

Technology Innovations and Experience Curves for Nitrogen Oxides Control Technologies

Sonia Yeh

*National Risk Management Research Laboratory, Office of Research and Development,
U.S. Environmental Protection Agency, Research Triangle Park, NC*

Edward S. Rubin

Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA

Margaret R. Taylor

*Richard and Rhoda Goldman School of Public Policy, University of California, Berkeley, Berkeley,
CA*

David A. Hounshell

*Departments of Engineering and Public Policy and Social and Decision Sciences, Carnegie Mellon
University, Pittsburgh, PA*

ABSTRACT

This paper reviews the regulatory history for nitrogen oxides (NO_x) pollutant emissions from stationary sources, primarily in coal-fired power plants. Nitrogen dioxide (NO₂) is one of the six criteria pollutants regulated by the 1970 Clean Air Act where National Ambient Air Quality Standards were established to protect public health and welfare. We use patent data to show that in the cases of Japan, Germany, and the United States, innovations in NO_x control technologies did not occur until stringent government regulations were in place, thus "forcing" innovation. We also demonstrate that reductions in the capital and operation and maintenance (O&M) costs of new generations of high-efficiency NO_x control technologies,

selective catalytic reduction (SCR), are consistently associated with the increasing adoption of the control technology: the so-called learning-by-doing phenomena. The results show that as cumulative world coal-fired SCR capacity doubles, capital costs decline to ~86% and O&M costs to 58% of their original values. The observed changes in SCR technology reflect the impact of technological advance as well as other factors, such as market competition and economies of scale.

INTRODUCTION

Nitrogen oxides (NO_x) emissions have been associated with a wide variety of health and environmental impacts, including an increase in ground-level O₃, the formation of fine particles in the atmosphere, acid rain, the acidification of aquatic systems, and, more recently, global warming effects.¹ Such concerns have led to a series of government actions to reduce NO_x emissions from fossil-fueled, stationary combustion sources, as well as from mobile sources.

Environmental control strategies pertinent to control NO_x emissions from stationary power sources can generally be divided into two categories: primary measures involving combustion modifications and postcombustion NO_x flue gas treatment processes. Primary measures for NO_x control, such as burner optimization, air staging (overfired air or two-stage combustion), flue gas recirculation, fuel staging, and low-NO_x burners (LNBs), generally require relatively little capital investment and do not

IMPLICATIONS

Government regulation has been found to stimulate development and reduce costs of environmental pollution control. This paper examines the effects of governmental actions on patenting activity for NO_x control from stationary sources, suggesting that the stringency of emission regulations has a major influence on the magnitude and direction of patenting activities. Significant cost-improvements and technological-advancement, the so-called "learning-by-doing" phenomena, are found to be associated with the deployment of the SCR system, a high-efficiency NO_x control technology. This study provides a reasonable guide for future rates of technological progress for other environmental technologies.

entail the use of chemical additives or reagents. Postcombustion processes reduce the NO_x in the flue gas to nitrogen and water downstream of the furnace by using reagents such as ammonia (NH₃) or urea, either via selective noncatalytic reduction (SNCR) or via selective catalytic reduction (SCR) technologies. These processes are more costly than combustion modifications. Typical reduction capabilities of NO_x control range from 30 to 60% for primary measures, 30 to 50% for SNCR, and 70 to 90% for SCR systems.²

In response to government regulations, NO_x control technology has been passing through various phases as the regulatory and commercial climates have changed since the early 1970s. The next section of this paper briefly reviews the NO_x regulatory history in the United States, along with parallel developments in Japan and Germany. Section examines the patterns of innovations in NO_x control technologies in Japan, Germany, and the United States and relates these to the characteristics of

government regulations in place in each country at different points in time. Section 4 examines the historical trends in the cost of new SCR systems and characterizes those trends in the form of experience curves (or learning curves). Finally, section 5 summarizes the conclusions from this work and discusses issues that require future research.

EXPERIMENTAL WORK

NO_x Emission Control Requirements

Regulations in the United States. Table 1 summarizes major U.S. regulations for NO_x emissions from electric power plants. The Clean Air Act (CAA) of 1970 first established National Ambient Air Quality Standards for several pollutants linked to adverse human health effects, including nitrogen dioxide (NO₂) and ground-level O₃. Both pollutants are formed by chemical reactions that occur in the atmosphere, although some NO₂ is also emitted directly

Table 1. Major U.S. regulations for NO_x emissions from electric power plants.

Year	Regulation	Content
1970	Clean Air Act	Established national ambient air quality standards for NO ₂ and NSPS for new plants > 73 MWe. NO _x limits were 0.7 lb NO ₂ /MBtu of fuel burned for coal units, 0.3 lb/MBtu for oil-fired units and 0.2 lb/MBtu for gas-fired units.
1977	Clean Air Act Amendments	NSPS revised for coal-fired plants. New NO _x emission limits for units built after 1978 are 0.6 lb NO ₂ /MBtu (bituminous coal) and 0.5 lb/MBtu (subbituminous coal).
1990	Clean Air Act Amendments	Two major portions of the CAA affecting power plant NO _x control are Title I (National Ambient Air Quality Standards), and Title IV (Acid Rain Control). Regulations stemming from 1990 amendments are discussed below.
1994	Title I: OTC NO _x Budget Program	A regional NO _x emissions control program in 12 Northeastern states and the District of Columbia to help attain the health-related NAAQS for ground-level O ₃ . These reductions are in addition to previous state requirements that included the installation of reasonably available control technology. States committed to developing and adopting regulations to reduce region-wide NO _x emissions by 1999 with further reductions by 2003.
1995	Title IV: U.S. Acid Rain Control Program	A two-phased reduction in NO _x emissions from coal-fired power plants to control acid deposition. Phase I, finalized in 1995, sought to reduce NO _x emissions by over 400,000 t/yr between 1996 and 1999. Phase II tightened and extended these requirements to reduce NO _x emissions by over 2 Mt/yr from 1980 levels beginning in 2000.
1998	Title I: NO _x SIP Call	EPA issues a rule requiring 22 states and the District of Columbia to revise their State Implementation Plan to further reduce NO _x emissions by 1.2 Mt/yr by 2007. The rule gives each affected state a NO _x emission budget. States have flexibility to determine how to reduce emissions to achieve the specified target. The NO _x emissions limit used by EPA to calculate NO _x SIP call budgets is 0.15 lb/mmBtu.
1999	Title I: Section 126 Federal NO _x Budget Trading Program (NBP)	For states opting to meet the NO _x SIP Call requirements through a cap and trade program, EPA developed a model NO _x Budget Trading Program rule to facilitate cost-effective NO _x emissions reductions from large stationary sources. The model rule includes provisions for applicability, allocations, monitoring, banking, penalties, trading protocols and program administration. States can modify certain provisions of the model rule. The allowance trading component provides incentives for units to over-control if the cost is less than the market price of NO _x allowances.
2003	NO _x Budget Trading Program	NBP was implemented by eight northeastern states and the District of Columbia in 2003 and joined by eleven additional states in May 2004. Twenty-one states and the District of Columbia are participating or will participate in the future.

from high-temperature combustion processes, such as occur at power plants. Nitric oxide (NO) is formed in much greater quantities during combustion and is gradually oxidized to nitrogen dioxide (NO₂) once emitted to the atmosphere. The combination of NO and NO₂, referred to as NO_x, also contributes to acid rain and (together with volatile organic compounds) the formation of ground-level O₃. Under the 1970 CAA, however, existing power plants were largely unaffected by state-level requirements to achieve the NO₂ and O₃ air quality standards. Before 1990, most efforts to reduce NO_x emissions were directed at automotive sources.

