statistical inference for the model estimation since this is a deterministic model.

Further study can be to follow up when Phase II of 1990 CAAA for all of electricity generating companies is completed in 2010. A thorough evaluation of power plants performances in pollution reduction among the different available technologies and pollution control policies can be examined. The comparisons of both the SO₂ and NO_x markets can be studied in order to provide valuable insight to design or develop a mature market to effectively reduce pollution and improve environmental quality. The technological jointness relationship among these pollutants, SO₂, NO_x, CO₂, mercury and others need to be specified in the model in order to explore the effectiveness of abatement cost when a comprehensive abatement approach can be designed.

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Appendices

Appendix A. CAAA Phase I Affected and Early Election Units

Plant name	Unit ID	Status	SO ₂	NO _x	SO ₂ control	NO _x control
Amos, John E (1)	1	P2	Not Affected	Not Affected	U	LNB
	2	P2	Not Affected	Not Affected	U	LNB
	3	P2	Not Affected	Not Affected	U	U
Clinch River (2)	1 ^c	P2	Not Affected	Not Affected	U	U
	2	P2	Not Affected	Not Affected	U	U
	3	P2	Not Affected	Not Affected	U	U
Glen Lyn 3	36 ^c	P2	Not Affected	Not Affected	U	U
	51	P2	Not Affected	Not Affected	U	U
	52	P2	Not Affected	Not Affected	U	U
Kammer 4	1	P1	Affected	Affected	U	U
	2	P1	Affected	Affected	U	U
	3	P1	Affected	Affected	U	U
Kanawha River 5	5 ^c	P2	Not affected	Not Affected	U	U
Mitchell 6	1	P1	Affected	Affected	U	LNB
	2	P1	Affected	Affected	U	LNB
Mountaineer 7	1	Early Election	Affected	Affected	U	LNB
Phil Sporn 8	11	P2	Not Affected	Not Affected	U	U
	21	P2	Not Affected	Not Affected	U	U
	31	P2	Not Affected	Not Affected	U	U
	41	P2	Not Affected	Not Affected	U	U
	51	P2	Not Affected	Not Affected	U	U
Albright 9	1	P1.5	Affected	Affected	U	LNB
	2	P1.5	Affected	Affected	U	LNB
	3	P1	Affected	Affected	U	LNC3
Ft Martin 10	1	P1	Affected	Affected	U	U
	2	P1	Affected	Affected	U	U
Harrison 11	1	P1	Affected	Affected	WL ^a	LNB
	2	P1	Affected	Affected	WL	LNB
	3	P1	Affected	Affected	WL	LNB
Mt. Storm 12	1	P1	Affected	Affected	U	LNC1
	2	P1	Affected	Affected	U	LNC1
	3	P1	Affected	Affected	WLS	LNC1
Pleasants 13	1	P1.5	Affected	Affected	WL	O
	2	P1.5	Affected	Affected	WL	LNB
Rivesville 14	7	P1.5	Affected	Affected	U	U
	8	P1.5	Affected	Affected	U	U
Willow Island 15	1	P2	Not Affected	Not Affected	U	U
	2	P2	Not Affected	Not Affected	U	U
R. Paul Smith 16	9 ^c	P1.5	Affected	Affected	U	U
	10	P1.5	Affected	Affected	U	LUC3

Source: US EPA Acid Rain Program website.

In Appendix A, the following definitions apply:

“P1” for the Phase I units identified in the Clean Air Act,

“P1.5” for the units which volunteered to meet 1995 emission limits as either substitution or compensating units, and

“P2” for the Phase II units.

The emissions of SO₂ and NO_x in the Phase I units and substitution units or compensating units were affected while those of Phase II units are not affected.

SO₂ control and NO_x control indicates if each unit adapts control technology to reduce emissions of SO₂ and NO_x.

“U” is for an uncontrolled unit,

“WL” is for wet line flue gas desulfurization,

“LNB” is for low NO_x burner technology,

“LNC3” for low NO_x -closed coupled separated OFA,

“LNC1” for low NO_x closed coupled OFA

Appendix B. Boiler Type and Pollution Controls for 16 West Virginia Plants

Plant	No. of Plant	Boiler Type	NO _x control	SO ₂ control
Amos, John E	1 ^c	DB	LNB	U
Clinch River	2 ^c	DVF	U	U
Glen Lyn	3 ^c	DB	LNB	U
Kammer	4 ^a	C	U	U
Kanawha River	5 ^c	DVF	U	U
Mitchell	6 ^a	DB	LNB	U
Mountaineer	7 ^b	DB	LNB	U
Phil Sporn	8 ^b	DVF	U	U
Albright	9 ^a	DB	LNB	U
Ft. Martin	10 ^a	CB	U	U
Harrison	11 ^a	DB	LNB	WL
Mt. Storm	12 ^a	T	LNC1	WLS
Pleasants	13 ^b	DB	LNB	WL
Rivesville	14 ^b	DB	U	U
Willow Island	15 ^c	DVF	U	U
R. Paul Smith	16 ^c	DB	U	U

^a represents Phase I plants;

^b represents substitute and compensation plants in Phase I; and

^c represents Phase II plants.

Abbreviations used:

DB = dry bottom wall-fired;

C = cyclone;

CB = cell burner wall-fired;

DVF = dry bottom vertically fired;

T = tangentially fired;

LNB = low NO_x burner technology;

LNC1 = low NO_x -close-coupled OFA;

LNC3 = low NO_x -close coupled and separated OFA;

U = uncontrolled.

WL = wet line flue gas desulfurization;

WLS = wet limestone.

Appendix C. Parameters Estimates for the Output Distance Function

Variables	Parameter Estimates	Gradient
Constant	4.8954	-80.0000
Y ₁	0.6170	-1742.4484
Y ₂	0.2112	-809.6146
Y ₃	0.1679	-753.2617
Y ₄	0.0040	-1207.0529
Y ₁₁	0.0255	-19039.4811
Y ₂₂	0.0200	-4160.7509
Y ₃₃	0.0070	-3615.9088
Y ₄₄	0.0001	-9169.0805
Y ₁₂	-0.0191	-8870.8072
Y ₁₃	-0.0062	-8266.5566
Y ₁₄	-0.0002	-13207.0274
Y ₂₁	-0.0191	-8870.8072
Y ₂₃	-0.0010	-3868.2183
Y ₂₄	0.0000	-6159.6606
Y ₃₁	-0.0062	-8266.5565
Y ₃₂	-0.0010	-3868.2183
Y ₃₄	0.0001	-5745.7853
Y ₄₁	-0.0002	-13207.0275
Y ₄₂	0.0000	-6159.6606
Y ₄₃	0.0001	-5745.7853
X ₁	0.3429	-1387.9733
X ₂	-2.0410	-914.3910
X ₃	1.0537	-1000.1661
X ₄	-1.6870	-1508.7836
X ₁₁	0.1428	-12102.9947
X ₁₂	0.0106	-7997.7537
X ₁₃	-0.2325	-8697.5640
X ₁₄	-0.0502	-13126.0626
X ₂₁	0.0106	-7997.7537
X ₂₂	0.0485	-6110.3384
X ₂₃	0.1813	-5715.0397
X ₂₄	-0.0450	-8731.4127
X ₃₁	-0.2325	-8697.5634
X ₃₂	0.1813	-5715.0398
X ₃₃	-0.1333	-6264.8951
X ₃₄	0.1504	-9441.1588
X ₄₁	-0.0502	-13126.0625
X ₄₂	-0.0450	-8731.4127
X ₄₃	0.1504	-9441.1588

Variables	Parameter Estimates	Gradient
X_{44}	0.0524	-14297.3451
Y_1X_1	0.0123	-30354.4653
Y_1X_2	-0.0049	-14149.5294
Y_1X_3	-0.0072	-13193.6888
Y_1X_4	-0.0002	-21067.0453
Y_2X_1	-0.0055	-20034.3369
Y_2X_2	-0.0002	-9332.984
Y_2X_3	0.0056	-8713.0230
Y_2X_4	0.0001	-13924.5379
Y_3X_1	-0.0112	-21831.8596
Y_3X_2	0.0120	-10163.6536
Y_3X_3	-0.0008	-9462.5975
Y_3X_4	0.0000	-15133.7223
Y_4X_1	0.0051	-32938.8876
Y_4X_2	-0.0041	-15327.0241
Y_4X_3	-0.0010	-14274.8518
Y_4X_4	0.0000	-22840.1893

Note:

Y_1 = electricity (KWh)

Y_2 = SO₂ (tons)

Y_3 = NO_x (tons)

Y_4 = CO₂ (tons)

X_1 = Heat input (mmBtu)

X_2 = Sulfur input (tons)

X_3 = Labor (hours)

X_4 = Capital (1997 dollar)

$Y_{jk} = Y_j * Y_k \quad j \in \{1,2,3,4\}, k \in \{1,2,3,4\}$

$X_{jk} = X_j * X_k \quad j \in \{1,2,3,4\}, k \in \{1,2,3,4\}$

$Y_j X_k = Y_j * Y_k \quad j \in \{1,2,3,4\}, k \in \{1,2,3,4\}$

Appendix D. Basic Information for 16 West Virginia Power Plants

Plant name	Status	Capacity (MW)	Year built (original)	Year last unit installed	Company
Amos, John E (1)	P2	2932.6	1971	1973	Appalachian Power Company
Clinch River (2)	P2	712.5	1958	1961	Appalachian Power Company
Glen Lyn (3)	P2	337.5	1918	1957	Appalachian Power Company
Kammer (4)	P1	713	1958	1959	Ohio Power Company
Kanawha River (5)	P2	439.4	1953	1953	Appalachian Power Company
Mitchell (6)	P1	1633	1971	1971	Ohio Power Company
Mountaineer (7)	Early Election	1300	1980	1980	Appalachian Power Company
Phil Sporn (8)	P2	1105.6	1950	1960	Appalachian Power Company
Albright (9)	P1, P1.5	487.5	1952	1954	The Potomac Company, MongahelaPower Company
Ft Martin (10)	P1	566	1967	1968	The Potomac Company, MongahelaPower Company
Harrison (11)	P1	1185.23	1972	1974	The Potomac Company,
Mt. Storm (12)	P1	650	1953	1962	Virginia Electric & Power Company
Pleasants (13)	P1. 5	410.4+342	1979	1980	The Potomac Company, MongahelaPower Company
Rivesville (14)	P1. 5	109.75	1919	1951	MongahelaPower Company
Willow Island (15)	P2	213.2	1949	1960	MongahelaPower Company
R. Paul Smith (16)	P1. 5	110	1923	1958	The Potomac Power Company

Source: FERC Form 1

The table provides technology information on plants in this study. Numbers in parenthesis in Column 1 of the table are plant numbers in tables used in chapter 5. In Column 2 of the table, Status: P1, power plant participates in Phase I; P2 in Phase II for SO₂ emission reduction required by Title IV of 1990 CAAA; and P1.5 for substitute and compensation plants.

Capacity represent total installed capacity (Max Generate Name Plate Ratings-MW). Since each plant has more than one generating unit, the original year of the plant built and the year last unit was installed are reported in FERC Form 1. This information can give some glimpse on some plants' decision among pollution control alternatives. The ownership and operation can be split. This can be seen in several plants, e.g. Albright, Fort Martin, and Pleasants. One unit is operated by owner and other units are operated by tenants.