Under the 1970 CAA, U.S. Environmental Protection Agency (EPA) also established New Source Performance Standards (NSPS) for major categories of new air pollution sources, including power plants. The NSPS was mandated to require Best Available Control Technology on all of the large new power plants. However, the NSPS levels of 1971 and 1979 imposed relatively modest requirements (see Table 1) that could be met at low cost using improved LNBs for combustion. During the decade of the 1970s, boiler manufacturers focused on developing field-demonstrated NO_x control technologies to meet the NSPS levels of 1971 and 1979. In the 1980s, with the reduced need for new utility generating capacity, emphasis shifted to retrofitable technologies to meet anticipated acid rain control legislation. Because NO_x also contributes to acidic deposition, the acid rain (Title IV) provisions of the 1990 CAA Amendments required many existing coal-fired plants to install LNBs and other cost-effective technologies. These requirements were introduced in two phases, with the goal of reducing power plant NO_x emissions by >2 Mt/yr from 1980 levels (see Table 1). The NO_x emission reductions for the purpose of compliance with Title I or Title IV (acid rain) could generally be met using low-cost combustion modification technologies, as seen in Figure 1.

During the 1990s, additional reductions in NO_x emissions were sought to achieve air quality standards for O₃. On January 1, 1994, the South Coast Air Quality Management District started the Regional Clean Air Incentives

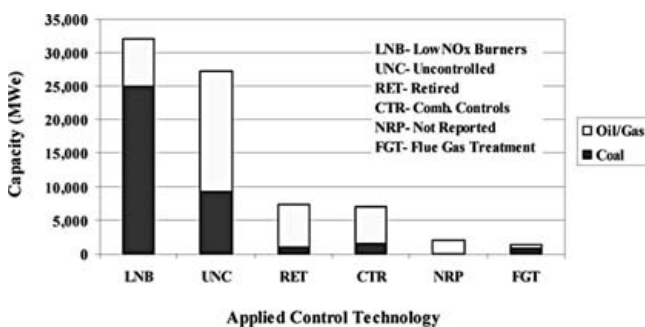


Figure 1. Total utility boiler capacity (coal and oil/gas) using NO_x control technology in 1996 Ozone Transport Region (OTR). Source: adapted from NESCAUM.³⁴

Market, which included a NO_x trading program. States in the Northeastern United States also cooperatively designed a regional NO_x cap and trade program to control transport of ground-level O₃ under the newly created Ozone Transport Commission. Market-based mechanisms for reducing NO_x emissions were subsequently introduced at the federal level as part of EPA NO_x State Implementation Plan Call in 1998, and by the Federal NO_x Budget Trading Program established in 1999. For the first time, the use of advanced NO_x control technologies, especially SCR, was needed to achieve the 75–90% regional NO_x reductions required to achieve air quality standards for O₃.^{3–5} By 2004, 19 states across the East and Midwest, plus the District of Columbia, joined the NO_x Budget Trading Program. The emission trading programs were designed to offer greater flexibility and financial incentives to reduce air pollution beyond what clean air laws and traditional command-and-control rules require.⁶ The overall result of NO_x regulations is a significant reduction in NO_x emissions from the electric sector. As shown in Figure 2, NO_x emissions from fuel combustion electric utility sources peaked in 1978, remained at approximately constant level through the mid-1990s, and declined sharply after 1998.

A massive expansion in SCR installations has been under way in the United States to meet the compliance deadline of 2004. EPA regulatory impact analyses predicted that to achieve overall NO_x SIP Call/Section 126 compliance, SCR retrofits would be installed at 142 utility units representing ~72,900 MW of capacity.⁷ A 1997 revision to the Federal NSPS for coal-burning plants also now requires a low level of NO_x emission currently achievable only with SCR systems in most cases.

Regulations in Japan and Germany. NO_x emission regulations in Japan were first established in 1973 and after review and revision were put into force in 1978 for both new and existing plants. Primary measures for NO_x control were widely used in coal-fired plants in combination with SCR. SCR installations started in 1977 for oil and gas-fired power plants and in 1980 for coal-fired boilers. Ambient NO₂ concentrations in Japan peaked in 1972 and have been decreasing steadily ever since to <40% of the highest level.

The most stringent and comprehensive emission requirements for stationary sources in Europe are found in Germany, which relies heavily on coal-fired power plants. In response to growing concerns about the effects of acid rain, the Statutory Ordinance for Large Furnaces was passed in June 1983 imposing control requirements on sulfur dioxide (SO₂) and NO_x emissions from both new and existing installations with a thermal heat input of

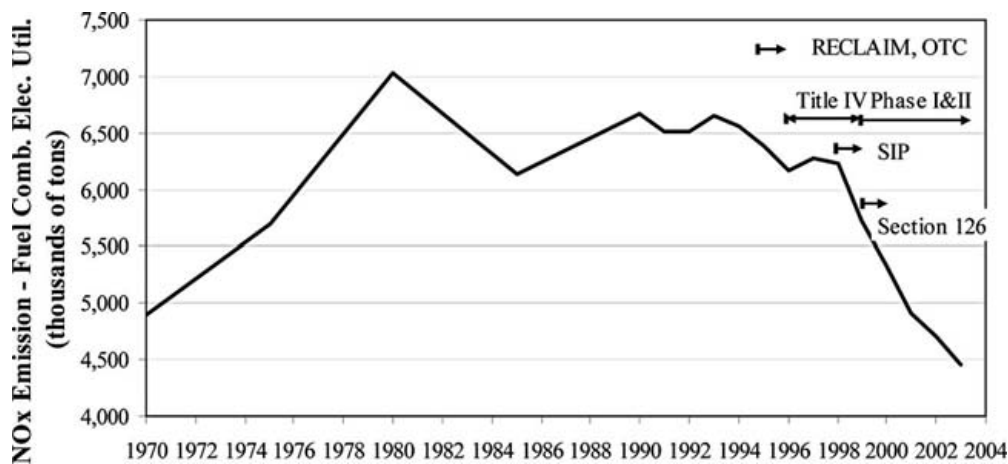


Figure 2. NO_x emissions from fuel combustion—electric power generator units (thousands of tons), 1970–2003.³⁵ See Table 1 for details on NO_x emission regulations for utility sector.

>50 MW. In 1984, the standards were tightened, necessitating the use of NO_x flue gas cleaning systems (principally SCR) on boilers of >300 MW. Later, under the United Nations Economic Commission for Europe protocol on the reduction of NO_x emissions, Germany committed itself to reducing NO_x emissions to 1987 levels by 1994. That goal was achieved and exceeded. More recently, Germany committed to reducing total NO_x emissions to 1051 kt/yr by 2010 under the European Union Directive on National Emissions Ceilings. The overall result has been that total NO_x emissions in 1999 were 39% below the 1970 level, despite significant increases in NO_x emissions from the transportation sector. NO_x emissions from the power and industrial sectors were reduced from 56% of total emission to 28% of the total today.⁸

NO_x Technology Innovation: Evidence from Patents

Patent Analysis Methodology. Researchers have long used patents as a measure of inventive activity,⁹ although applications to environmental technologies have been rather limited. A recent study of SO₂ control technologies by Taylor et al.¹⁰ showed that the anticipation of regulation on SO₂ spurred inventive activity and that the stringency of emission regulations appeared to provide a greater stimulus to inventive activity than government-sponsored research support alone. In particular, innovations in flue gas desulfurization (FGD) systems accelerated significantly in response to stringent regulatory requirements, with consequent cost reductions over a period of two decades. In this paper, the authors apply a similar method of patent analysis to examine innovation trends in NO_x controls that are relevant to technical solutions to NO_x emissions from stationary sources.

This patent activity analysis drew on data from the U.S. Patent and Trademark Office (USPTO) patent database from 1887 to 2003. The authors used an iterative

process to conduct patent analysis and to link inventive activity in NO_x control technologies to government actions. The first step was the identification of a few highly relevant NO_x control technology patents based on iteratively conducted, small-scale searches of the USPTO database. A list of potential USPTO class/subclass combinations was developed from these preliminary searches. Then, interviews were conducted with the U.S. patent examiners responsible for these classes to verify their relevance and to identify any other relevant classes applicable to technical solutions to NO_x emissions from stationary sources. This process yielded a “NO_x class-based dataset” of all of the patents in selected USPTO categories relevant to NO_x control between 1790 and July 2003.

Because the USPTO class designations also include patents unrelated to NO_x control, a second, abstract-based patent dataset was developed next to more selectively identify relevant patents. The preliminary searches conducted earlier were analyzed for frequently occurring keywords within the patent titles and abstracts. The resulting keywords and their likely variations were then used to conduct additional searches to identify relevant patents based on a reading of the full abstract. The process was repeated until the combination of keywords selected appeared to maximize the number of relevant patents and minimize the number of irrelevant patents captured with each search. The final list of keywords was then used to search the entire USPTO database for patents granted after January 1, 1976 (because patents from January 1976 to the present offer the full searchable text, whereas patents from 1790 to December 1975 offer only the patent number and the current U.S. patent classification in the text display and can be searched only by those two fields).

A detailed description of these two search methods (class-based and abstract-based) can be found in Taylor et al.¹⁰ In this paper, the authors combine the two methods

Table 2. U.S. patent classes and subclasses that comprise the NO_x patent dataset.³⁰

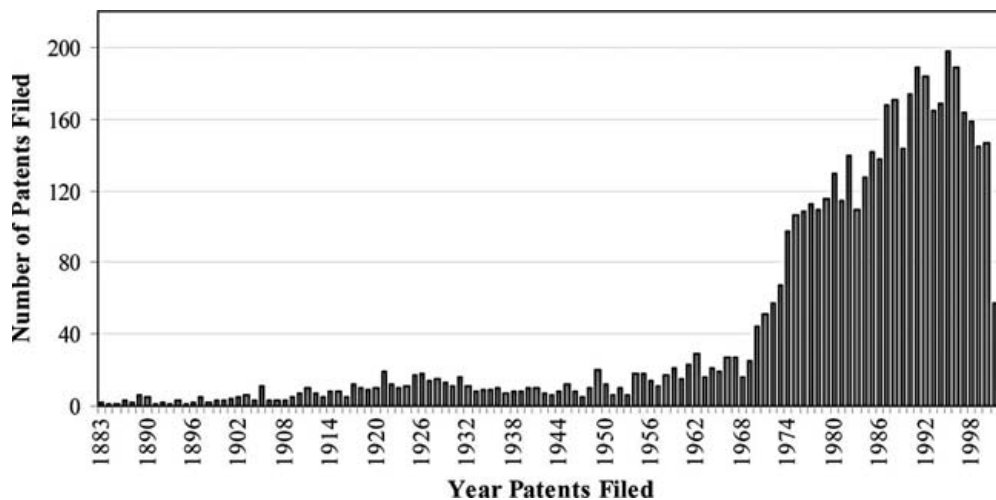
USPTO Patent	
Class/Subclasses	Definition of USPTO Class/Subclasses
423/235, 239.1	Class 423, the "chemistry of inorganic compounds," includes these subclasses representing (235) the modification or removal of nitrogen or nitrogenous components of a normally gaseous mixture, (239.1) including through use of a solid sorbent, catalyst, or reactant.
122/4D	Class 122, "liquid heaters and vaporizers," includes this subclass for miscellaneous boilers and boiler parts that are not otherwise classifiable.
110/345, 347	Class 110, "furnaces," includes these subclasses representing (345) processes to treat combustion exhaust gases, for example, in order to control pollution and (347) processes related to the burning of pulverized fuel.
431/4, 8-10	Class 431, "combustion" includes these subclasses representing a combustion process or burner operation that includes (4) feeding an additive to a flame in order to give it a special characteristic; (8) flame shaping or distributing components in a combustion zone; (9) whirling, recycling, or reversing flow in an enclosed flame zone; (10) supplying a distinct stream of an oxidizer to a region of incomplete combustion.

by examining the class/subclass in the abstract-based database, compare it with the list of class/subclass recorded previously in the class-based dataset, and select only those classes/subclasses that have high frequencies in the abstract-based database. The resulting class/subclass combinations that emerged from this method are displayed in Table 2. This list of class/subclass was used to search the entire USPTO database from 1790 to July 2003. The resulting dataset encompassed 5071 patents.

Patenting Activities over Time. Figure 3 displays the trend in NO_x-related patenting activities according to patent filing date. One sees a striking increase in activities beginning in 1970. Before then, the data averaged ~10 patents per year since the early 1900s. But between 1971 and 1984, patenting activity increased 10-fold to an average of 100 patents per year and continued to rise to an average of 165 per year from 1985 to 2000. The falloff in the last few years is largely an artifact of "truncation effects" in the dataset because of the time lag between file dates and

grant dates (in this dataset, the average lag time is 2.1 yr, ranging from 3 months to 20 yr). Thus, data after 2000 are not included in the analyses that follow. It is likely that there are other factors contributing to the drop of patent numbers after 1998. However, more data will be needed in the future to analyze whether it is a random fluctuation or a downward trend that can be attributed to other factors.

As elaborated below, the authors attribute the dramatic rise in post-1970 patenting activity as a response to NO_x emission regulations in Japan, Germany, and the United States. Whereas most of the patents filed before and after 1970 dealt with low-to-moderate levels of NO_x control via combustion modifications, higher efficiency chemical removal systems are prevalent only after 1970. In particular, patenting activity in the two class/subclass combinations of 423/235 and 423/239.1 increased significantly in the early 1970s, then rose sharply again in the mid-1980s and was sustained through the 1990s. These two class/subclasses were noted by patent examiners as

**Figure 3.** Patenting trends for technologies to control NO_x emissions from stationary power sources.

particularly pertinent to SCR and SNCR technology (see Table 2 for a more detailed description).