Appendix E. GAUSS Program to Estimate Distance Function and Shadow Values for Pollutants

(GAUSS version 7, and Constraint Optimization Version 2.0.7)

```
new;
library co;
#include co.ext;
coset;
output file= distthre_nov2306.out reset;
format /rdn 11,4;
@__output=0; @

load wv95[16,9] = 1995_16plants.txt;
load wv96[16,9] = 1996_16plants.txt;
load wv97[16,9] = 1997_16plants.txt;
load wv98[16,9] = 1998_16plants.txt;
load wv99[16,9] = 1999_16plants.txt;

let runnum = 1;
M=16;
N=80;

row1 = wv95[1:16,.];
row2 = wv96[1:16,.];
row3 = wv97[1:16,.];
row4 = wv98[1:16,.];
row5 = wv99[1:16,.];

choose = seqa(1,1,16);

inout = row1|row2|row3|row4|row5; /* regular sample */

/* define variables */
one = ones(N,1);
zero = zeros(N,1);

/* outputs */
Y1 = inout[.,1]; /* electricity */
Y2 = inout[.,2]; /* SO2 */
Y3 = inout[.,3]; /* NOx */
Y4 = inout[.,4]; /* CO2 */

/* inputs */
X1 = inout[.,5]; /* mmbtu */
X2 = inout[.,6]; /* sulfur */
X3 = inout[.,7]; /* labor */
X4 = inout[.,8]; /* capital */

/* price */
```

```

py1 = inout[.,9]; /* electricity price */

/* parameter starting values */
/* Need rewrite parameter values */
start= {5,
        0.96000, 0.01000, 0.01000, 0.01000,
        0.00500, 0.00500, 0.00500, 0.00500,
        -0.00250, -0.00250, 0.00000,
        -0.00250, -0.00250, 0.00000,
        -0.00250, -0.00250, 0.00000,
        -0.00250, -0.00250, 0.00000,
        1.10850, -1.71450, 1.71690, -1.01280,
        -0.009700, 0.36990, -0.49630, -0.05710,
        0.36990, -1.13920, 0.24810, -0.68880,
        -0.49630, 0.24810, -0.21080, -0.18520,
        -0.05710, -0.68880, -0.18520, -0.40670,
        0.00000, -0.00000, 0.00000, 0.00000,
        0.00000, -0.00000, 0.00000, 0.00000,
        0.00000, -0.00000, 0.00000, 0.00000,
        -0.00000, 0.00000, 0.00000, 0.00000};

/* take natural log of variables */
LY1 = LN(Y1);
LY2 = LN(Y2);
LY3 = LN(Y3);
LY4 = LN(Y4);
LX1 = LN(X1);
LX2 = LN(X2);
LX3 = LN(X3);
LX4 = LN(X4);

/* create ln interactive terms */
LY11 = (LY1.*LY1); /* outputs */
LY22 = (LY2.*LY2);
LY33 = (LY3.*LY3);
LY44 = (LY4.*LY4);
LY12 = (LY1.*LY2); /* output interactive term */
LY13 = (LY1.*LY3);
LY14 = (LY1.*LY4);
LY21 = (LY2.*LY1);
LY23 = (LY2.*LY3);
LY24 = (LY2.*LY4);
LY31 = (LY3.*LY1);
LY32 = (LY3.*LY2);
LY34 = (LY3.*LY4);
LY41 = (LY4.*LY1);
LY42 = (LY4.*LY2);
LY43 = (LY4.*LY3);
LX11 = (LX1.*LX1); /* inputs */
LX22 = (LX2.*LX2);
LX33 = (LX3.*LX3);
LX44 = (LX4.*LX4);
LX12 = (LX1.*LX2); /* input interactive terms */
LX13 = (LX1.*LX3);
LX14 = (LX1.*LX4);
LX21 = (LX2.*LX1);

```

```

LX23 = (LX2.*LX3);
LX24 = (LX2.*LX4);
LX31 = (LX3.*LX1);
LX32 = (LX3.*LX2);
LX34 = (LX3.*LX4);
LX41 = (LX4.*LX1);
LX42 = (LX4.*LX2);
LX43 = (LX4.*LX3);

LY1X1 = (LY1.*LX1);      /* input output cross terms */
LY1X2 = (LY1.*LX2);
LY1X3 = (LY1.*LX3);
LY1X4 = (LY1.*LX4);

LY2X1 = (LY2.*LX1);
LY2X2 = (LY2.*LX2);
LY2X3 = (LY2.*LX3);
LY2X4 = (LY2.*LX4);

LY3X1 = (LY3.*LX1);
LY3X2 = (LY3.*LX2);
LY3X3 = (LY3.*LX3);
LY3X4 = (LY3.*LX4);

LY4X1 = (LY4.*LX1);
LY4X2 = (LY4.*LX2);
LY4X3 = (LY4.*LX3);
LY4X4 = (LY4.*LX4);

/* define the objective function */
/* Ainger Chu translog function */
lobj = one~LY1~LY2~LY3~LY4~
      .5*LY11~.5*LY22~.5*LY33~.5*LY44~
      .5*LY12~.5*LY13~.5*LY14~
      .5*LY21~.5*LY23~.5*LY24~
      .5*LY31~.5*LY32~.5*LY34~
      .5*LY41~.5*LY42~.5*LY43~
      LX1~LX2~LX3~LX4~
      .5*LX11~.5*LX12~.5*LX13~.5*LX14~
      .5*LX21~.5*LX22~.5*LX23~.5*LX24~
      .5*LX31~.5*LX32~.5*LX33~.5*LX34~
      .5*LX41~.5*LX42~.5*LX43~.5*LX44~
      LY1X1~LY2X1~LY3X1~LY4X1~
      LY1X2~LY2X2~LY3X2~LY4X2~
      LY1X3~LY2X3~LY3X3~LY4X3~
      LY1X4~LY2X4~LY3X4~LY4X4;

/* positive derivative with respect to electricity output */
grady1 = zero~one~zero~zero~zero~
        LY1~zero~zero~zero~
        LY2~LY3~LY4~
        zero~zero~zero~
        zero~zero~zero~
        zero~zero~zero~
        zero~zero~zero~zero~
        zero~zero~zero~zero~