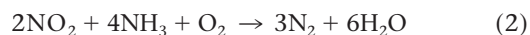
Patenting Activities by Nations. The importance of other nations in the NO_x innovation story is evident. On average from 1963 to 2000, the U.S.-based inventors held 62% of all USPTO patents, whereas Japan-based and Germany-based inventors held ~13% and 8%, respectively. However, the United States held only ~56% of all patents in NO_x control, whereas Japan and Germany held greater proportions (16% and 10%, respectively) than the average of their portfolio in all of the U.S. patents. Figure 4 shows the trends in "patent activity index," defined as the ratio of the patents of a country in NO_x control to their annual total national patent portfolio in the USPTO database for the class/subclass combinations of 423/235 and 423/239.1, that is, the classes relevant to postcombustion treatment. Patent Activity Index for country *i* in year *j* = (Number of NO_x patents for country_{*i*}/Number of NO_x patents for all countries)_{*i*}/(Number of patents for country_{*i*}/Number of patents for all countries)_{*j*}. The patterns and timing of high-patenting activity are consistent with the adoption of national regulations requiring postcombustion technologies, first in Japan (in the mid-to-late 1970s), then in Germany (in the mid-to-late 1980s). The U.S. activity index, however, shows no increased activity in postcombustion patents, consistent with the lack of sufficiently stringent standards requiring such technology before the late 1990s. Although one cannot assert causality from these data, the strong implication is that the stringency of regulatory requirements appears to be a major factor in accentuating the timing and magnitude of innovation activity pertinent to the SCR and SNCR patent classes.

Interestingly, there is a lack of high-patenting activity by U.S. inventors after the imposition of stringent NO_x control requirements in the mid-to-late 1990s. A plausible

explanation is that the United States is able to meet the more stringent regulations by acquiring mature high-efficiency SCR technologies or licensing patents on these technologies from Japan and Germany. The fact that Japan (e.g., Hitachi) and Germany (e.g., Siemens) are very important licensors of SCR technology supports this hypothesis. It remains to be seen, however, whether there will be a new burst of U.S.-based patenting activity in the post-2000 period, when most SCR retrofits of U.S. plants will occur.

NO_x Technology Innovation: Evidence from SCR Technology

SCR for NO_x Control. The authors are especially interested in SCR technology, because it represents the most effective (as well as the most costly) method of postcombustion emission control. The basic principle of SCR is the reduction of NO_x to N₂ and H₂O by the reaction of NO_x and NH₃ within a catalyst bed. The basic chemistry is as follows:



The reagent NH₃ is injected into the flue gas stream exiting the boiler. To achieve high (80–90%) NO_x removal, a catalyst operating at a high temperature is required. For this reason, a SCR system is typically located at the boiler exit upstream of the power plant air preheater. The control of NH₃ slip (excess NH₃ in the flue gas) is a secondary environmental impact of concern in SCR system design. Several different catalysts are available for use at different exhaust gas temperatures. The longest used and most common are base metal catalysts, which typically contain titanium and vanadium oxides and which

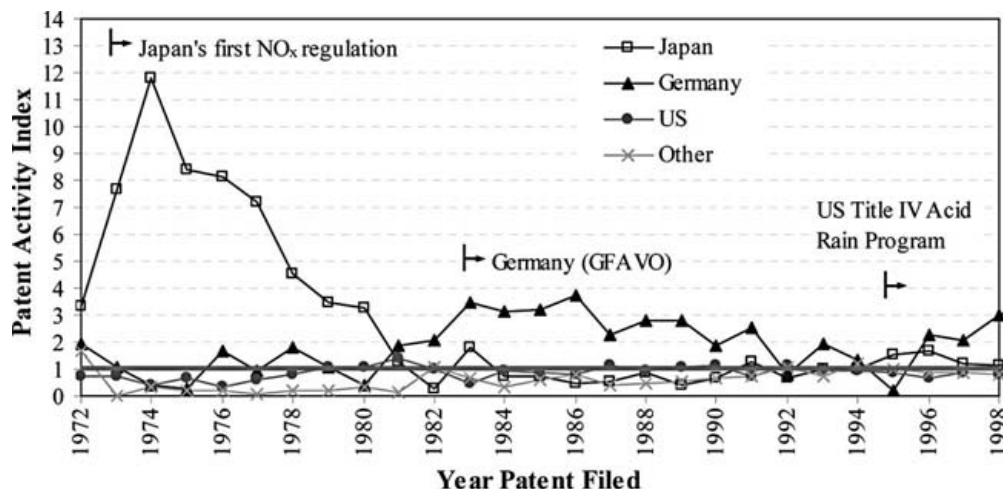


Figure 4. Patent activity indices by countries for patents in the main postcombustion control technology classes (423/235 and 423/239.1).

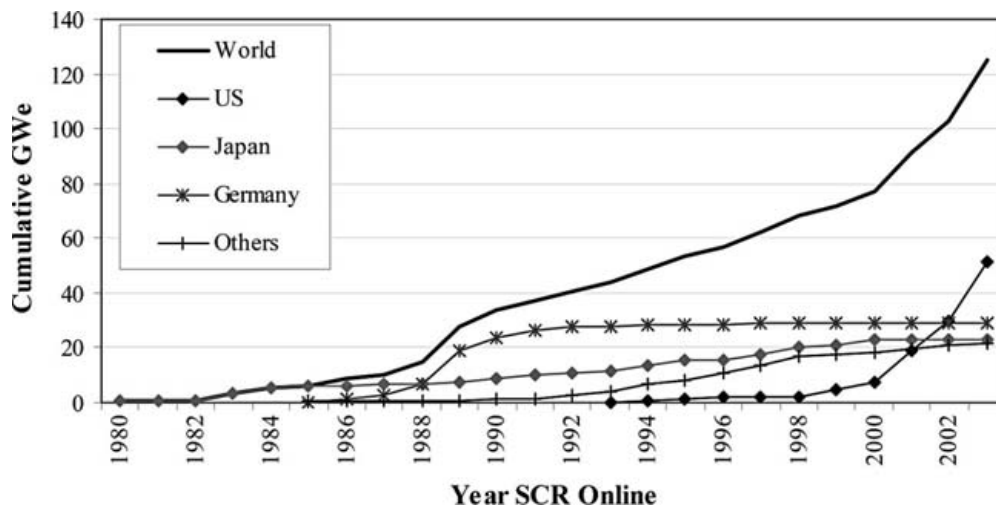


Figure 5. Cumulative installed capacity of SCR systems on coal-fired power plants in different countries.³⁶

also may contain molybdenum, tungsten, and other elements. The mechanical operation of an SCR system is relatively simple. It consists of a reactor chamber with a catalyst bed and an NH_3 handling and injection system, with the NH_3 injected into the flue gas upstream of the catalyst. The SCR catalyst can have different compositions based on titanium oxide, zeolite, iron oxide, or activated carbon. Most catalysts in use in coal-fired plants consist of a vanadium (active catalyst) and titanium (used to disperse and support the vanadium) mixture. However, the final catalyst composition can consist of many active metals and support materials to meet specific requirements in each SCR installation.¹¹

Worldwide Use of SCR Systems. Figure 5 shows the historical trend in the worldwide growth of the SCR capacity, which followed the introduction of stringent limits to regulate NO_x emissions in different countries. As noted earlier, the first use of SCR at coal-fired power plants was seen in Japan in 1980, followed by widespread adoption in Germany in the mid-1980s, and in other (mostly European) countries shortly afterward. The United States has lagged in SCR use, with the first unit on a coal-fired plant installed only in 1993. The principal reasons were the lack of stringent regulatory requirements, as well as projections of high cost and potential technical problems with U.S. high-sulfur coal.¹² However, the U.S. capacity of SCR systems is now expected to grow to ≥ 100 GW,^{4,7,13} far exceeding the capacity in all of the other countries combined.