```

```

zero~zero~zero~zero~
zero~zero~zero~zero~
zero~zero~zero~zero~
LX1~zero~zero~zero~
LX2~zero~zero~zero~
LX3~zero~zero~zero~
LX4~zero~zero~zero;

```

/* negative derivative with respect to SO_2 output */

```

grady2 = zero~zero~one~zero~zero~
zero~ly2~zero~zero~
zero~zero~zero~
LY1~LY3~LY4~
zero~zero~zero~
zero~zero~zero~
zero~zero~zero~zero~
zero~zero~zero~zero~
zero~zero~zero~zero~
zero~zero~zero~zero~
zero~zero~zero~zero~
zero~LX1~zero~zero~
zero~LX2~zero~zero~
zero~LX3~zero~zero~
zero~LX4~zero~zero;

```

/* negative derivative with respect to NOx output */

```

grady3 = zero~zero~zero~one~zero~
zero~zero~ly3~zero~
zero~zero~zero~
zero~zero~zero~
LY1~LY2~LY4~
zero~zero~zero~
zero~zero~zero~zero~
zero~zero~zero~zero~
zero~zero~zero~zero~
zero~zero~zero~zero~
zero~zero~zero~zero~
zero~zero~LX1~zero~
zero~zero~LX2~zero~
zero~zero~LX3~zero~
zero~zero~LX4~zero;

```

/* negative derivative with respect to CO2 output */

```

grady4 = zero~zero~zero~zero~one~
zero~zero~zero~ly4~
zero~zero~zero~
zero~zero~zero~
zero~zero~zero~
LY1~LY2~LY3~
zero~zero~zero~zero~
zero~zero~zero~zero~
zero~zero~zero~zero~
zero~zero~zero~zero~
zero~zero~zero~zero~
zero~zero~zero~LX1~
zero~zero~zero~LX2~

```

[illegible]

```

0000
0000,
00000 /* symmetry  A14=A41  */
0000
001
000
000
-100
0000
0000
0000
0000
0000
0000
0000
0000
0000,
00000 /* symmetry  A23=A32  */
0000
000
010
0-10
000
0000
0000
0000
0000
0000
0000
0000
0000,
00000 /* symmetry  A24=A42  */
0000
000
001
000
0-10
0000
0000
0000
0000
0000
0000
0000
0000,
00000 /* symmetry  A34=A43  */
0000
000
000
001
00-1
0000
0000
0000

```

```

0000
0000
0000
0000
0000
0000,
00000 /* symmetry B12=B21 */
0000
000
000
000
000
000
0000
0100
-1000
0000
0000
0000
0000
0000
0000,
00000 /* symmetry B13=B31 */
0000
000
000
000
000
0000
0010
0000
-1000
0000
0000
0000
0000
0000
0000,
00000 /* symmetry B14=B41 */
0000
000
000
000
000
0000
0001
0000
0000
0000
-1000
0000
0000
0000
0000,
00000 /* symmetry B23=B32 */
0000
000
000
000

```



```

0 0 0
0 0 0 0
0 0 0 0
0 0 1 0
0 -1 0 0
0 0 0 0
0 0 0 0
0 0 0 0
0 0 0 0
0 0 0 0,
0 0 0 0 0 /* symmetry B24=B42 */
0 0 0 0
0 0 0
0 0 0
0 0 0
0 0 0 0
0 0 0 0
0 0 0 1
0 0 0 0
0 -1 0 0
0 0 0 0
0 0 0 0
0 0 0 0
0 0 0 0,
0 0 0 0 0 /* symmetry B34=B43 */
0 0 0 0
0 0 0
0 0 0
0 0 0
0 0 0 0
0 0 0 0
0 0 0 0
0 0 0 1
0 0 -1 0
0 0 0 0
0 0 0 0
0 0 0 0
0 0 0 0,
0 0 0 0 0 /* Homogeneity degree of zero for cross term of output and input */
0 0 0 0
0 0 0 /* c11=-c21-c31-c41 */
0 0 0
0 0 0
0 0 0
0 0 0 0
0 0 0 0
0 0 0 0
0 0 0 0
0 0 0 0
0 0 0 0
1 1 1 1
0 0 0 0
0 0 0 0
0 0 0 0,
0 0 0 0 0 /* Homogeneity degree of zero for cross term of output and input */

```

```

0000
000 /* c12=-c22-c32-c42 */
000
000
000
0000
0000
0000
0000
0000
0000
0000
1111
0000
0000,
00000 /* Homogeneity degree of zero for cross term of output and input */
0000
000 /* c13=-c23-c33-c43 */
000
000
000
0000
0000
0000
0000
0000
0000
0000
0000
1111
0000,
00000 /* Homogeneity degree of zero for cross term of output and input */
0000
000 /* c14=-c24-c34-c44 */
000
000
000
0000
0000
0000
0000
0000
0000
0000
0000
1111,
00000 /* Homogeneity degree of zero for 2nd order output */
1000
111 /* a11=-a12-a13-a14 */
000
000
000
0000
0000
0000
0000
0000
0000