Technological Change and Cost Trends. To examine the effects of technology change, cost trends for SCR systems were developed using historic cost studies for a new U.S. installation based on a standardized power plant design

(500 MWe, medium sulfur coal) and NO_x removal efficiency (0.6 lb/MBtu inlet NO_x , 80% NO_x removal). Where necessary, a detailed computer model¹⁴ was used to adjust key design parameters to a consistent basis, with all of the results adjusted to \$2000 using the chemical engineering construction cost index.

Figure 6 shows the resulting trend for SCR capital costs. The relevant measure of cumulative production in the X-axis was taken to be the worldwide capacity of coal-based SCR installations, as shown in Figure 5, to reflect the global nature of markets and innovations in these environmental technologies. Significant cost decreases have occurred as worldwide use of SCR systems has grown. This trend reflects the effects of investments in R&D, as well as learning by doing and other factors. Much of the decrease in capital cost is related to the initial cost of SCR catalyst, because SCR process improvements, coupled with improvements in catalyst manufacturing methods and competition among catalyst manufacturers, lowered both the total catalyst requirements and the unit cost of catalyst significantly.

Figure 7 shows the total annual operation and maintenance (O&M) costs estimated from several studies over a 13-yr period, again adjusted to a common basis. Whereas several factors contribute to O&M cost declines, the single dominant factor is the cost of replacement catalyst.^{15,16} Additional improvements in catalyst formulations have resulted in decreased unwanted side reactions, such as SO_2 to sulfur trioxide (SO_3) conversions, increased resistance to flue gas poisoning, and increased catalyst activity. Consequently, catalyst volumes needed to achieve a given level of NO_x reduction have decreased, and the operating life of catalysts has increased.¹⁷ The overall result has been a sharp drop in expected annualized O&M costs.

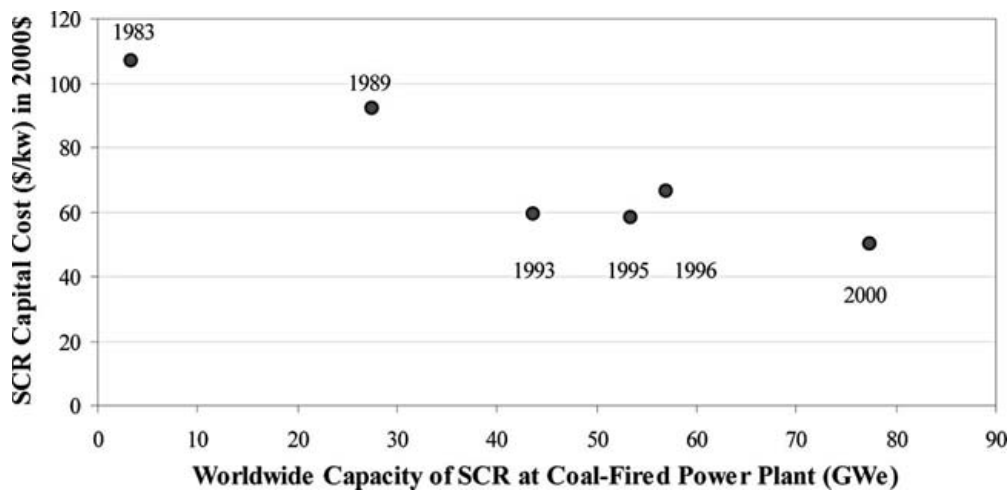


Figure 6. Capital cost of a new SCR system for a standard U.S. coal-fired power plant (500 MWe, medium sulfur coal, 0.6 lb/MBtu inlet NO_x, 80% NO_x removal) as a function of cumulative worldwide capacity of coal-based SCR installations.^{17,20,21,37,38}

The initial catalyst cost, the catalyst replacement cost, and catalyst life are the main drivers of SCR process economics. Much longer catalyst lives and lower catalyst prices have contributed substantially to reduced operating costs.^{15,16,18,19} For example, a 1985 study found that the cost of catalysts constituted ~30% of the total capital requirement and 88% of the total O&M cost.²⁰ By 1996, those ratios dropped to 16% and 43%, respectively (Figure 8).²¹ SCR catalyst prices in the United States dropped >70% in a 13-yr period (1987–2000) from \$830/ft³ to \$220/ft³ (in constant 2000 dollars) (Figure 9). Over that period, there was no observable relationship between the price of a SCR catalyst and the prices of constituent minerals (mainly vanadium and titanium) in the world commodity markets.²² The expected lifetime of SCR catalysts also improved significantly over the past 20 yr (Table 3). SCR economic evaluations in the 1980s normally assumed a 1-yr (5700-hr) catalyst life (e.g., Damon et al.²³).

As more experience was gained, the expected lifetime has increased 10-fold (see Table 3), in part from the use of sophisticated catalyst management methods.²⁴

Experience Curves for SCR Systems. Research dating back to 1936 found that the rate of improvement in a wide range of technologies was well-described by an equation of the form:

$$y_i = ax_i^{-b} \quad (3)$$

where, y_i is the time or cost to produce the i^{th} unit of product, x_i is the cumulative production through period i , a is the coefficient (constant), and b is the learning rate exponent (constant). According to this equation, each doubling of cumulative production results in a time or cost savings of $(1 - 2^{-b})$. The latter quantity is defined as

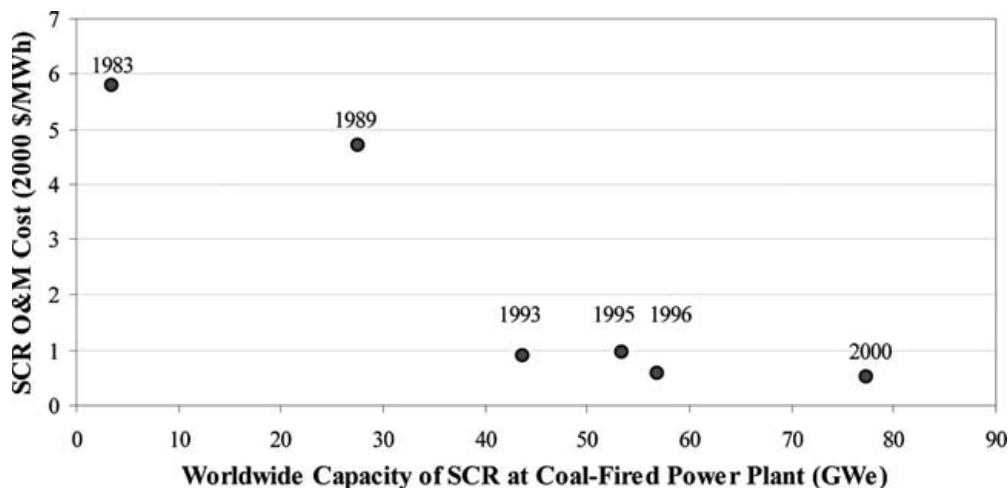


Figure 7. Annualized O&M cost of a new SCR system for a standard U.S. coal-fired power plant (500 MWe, medium sulfur coal, 0.6 lb/MBtu inlet NO_x, 80% NO_x removal, 65% capacity factor) as a function of cumulative worldwide capacity of coal-based SCR installations.^{17,20,21,37,38}