```

```

0 0 0 0
0 0 0 0
0 0 0 0,
0 0 0 0 0 /* Homogeneity degree of zero for 2nd order output */
0 1 0 0
0 0 0 /* a22=-a21-a23-a24 */
1 1 1
0 0 0
0 0 0
0 0 0 0
0 0 0 0
0 0 0 0
0 0 0 0
0 0 0 0
0 0 0 0
0 0 0 0
0 0 0 0
0 0 0 0,
0 0 0 0 0 /* Homogeneity degree of zero for 2nd order output */
0 0 1 0
0 0 0 /* a33=-a31-a32-a34 */
0 0 0
1 1 1
0 0 0
0 0 0 0
0 0 0 0
0 0 0 0
0 0 0 0
0 0 0 0
0 0 0 0
0 0 0 0
0 0 0 0,
0 0 0 0 0 /* Homogeneity degree of zero for 2nd order output */
0 0 0 1
0 0 0 /* a44=-a41-a42-a43 */
0 0 0
0 0 0
1 1 1
0 0 0 0
0 0 0 0
0 0 0 0
0 0 0 0
0 0 0 0
0 0 0 0
0 0 0 0
0 0 0 0
0 0 0 0
};
_co_B={1,
0,
0,
0,
0,
0,
};

```



```

aa14 = v1[12,1];
aa21 = v1[13,1];
aa23 = v1[14,1];
aa24 = v1[15,1];
aa31 = v1[16,1];
aa32 = v1[17,1];
aa34 = v1[18,1];
aa41 = v1[19,1];
aa42 = v1[20,1];
aa43 = v1[21,1];

aa = (aa11~aa12~aa13~aa14)|(aa21~aa22~aa23~aa24)|
      (aa31~aa32~aa33~aa34)|(aa41~aa42~aa43~aa44) ;          /* alpha sub ii' */

bb1 = v1[26:29,1];
bb2 = v1[30:33,1];
bb3 = v1[34:37,1];
bb4 = v1[38:41,1];
bb = bb1'|bb2'|bb3'|bb4';          /* beta sub jj' */

cc1 = v1[42:45,1];
cc2 = v1[46:49,1];
cc3 = v1[50:53,1];
cc4 = v1[54:57,1];
cc = cc1'|cc2'|cc3'|cc4';          /* gamma sub ij' */

Ind0 = a0 + lny*a + lnx*b
      + .5*diag( (lny*aa)*lny' )
      + .5*diag( (lnx*bb)*lnx' )
      + diag( (lnx*cc)*lny' );

d0 = exp(Ind0);
"Distance function: " d0'; ?;

wtmndist = sumc( ( inout[:,1]/sumc(inout[:,1]) ) .* d0 );
"(Weighted) Mean distance function: " wtmndist'; ?;

/***** Derivatives of d0 wrt outputs. *****/

del_y = ( a[1,1] + lny*aa[:,1] + lnx*cc[:,1] ) ./ y[:,1];
del_s = ( a[2,1] + lny*aa[:,2] + lnx*cc[:,2] ) ./ y[:,2];
del_n = ( a[3,1] + lny*aa[:,3] + lnx*cc[:,3] ) ./ y[:,3];
del_c = ( a[4,1] + lny*aa[:,4] + lnx*cc[:,4] ) ./ y[:,3];

/***** Derivatives of d0 wrt inputs. *****/

del_btu = ( b[1,1] + lnx*bb[:,1] + lny*(cc[1,:]) ) ./ x[:,1];
del_sul = ( b[2,1] + lnx*bb[:,2] + lny*(cc[2,:]) ) ./ x[:,2];
del_lab = ( b[3,1] + lnx*bb[:,3] + lny*(cc[3,:]) ) ./ x[:,3];
del_kap = ( b[4,1] + lnx*bb[:,4] + lny*(cc[4,:]) ) ./ x[:,4];

shadvalu_s = (py1/100).*( del_s ./ del_y );
"shadvalu_s = " shadvalu_s ; ?;

wtmnsv_s = sumc( ( inout[:,2]/sumc(inout[:,2]) ) .* shadvalu_s );

```

```

"(Weighted) Mean shadow value of SO2 = " wtmnsv_s;

shadvalu_n = (py1/100).*( del_n ./ del_y );
"shadvalu_n = " shadvalu_n ; ?;

wtmnsv_n = sumc( ( inout[:,3]./sumc(inout[:,3]) ) .* shadvalu_n );

"(Weighted) Mean shadow value of NOx = " wtmnsv_n;

shadvalu_c = (py1/100).*( del_c ./ del_y );
"shadvalu_c = " shadvalu_c ; ?;

wtmnsv_c = sumc( ( inout[:,4]./sumc(inout[:,4]) ) .* shadvalu_c );

"(Weighted) Mean shadow value of CO2 = " wtmnsv_c;

/* ***** Build 5 13x1 vectors to get annual averages ***** */

so2_95 = row1[:,2]; /* SO2 levels in 1995, etc. */
so2_96 = row2[:,2];
so2_97 = row3[:,2];
so2_98 = row4[:,2];
so2_99 = row5[:,2];

nox_95 = row1[:,3];
nox_96 = row1[:,3];
nox_97 = row1[:,3];
nox_98 = row1[:,3];
nox_99 = row1[:,3];

co2_95 = row1[:,4];
co2_96 = row1[:,4];
co2_97 = row1[:,4];
co2_98 = row1[:,4];
co2_99 = row1[:,4];

shad_95_s = shadvalu_s[1:16]; /* Shadow values for SO2 in 1995, etc. */
shad_96_s = shadvalu_s[17:32];
shad_97_s = shadvalu_s[33:48];
shad_98_s = shadvalu_s[49:64];
shad_99_s = shadvalu_s[65:80];

shad_95_n = shadvalu_n[1:16]; /* Shadow values for NOx in 1995, etc. */
shad_96_n = shadvalu_n[17:32];
shad_97_n = shadvalu_n[33:48];
shad_98_n = shadvalu_n[49:64];
shad_99_n = shadvalu_n[65:80];

shad_95_c = shadvalu_c[1:16]; /* Shadow values for CO2 in 1995, etc. */
shad_96_c = shadvalu_c[17:32];
shad_97_c = shadvalu_c[33:48];
shad_98_c = shadvalu_c[49:64];
shad_99_c = shadvalu_c[65:80];

sval_95_s = sumc( ( so2_95./sumc(so2_95) ) .* shad_95_s );
"(Weighted) 1995 SO2 Mean shadow value = " sval_95_s;