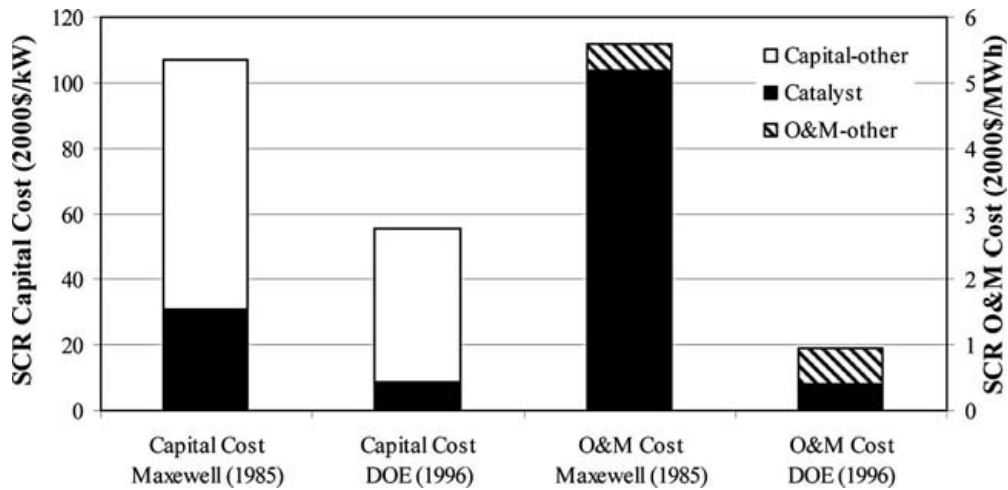


Figure 8. Cost breakdown of SCR capital and O&M costs at a standard new U.S. coal-fired power plant. “Capital other” includes reactor housing, ductwork, NH₃ storage and handling, contingency, and royalty. “O&M Others” includes the cost of NH₃, operating labor, utilities, maintenance, overhead, and administrative costs.

the learning rate, whereas the quantity 2^{-b} is defined as the progress ratio. This equation has been used extensively to describe the phenomenon of learning by doing and, more generally, the combined effect of experience and other factors on technology cost trends (hence, the term “experience curve”). Systematic reviews of this extensive literature can be found elsewhere.^{25–28}

Figure 10 shows that when the data from Figures 6 and 7 are fitted to eq 1, the learning rates are ~14% for the capital cost and 42% for the O&M cost for an SCR system fitted to a new coal-fired power plant. Thus, as cumulative world coal-fired SCR capacity doubled, capital costs declined to ~86% and O&M costs to ~58% of their original values. Also recall that these data are for a standardized new plant and do not apply to SCR retrofit systems, of which the costs tend to be higher and more variable because of the site-specific difficulties typically encountered at an existing plant. In general, the capital cost of a

retrofit unit is estimated to be 20–50% higher compared with that of a new application.¹⁷

Although the authors used the standard log-linear experience curve (eq 1) to characterize SCR learning rates in the United States, the data in Figure 10 for both capital and O&M costs are better described by a concave rather than log-linear shape in the early part of the curve. This is probably an artifact of the lack of early experience with SCR in the United States. Before 1993, there were great uncertainties about the applicability and reliability of SCR for coal-fired power plants in the United States. A number of technical problems were anticipated because of the much higher sulfur content of U.S. coals relative to those used in Japan and Germany, and such concerns were reflected in more conservative and more costly designs for U.S. plants. Cumulative foreign experience and later applications with U.S. coals subsequently demonstrated that less conservative (and less expensive) designs were indeed

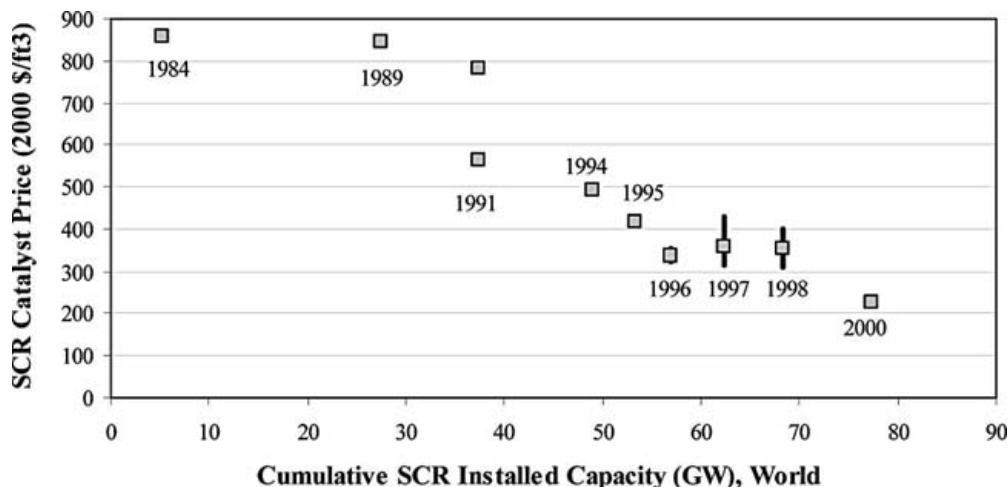


Figure 9. Trend of SCR catalyst unit cost, 1984–2000.

Table 3. Estimated catalyst lifetime in economic assessment studies.

Year	Catalyst Lifetime (Operation Hours)			Description
	Base Estimate	Low Value	High Value	
1984	5694	5694	11,388	Catalyst life guarantees are usually 1 yr. ^{20,31} Limited operational experiences on coal-fired boilers.
1987	5694	5694	28,470	Catalyst life is generally specified at 1 yr, but manufacturers expect a 2–3 yr life. ¹²
1991	22,776	5694	39,858	A 4-yr catalyst life was used in the cost development, 6 yr of use is closer to the currently expected life. ³²
1994	22,776	17,082	22,776	Sophisticated management by partially replacing the catalyst can lengthen catalyst life to the range of 3 to 11 yr for a coal-fired power station. ²⁴ New coal-fired boilers (e.g., Carneys Point, 1993; Logan, 1994) are securing vendor guarantees of a 10-yr catalyst life. ³³
1997		24,000	48,000	The effective SCR catalyst life at coal-fired boilers is now expected to be about nine years, with some power plants (currently in operation) expect their catalyst effective life of 8–14 yr. ¹⁶

viable for U.S. facilities. A number of technological improvements also contributed to the reduction of capital cost, such as efficient catalyst designs that reduced the size and cost of the support structures, sophisticated catalyst management practices, and advanced flow modeling that allowed uniform gas flow and lower NH₃/NO_x ratios, which reduced the required catalyst volumes. Improvement to both catalyst geometry and composition led to cost reductions as compared with earlier generations of these products. For example, in the period 1988–1993, initial volumes of catalyst were reduced by 30–35% without sacrificing the performance of NO_x reduction.¹¹ As demand for SCR systems grew, market competition also contributed to the observed cost reductions.

Note that the potential contribution of SCR experience at oil-fired and gas-fired facilities is not reflected in these estimates, in part because of data limitations, but also because many of the designs and technical problems

associated with coal-fired plants (such as high-fly-ash loadings and trace contaminants that can poison SCR catalysts) do not apply in these cases. Nonetheless, to the extent that any spillover effects from these SCR markets have benefited coal-fired plants, the learning rates derived in this study would decline slightly as the experience base (cumulative capacity) is expanded. In 1997, retrofit SCR systems in the United States were in operation on 5.5 GW of gas-fired utility boilers and ~7.8 GW of gas turbines.¹⁶

DISCUSSION AND CONCLUSIONS

The history of NO_x control at U.S. power plants was characterized by relatively weak regulatory demands before 1995, requiring only the use of inexpensive LNBS and other combustion controls at new power plants; relatively few existing plants (mainly gas-fired facilities) were affected by stationary source NO_x regulations before 1995. Accordingly, the technological response in the United

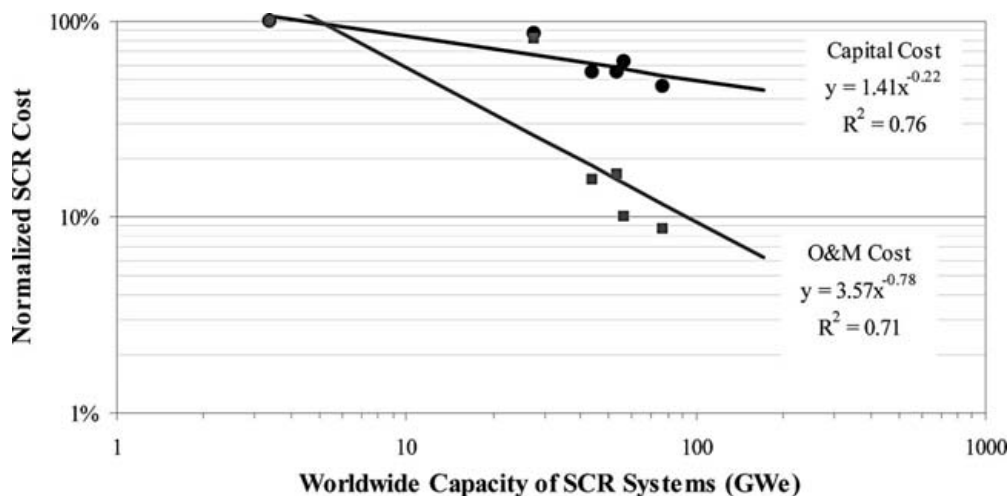


Figure 10. The experience curves of capital and O&M costs for SCR systems. Based on eq 1 using data from Figures 6 and 7. The regression exponents correspond to learning rates of 14% and 42% for capital and O&M costs, respectively.

States was focused largely on the development of primary (combustion-based) controls. In contrast, postcombustion SCR technology achieving higher levels of NO_x reduction was deployed widely on coal-fired power plants in Japan, Germany, and other European countries in response to stringent emission regulations adopted in those countries in the late 1970s and 1980s. Technology innovation activities in Japan and Germany also showed a strong focus on advanced postcombustion systems. SCR technology, much of it licensed from Japanese or German firms, was subsequently deployed at U.S. coal plants in the mid-1990s to meet more stringent NO_x regulations aimed mainly at ground-level O₃ control.

The history of SCR deployment at U.S. power plants contrasts sharply with the widespread deployment of postcombustion FGD systems for SO₂ control at U.S. power plants during the 1970s and 1980s, which generally preceded their later adoption in Europe. The study by Taylor et al.¹⁰ demonstrated that the stringent SO₂ regulations during that era evoked a strong response in terms of U.S.-based technological innovations that substantially reduced the cost of FGD systems.

The results from this patent analysis of NO_x control technology appear to confirm the finding of Taylor et al.¹⁰ that the stringency of emission regulations has a major influence on the magnitude and direction of inventive activities on emission control technologies. The substantial increase in the number of patents filed for NO_x control technology for stationary sources coincided with the adoption of federal regulations in Japan, Germany, and the United States. Especially significant was the trend in patenting activity in postcombustion technology by innovators in Japan and Germany: Japanese patents surged from 1974 to 1980, and German patents rose markedly from 1982 to 1992. In both instances, these eras of surging innovation corresponded with periods in which stringent regulations were being imposed in those countries. In contrast, no analogous increase in U.S.-based activity in postcombustion controls was observed during that period, consistent with the lack of regulations that required such technology at the time. These findings lend additional support to the link between regulatory stringency and the direction of environmental control technology innovation.

A limitation of this study is that it examines only technological learning and cost reductions for SCR systems installed at a representative new plant. This study does not consider costs for SCR retrofits nor cost reductions that may occur through learning by using after an SCR system is installed at a plant. However, evidence that learning by using may reduce annual O&M costs within a plant can be found in reports of SCR impacts on other environmental control equipment and on the power

plant itself.¹⁸ Hot-side SCR, the dominant design in the United States, is located directly downstream of the boiler and upstream of the air preheater and, thus, affects every component of the flue gas train, as well as the boiler (through economizer/air preheater interactions). SCR process improvements that have been reported include reductions in NH₃ slip that eliminated plugging of the air preheater, with additional benefits to the wastewater treatment system. Additional issues related to technological learning, including issues of technology and cost uncertainties, are discussed and analyzed elsewhere.²⁹

ACKNOWLEDGMENTS

The authors thank Dr. Ravi K. Srivastava for helpful comments on an earlier draft of the paper. This project was supported by the Office of Biological and Environmental Research, U.S. Department of Energy, under Grant No. DE-FG02-00ER63037.