```

```

sval_96_s = sumc( ( so2_96./sumc(so2_96) ) .* shad_96_s );
"(Weighted) 1996 SO2 Mean shadow value = " sval_96_s;

sval_97_s = sumc( ( so2_97./sumc(so2_97) ) .* shad_97_s );
"(Weighted) 1997 SO2 Mean shadow value = " sval_97_s;

sval_98_s = sumc( ( so2_98./sumc(so2_98) ) .* shad_98_s );
"(Weighted) 1998 SO2 Mean shadow value = " sval_98_s;

sval_99_s = sumc( ( so2_99./sumc(so2_99) ) .* shad_99_s );
"(Weighted) 1999 SO2 Mean shadow value = " sval_99_s;
?;
```

```

sval_95_n = sumc( ( nox_95./sumc(nox_95) ) .* shad_95_n );
"(Weighted) 1995 NOx Mean shadow value = " sval_95_n;

sval_96_n = sumc( ( nox_96./sumc(nox_96) ) .* shad_96_n );
"(Weighted) 1996 NOx Mean shadow value = " sval_96_n;

sval_97_n = sumc( ( nox_97./sumc(nox_97) ) .* shad_97_n );
"(Weighted) 1997 NOx Mean shadow value = " sval_97_n;

sval_98_n = sumc( ( nox_98./sumc(nox_98) ) .* shad_98_n );
"(Weighted) 1998 NOx Mean shadow value = " sval_98_n;

sval_99_n = sumc( ( nox_99./sumc(nox_99) ) .* shad_99_n );
"(Weighted) 1999 NOx Mean shadow value = " sval_99_n;
?;
```

```

sval_95_c = sumc( ( co2_95./sumc(co2_95) ) .* shad_95_c );
"(Weighted) 1995 CO2 Mean shadow value = " sval_95_c;

sval_96_c = sumc( ( co2_96./sumc(co2_96) ) .* shad_96_c );
"(Weighted) 1996 CO2 Mean shadow value = " sval_96_c;

sval_97_c = sumc( ( co2_97./sumc(co2_97) ) .* shad_97_c );
"(Weighted) 1997 CO2 Mean shadow value = " sval_97_c;

sval_98_c = sumc( ( co2_98./sumc(co2_98) ) .* shad_98_c );
"(Weighted) 1998 CO2 Mean shadow value = " sval_98_c;

sval_99_c = sumc( ( co2_99./sumc(co2_99) ) .* shad_99_c );
"(Weighted) 1999 CO2 Mean shadow value = " sval_99_c;
?;
```

```

/*****/
/* Compute SO2 average shadow price */
/* for each plant */
/*****/
```

```

rux1 = shadvalu_s[1:16,1];
rux2 = shadvalu_s[17:32,1];
rux3 = shadvalu_s[33:48,1];
rux4 = shadvalu_s[49:64,1];
```

```

rux5 = shadvalu_s[65:80,1];
dux1 = d0[1:16,1];
dux2 = d0[17:32,1];
dux3 = d0[33:48,1];
dux4 = d0[49:64,1];
dux5 = d0[65:80,1];

elc1 = ly1[1:16,1];
elc2 = ly1[17:32,1];
elc3 = ly1[33:48,1];
elc4 = ly1[49:64,1];
elc5 = ly1[65:80,1];
avgp_s = (rux1 .* elc1 + rux2 .* elc2 + rux3 .* elc3 + rux4 .* elc4 + rux5 .* elc5) ./
    (elc1 + elc2 + elc3 + elc4 + elc5);
"(Weighted) Mean Shadow Value of SO2 by plant= " avgp_s; ?;

/*****/
/* Compute NOx average shadow price */
/* for each plant */
/*****/

rux1_n = shadvalu_n[1:16,1];
rux2_n = shadvalu_s[17:32,1];
rux3_n = shadvalu_s[33:48,1];
rux4_n = shadvalu_s[49:64,1];
rux5_n = shadvalu_s[65:80,1];
dux1 = d0[1:16,1];
dux2 = d0[17:32,1];
dux3 = d0[33:48,1];
dux4 = d0[49:64,1];
dux5 = d0[65:80,1];

elc1 = ly1[1:16,1];
elc2 = ly1[17:32,1];
elc3 = ly1[33:48,1];
elc4 = ly1[49:64,1];
elc5 = ly1[65:80,1];
avgp_n = (rux1_n .* elc1 + rux2_n .* elc2 + rux3_n .* elc3 + rux4_n .* elc4 + rux5_n .* elc5) ./
    (elc1 + elc2 + elc3 + elc4 + elc5);
"(Weighted) Mean Shadow Value of NOx by plant= " avgp_n; ?;

/*****/
/* Compute CO2 average shadow price */
/* for each plant */
/*****/

rux1_c = shadvalu_c[1:16,1];
rux2_c = shadvalu_c[17:32,1];
rux3_c = shadvalu_c[33:48,1];
rux4_c = shadvalu_c[49:64,1];
rux5_c = shadvalu_c[65:80,1];

avgp_c = (rux1_c .* elc1 + rux2_c .* elc2 + rux3_c .* elc3 + rux4_c .* elc4 + rux5_c .* elc5) ./
    (elc1 + elc2 + elc3 + elc4 + elc5);
"(Weighted) Mean Shadow Value of CO2 by plant= " avgp_c; ?;