REFERENCES

1. Price, D.; Birnbaum, R.; Batiuk, R.; McCullough, M., Smith, R. Nitrogen Oxides: Impacts on Public Health and the Environment; EPA-452/R-97-002 (NTIS PB98-104631); U.S. Environmental Protection Agency; Office of Air and Radiation: Washington, DC, 1997.
2. Srivastava, R.; Hall, R.E.; Khan, S.; Culligan, K., Lani, B.W. NO_x Emission Control Options for Coal-Fired Electric Utility Boilers; *J. Air & Waste Manage. Assoc.*, in press.
3. Krolewski, M.J.; Mingst, A.S. Recent NO_x Reduction Efforts: An Overview; Clean Air Markets Division, Office of Atmospheric Programs, U.S. Environmental Protection Agency: Washington, DC, 2000.
4. Power Companies' Efforts to Comply with the NO_x SIP Call and Section 126; Northeast States for Coordinated Air Use Management: Boston, MA, 2001; p 13.
5. Controlling Nitrogen Oxides Under the Clean Air Act: A Menu of Options; State and Territorial Air Pollution Program Administrators and the Association of Local Air Pollution Control Officials: Washington, DC, 1994.
6. NO_x Budget Trading Program: 2003 Progress and Compliance Report; U.S. Environmental Protection Agency: Washington, DC, 2004.
7. Regulatory Impact Analysis for the NO_x SIP Call, FIP, and Section 126 Petitions; U.S. Environmental Protection Agency, Office of Air and Radiation: Washington, DC, 1999.
8. German Environment Index Air; The Federal Environmental Agency (UBA): Dessau, Germany; 2004.
9. Griliches, Z. Patent Statistics as Economic Indicators: A Survey; *J. Econ. Lit.* **1990**, *28*, 1661-1707.
10. Taylor, M.; Rubin, E.S.; Hounshell, D.A. The Effect of Government Actions on Technological Innovation for SO₂ Control; *Environ. Sci. Technol.* **2003**, *37*, 4527-4534.
11. Soud, H.; Fukasawa, K. *Developments in NO_x Abatement and Control*. IEA Coal Research: London, United Kingdom, 1996; p 123.
12. Damon, J.E.; Ireland, P.A.; Giovanni, D.V. Updated Technical and Economic Review of Selective Catalytic NO_x Reduction Systems. In *1987 Symposium on Stationary Combustion Nitrogen Oxide Control*. Electric Power Research Inc.: New Orleans, LA, 1987; CS-5361s. 13.
13. *SCR Projects Bid and Award Tracking*; The McIlvaine Company: Northfield, IL; 2002.
14. Integrated Environmental Control Model (IECM); developed for U.S. Department of Energy by Carnegie Mellon University, available at <http://www.iecm-online.com> (accessed November 8, 2005).
15. Hjalmarsson, A-K. *NO_x Control Technologies for Coal Combustion*; IEA Coal Research: London, United Kingdom; 1990.
16. Selective Catalytic Reduction (SCR) Control of NO_x Emissions; SCR Committee of Institute of Clean Air Companies, Inc: Washington, DC, 1997; p 33.
17. Foerter, D.; Jozewicz, W. Cost of Selective Catalytic Reduction (SCR) Applications for NO_x Control on Coal-Fired Boilers; U.S. Environmental Protection Agency, Office of Research and Development: Washington, DC, 2001.
18. Performance of Selective Catalytic Reduction (SCR) on Coal-Fired Steam Generating Units. Office of Air and Radiation, U.S. Environmental Protection Agency: Washington, DC, 1997.

19. Environmental Regulation and Technology Innovation: Controlling Mercury Emissions from Coal-Fired Boilers; Northeast States for Coordinated Air Use Management: Boston, MA, 2001.
20. Maxwell, J.D.; Humphries, L.R. Economics of Nitrogen Oxides, Sulfur Oxides, and As Control Systems for Coal-Fired Utility Power Plants. U.S. Environmental Protection Agency: Washington, DC, 1985; p 277.
21. Healy, E.C.; Maxwell, J.D.; Hinton, W.S. Demonstration of Selective Catalytic Reduction (SCR) Technology for the Control of Nitrogen Oxide (NO_x) Emissions from High-Sulfur Coal-Fired Boiler; Final Report; Southern Company Services, Inc.: Birmingham, AL, 1996.
22. Minerals Information: Commodity Statistics and Information. U.S. Geological Survey: Washington, DC; 2001.
23. Damon, J.E.; Scheck, R.W.; Cichanowicz, J.E. Economics of SCR Post Combustion NO_x Control Processes. In *Proceedings of the 1982 Joint Symposium on Stationary Combustion NO_x Control. Volume 1: Utility Boiler Applications*; Electric Power Research Institute: Palo Alto, CA, 1983.
24. Takeshita, M. *Air Pollution Control Costs for Coal-Fired Power Stations*; IEA Coal Research: London, UK, 1995.
25. Arrow, K. The Economic Implications of Learning by Doing; *Rev. Econ. Studies* **1962**, *29*, 155-173.
26. Yelle, L.E. The Learning Curve: Historical Review and Comprehensive Survey; *Decision Sci.* **1979**, *10*, 302-328.
27. Dutton, J.M.; Thomas, A. Treating Progress Functions as a Managerial Opportunity; *Acad. Manage. Rev.* **1984**, *9*, 235-247.
28. McDonald, A.; Schrattenholzer, L. Learning Rates for Energy Technologies; *Energy Policy* **2001**, *29*, 255-261.
29. Yeh, S.; Rubin, E.S.; Hounshell, D.A. On the Use of Technology Experience Curves in Integrated Assessment Models (working paper); Carnegie Mellon University: Pittsburgh, PA, 2004.
30. Patents Bibliographic Database; U.S. Patent and Trademark Office: Washington, DC; 2003.
31. Control Techniques for Nitrogen Oxides Emissions from Stationary Sources, Revised 2nd ed.; U.S. Environmental Protection Agency: Research Triangle Park, NC, 1983.
32. Robie, C.P.; Ireland, P.A. Technical Feasibility and Cost of Selective Catalytic Reduction (SCR) NO_x Control; Prepared by United Engineers and Constructors, Inc. for the Electric Power Research Institute: Palo Alto, CA, 1991.
33. OTAG Technical Supporting Document: Appendix A. States' Report on Electric Utility Nitrogen Oxides Reduction Technology Options for Application by the Ozone Transport Assessment Group; Ozone Transport Assessment Group: Springfield, IL, 1996.
34. Status Report on NO_x Control Technologies and Cost Effectiveness for Utility Boilers; Executive Summary; Northeast States for Coordinated Air Use Management: Boston, MA, 1998.
35. Air Trends: Nitrogen Oxides National Emissions Totals; U.S. Environmental Protection Agency. Washington, DC; 2004.
36. Soud, H. IEA Coal Research, London, United Kingdom. Personal communication, 2001.
37. Robie, C.P.; Ireland, P.A. Technical Feasibility and Cost of Selective Catalytic Reduction (SCR) NO_x Control; Prepared by United Engineers and Constructors, Inc. for the Electric Power Research Institute: Palo Alto, CA, 1991.
38. Rao, S.N.; McIlvried, H.G.; Mann, A. Evaluation of NO_x Removal Technologies. Volume 1. Selective Catalytic Reduction. Revision 1; Burns & Roe Services Corporation, prepared for the U.S. Department of Energy, Pittsburgh Energy Technology Center: Pittsburgh, PA: 1994.

About the Authors

Sonia Yeh is the Oak Ridge Institute for Science and Education Research Fellow in the U.S. Environmental Protection Agency Postdoctoral Research Program, Office of Research and Development, and adjunct assistant professor at the Department of Engineering and Public Policy, Carnegie Mellon University. Edward S. Rubin is the Alumni Professor of Environmental Engineering and Science at the Departments of Engineering and Public Policy and Mechanical Engineering at Carnegie Mellon University. Margaret Taylor is an assistant professor of Public Policy at the Richard and Rhoda Goldman School of Public Policy, at the University of California, Berkeley. David A. Hounshell is the David M. Roderick Professor of Technology and Social Change at the Departments of History, Social and Decision Sciences, and Engineering and Public Policy at Carnegie Mellon University. Address correspondence to: Sonia Yeh, National Risk Management Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Research Triangle Park, NC 27711; phone: +1-919-541-0809; fax: +1-919-541-7885; e-mail: yeh.sonia@epa.gov.

Copyright of Journal of the Air & Waste Management Association (1995) is the property of Air & Waste Management Association. The copyright in an individual article may be maintained by the author in certain cases. Content may not be copied or emailed to multiple sites or posted to a listserv without the copyright holder's express written permission. However, users may print, download, or email articles for individual use.