```



```

    avgd = (dux1 .* elc1 + dux2 .* elc2 + dux3 .* elc3 + dux4 .* elc4 + dux5 .* elc5) ./
        (elc1 + elc2 + elc3 + elc4 + elc5);
"(Weighted) Mean Distance Function by plant = " avgd; ?;

/*****
/* Compute average so2 emission for each plant */
*****/
plant_so2 = ((so2_95 + so2_96 + so2_97 + so2_98 + so2_99).*2000);

ene_95=row1[:,5];
ene_96=row2[:,5];
ene_97=row3[:,5];
ene_98=row4[:,5];
ene_99=row5[:,5];
plant_ene = ene_95 + ene_96 + ene_97 + ene_98 + ene_99;
avg_so2 = plant_so2 ./ plant_ene ;
"1995-1999 Mean so2 emission by plant = " avg_so2; ?;

output off;
end;

```

Appendix F. Final GAUSS Estimation Results

return code = 0

normal convergence

Value of objective function 19.750563

Parameters Estimates Gradient

Parameters	Estimates	Gradient
P01	4.8954	-80.0000
P02	0.6170	-1742.4484
P03	0.2112	-809.6145
P04	0.1679	-753.2618
P05	0.0040	-1207.0526
P06	0.0255	-19039.4808
P07	0.0200	-4160.7511
P08	0.0070	-3615.9085
P09	0.0001	-9169.0811
P10	-0.0191	-8870.8072
P11	-0.0062	-8266.5567
P12	-0.0002	-13207.0273
P13	-0.0191	-8870.8071
P14	-0.0010	-3868.2177
P15	0.0000	-6159.6605
P16	-0.0062	-8266.5566
P17	-0.0010	-3868.2175
P18	0.0001	-5745.7854
P19	-0.0002	-13207.0272
P20	0.0000	-6159.6604
P21	0.0001	-5745.7854
P22	0.3429	-1387.9733
P23	-2.0410	-764.7229
P24	1.0537	-1000.1661
P25	-1.6870	-1508.7836
P26	0.1428	-12102.9947
P27	0.0106	-6701.8138
P28	-0.2325	-8697.5634
P29	-0.0502	-13126.0626
P30	0.0106	-6701.8141
P31	0.0485	-3799.0113
P32	0.1813	-4796.3740
P33	-0.0450	-7268.6729
P34	-0.2325	-8697.5634
P35	0.1813	-4796.3740

P36	-0.1333	-6264.8951
P37	0.1504	-9441.1588
P38	-0.0502	-13126.0625
P39	-0.0450	-7268.6729
P40	0.1504	-9441.1588
P41	0.0524	-14297.3451
P42	0.0123	-30354.4653
P43	-0.0049	-14149.5294
P44	-0.0072	-13193.6889
P45	-0.0002	-21067.0452
P46	-0.0055	-16781.7552
P47	-0.0002	-7844.0920
P48	0.0056	-7326.2716
P49	0.0001	-11673.4404
P50	-0.0112	-21831.8596
P51	0.0120	-10163.6536
P52	-0.0008	-9462.5975
P53	0.0000	-15133.7224
P54	0.0051	-32938.8877
P55	-0.0041	-15327.0241
P56	-0.0010	-14274.8518
P57	0.0000	-22840.1894

Number of iterations 25

Minutes to convergence 0.01302

Distance function:	0.7961	0.9975	0.7749	0.9098	0.8148
0.8720	0.7985	0.3767	0.7502	0.8826	1.0000
0.7359	0.7751	1.0000	1.0000	0.9037	0.8740
0.8839	0.7796	1.0000	0.9587	1.0000	0.6737
0.6160	0.9234	0.4700	0.9996	0.7054	0.9537
0.7962	0.6367	0.8377	0.8489	0.9380	0.9987
0.6678	0.5137	0.6548	0.8560	0.4687	0.8569
0.9810	0.9064	0.8708	0.7127	0.8131	0.8326
0.9647	0.9108	0.6292	0.4917	0.6561	0.9130
0.7372	0.6964	0.8776	0.9588	0.9049	0.7374
0.8609	1.0000	0.9853	0.8990	0.6569	0.5666
0.8801	0.4678	0.7257	0.5771	1.0000	

(Weighted) Mean distance function: 0.8391

shadvalu_s =

-135.6536
-189.5643
-60.2219
-0.0066
-117.6784

-165.4190
-227.9225
-0.9156
-0.0002
-6.6028
-2486.4273
-129.5728
-116.0695
0.0000
-41.8320
-41.5859
-442.5066
-571.3573
-71.8273
-2.0186
-395.6019
-224.7010
-751.7688
-95.5026
-90.1686
-46.5451
-3182.6993
-78.3082
-318.3319
-87.9146
-185.8697
-227.2036
-467.7720
-462.5629
-205.2086
-5.3298
-478.6199
-239.9756
-790.4674
-121.1247
-59.9857
-50.3654
-7425.8904
-200.0719
-238.6719
-100.6436
-206.2697
-120.9611
-468.2888
-550.4622
-273.3203

-5.1265
 -450.9651
 -260.7946
 -772.7211
 -114.2316
 -68.6720
 -56.5413
 -7146.3631
 -187.1955
 -236.3026
 -72.0339
 -100.0076
 -130.5773
 -259.7970
 -316.4006
 -159.1026
 -10.0362
 -238.6380
 -278.5885
 -390.6341
 -61.2436
 -58.1886
 -39.0810
 -5042.3168
 -175.3315
 -177.8785
 -152.6720
 -162.6663
 -191.3889

(Weighted) Mean shadow value of SO2 = -239.8081

shadvalu_n =

-171.5198
 -41.9904
 -132.4752
 -0.0001
 -21.2863
 -244.4683
 -222.0436
 -404.0580
 -76.7204
 0.0000
 -0.2719
 -91.5850
 -28.5291
 0.0000

-3.5339
-99.4042
-364.1996
-118.0401
0.0000
-3.2566
-80.9173
-95.5107
-738.8975
-818.4535
-314.7445
-38.6021
-96.0017
-142.3552
-141.0343
-91.9798
-38.7635
-360.4200
-310.7473
-92.9553
-261.1896
-1.8281
-82.5511
-261.6131
-722.8690
-112.9262
-217.4178
-29.3929
-46.1360
-85.9796
-79.7438
-47.8055
-41.9478
-167.3346
-472.7396
-108.9175
-310.3645
-2.9715
-74.0388
-253.6319
-673.7813
-161.3606
-151.5079
-48.0302
-52.4009
-175.5782

-106.9279
-21.4382
0.0000
-125.2780
-239.5784
-106.0272
-138.6755
-27.0872
-54.8464
-233.7174
-315.8573
-116.2149
-155.0048
-24.4160
-29.6150
-176.1763
-76.1025
-58.3869
-39.5045
-240.6815

(Weighted) Mean shadow value of NO_x = -168.9050

shadvalu_c =

-4.3744
-1.4458
-3.0632
-0.0237
-0.8760
-5.2633
-5.2777
-10.4311
-1.3564
0.0000
-0.0003
-1.9722
-0.0001
0.0000
-0.2955
-1.9977
-8.6254
-3.2505
0.0000
-0.0853
-2.2105
-1.6201
-16.1026

-20.5380
-5.3572
-0.3997
-1.6137
-3.0119
-0.8522
-1.3024
-0.7802
-6.3271
-7.5715
-2.6281
-5.4538
-0.0298
-2.3310
-5.7477
-15.9160
-3.0560
-3.5972
-0.3718
-0.6515
-1.6384
-0.1422
-0.4127
-0.9868
-2.9589
-10.7583
-3.0229
-6.5992
-0.0013
-2.0932
-5.6057
-14.6777
-4.0906
-2.1624
-0.7266
-0.7775
-3.7264
-0.7542
-0.2738
-0.0001
-1.8491
-5.4953
-2.6138
-2.9688
-0.4718
-1.4024

-5.1317
-6.8046
-2.6503
-2.6617
-0.2970
-0.3734
-3.6432
-0.3552
-0.7897
-0.6454
-4.0286

(Weighted) Mean shadow value of CO₂ = -3.8435
(Weighted) 1995 SO₂ Mean shadow value = -119.1774
(Weighted) 1996 SO₂ Mean shadow value = -261.0716
(Weighted) 1997 SO₂ Mean shadow value = -297.7651
(Weighted) 1998 SO₂ Mean shadow value = -303.6555
(Weighted) 1999 SO₂ Mean shadow value = -204.5988

(Weighted) 1995 NO_x Mean shadow value = -110.0616
(Weighted) 1996 NO_x Mean shadow value = -227.8685
(Weighted) 1997 NO_x Mean shadow value = -145.0575
(Weighted) 1998 NO_x Mean shadow value = -184.1006
(Weighted) 1999 NO_x Mean shadow value = -125.7189

(Weighted) 1995 CO₂ Mean shadow value = -2.5537
(Weighted) 1996 CO₂ Mean shadow value = -4.7460
(Weighted) 1997 CO₂ Mean shadow value = -3.4717
(Weighted) 1998 CO₂ Mean shadow value = -4.2562
(Weighted) 1999 CO₂ Mean shadow value = -2.7230

(Weighted) Mean Shadow Value of SO₂ by plant=

-355.2610
-418.3837
-154.1900
-4.4970
-337.8402
-233.9734
-587.7049
-78.6605
-55.3504
-39.8802
-5058.7743
-154.0984
-217.4666
-83.0717

-139.4197
-142.7393

(Weighted) Mean Shadow Value of NO_x by plant=

-362.3555
-389.0123
-168.5641
-4.4957
-319.0190
-249.7415
-586.5454
-159.0770
-70.7321
-38.5699
-4563.1263
-146.4980
-199.9502
-83.0717
-131.7954
-154.1244

(Weighted) Mean Shadow Value of CO₂ by plant=

-7.3700
-2.5935
-3.6207
-0.1222
-1.7885
-4.6763
-11.7722
-8.1474
-3.0258
-0.3595
-0.6838
-2.7991
-0.4209
-0.5539
-0.5420
-3.4364

(Weighted) Mean Distance Function by plant =

0.8914
0.8885
0.7011
0.8539
0.8275
0.9598

0.9417
0.8070
0.6756
0.5819
0.7184
0.9079
0.5224
0.8171
0.7465
0.9624

1995-1999 Mean so2 emission by plant =

1.2972
1.1931
1.6146
5.5073
1.2696
1.3173
1.0847
2.2717
2.4382
2.4289
0.1280
1.9581
1.0792
1.5779
1.9934
1.4881