

**The Effect of Government Actions on
Environmental Technology Innovation:
Applications to the Integrated Assessment of
Carbon Sequestration Technologies**

A Mid-Project Progress Report submitted under
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Integrated Assessment of Global Climate Change Research

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I. Background and Motivation

A. Project Goals

Assumptions about technological innovation and diffusion are among the most important uncertainties in integrated assessment models used to study global climate change and the impacts of climate policy options. Most integrated assessment models use fairly simple metrics and methods to characterize technological innovation. For example, the cost of a technology or an energy carrier might be assumed to decrease over time in some exogenously-specified manner. Or the concept of autonomous energy efficiency might be invoked to predict reductions in future energy demand growth due to technological change. In some cases, assumptions about “backstop” technologies and technology “learning curves” are used to guide integrated assessment efforts and to estimate future technology costs and capabilities. Several models are beginning to incorporate more sophisticated methods that treat technological change endogenously.

Whatever the method used to model or characterize the role of technological innovation and diffusion, scenarios of future environmental change, and the predicted impacts of proposed policy measures, depend critically upon these assumptions. The purpose of the present project is to substantially improve the capability to model technological innovations for an important new class of environmental technology: carbon capture and sequestration. Understanding the effects of government actions on technological innovation will be particularly important to a successful effort in this area.

B. Report Goals

This mid-project report seeks to convey progress on and early results of our research project. In our original proposal, we stated that we would carry out our work in four phases:

(1) extension and refinement of the newly developed prediction and assessment methods for sulfur dioxide control technologies; (2) application and further refinement of these methods to another class of environmental technology relevant to global change, but with different regulatory attributes; (3) application of the refined methods to carbon sequestration technologies; and (4) using the IIASA-ECS models, together with the results of the first three phases, to assess prospects for carbon sequestration technologies in an integrated assessment framework.

The project has stayed close to this plan, as is made clear in this report.

Section II below is one of the report's two major sections. It reports our refined data and analysis of patterns of innovation in SO₂ control technologies in the United States from 1887 to 1999 and how these patterns are correlated with the timing and stringency of regulations of the pollutant in stationary electric power plants. The section further reports on "experience curves" and "experience functions" of commercial technologies developed to meet these regulations. In addition, it reports on our initial application of these experience functions to carbon capture and management technology scenarios in IIASA's Integrated Assessment model. This preliminary exercise yielded results that differed significantly from earlier runs carried out with the model that either ignored or used different assumptions about rates of learning in stationary electric power plants.

Section III below is the report's other major section. It reports our data and analysis of patterns of innovation in NO_x control technologies in the United States during the post-World War II period and how these patterns are correlated with the timing and stringency of regulations of the pollutant in stationary electric power plants. NO_x regulation differed significantly from

SO₂ regulation, and the section demonstrates how the different regulatory regimes yielded different patterns of innovation in and development of NO_x control technologies than those for SO₂. The section also reports on experience curves and experience functions of NO_x control technologies for commercial electric power plants. Finally, it discusses how these functions differ from those derived from the SO₂ case, as well as how the NO_x functions can be applied to carbon capture and management technology scenarios in IIASA's Integrated Assessment model

Section IV presents preliminary results of our initial screening of carbon capture and sequestration patents using methods developed for analyzing innovation in SO₂ and NO_x control technologies. We comment briefly on these preliminary yields in light of anticipated regulation in carbon emissions.

Section V describes our interaction with the principals of other IA models and suggests our plans for further work with these principals.

Finally, Section VI presents our general conclusions about the state of our project at its mid-point and plans for the final phases of the project.

Relevant appendices are also included.

II. The Case of SO₂ Control Technologies

A. Overview

Sulfur dioxide (SO₂) is primarily emitted to the atmosphere through the burning of sulfur-containing materials, of which fossil fuels such as coal and oil are the most important examples. SO₂ is, therefore, the byproduct of many long-standing economically productive processes. Although the importance of selected sources of SO₂ emissions in the United States has changed over time, coal-fired electric power plants have been the primary source of these emissions since 1960. Public concern about SO₂ pertains to its negative effects both on human health and on ecosystem well being.

For over three decades, government actions in the United States have had a considerable influence on the development of SO₂ control technologies. Innovation in these technologies (which includes the processes of invention, adoption and diffusion, and learning by doing) has been affected by organizational actors such as FGD vendors, utilities, and the government.¹ To the first order, government is vital to innovation in SO₂ control technologies because it has worked to define, through such actions as legislation, executive orders, and litigation, the need for emission control that abatement technologies seek to address. Some of these government actions, however, have been used not only to define the rationale for and level of SO₂ emissions reductions needed, but have also defined, in various ways, the manner in which emissions reductions should be achieved.

¹ “Invention” refers to the development of a new technical idea. “Adoption” refers to the first commercial implementation of an invention. “Diffusion” refers to the process by which an adopted technology enters widespread use. Diffusion is often studied as a communication process. Finally, “learning by doing” refers to post-adoption innovative activities that result from knowledge gained from operating experience. Studies have shown that a considerable amount of innovative activity can be traced to operating personnel or to the contact of other researchers with operating personnel. See Rogers (1995), Rosenberg (1994), Schumpeter (1942), and Cohen and Levin (1989).

For example, SO₂ legislation and its sometimes-accompanying regulation, has: proposed financial incentives for installing abatement equipment; set the stringency of emissions control that technological solutions must meet; defined the flexibility and time constraints that SO₂ polluting organizations have to address abatement requirements; and defined – through their scope – the market size of equipment suppliers. In addition, government has funded research, training, and technical assistance programs including demonstration projects, grants to vendors, and technology transfer opportunities that directly affected the operation and design of equipment used to control SO₂ emissions.

Environmental technology strategies pertinent to SO₂ emissions take one of three approaches: (1) alternative power generation technologies such as fluidized bed combustion and synthetic fuels; (2) pre-combustion reduction of sulfur in the burning of lower-sulfur fuels, either naturally as in the case of switching to low-sulfur coal, or technologically through the removal of sulfur from existing coals; and (3) removal of SO₂ from the post-combustion gas stream.² Only the latter two of these strategies, pre-combustion and post-combustion removal, involve a technological response relevant to the standard coal-fired power generation processes generally in use over the last thirty years.³ Pre-combustion control technologies primarily involve physical removal processes such as crushing and grinding to remove inorganic sulfur in the form of pyrite from coal. More advanced chemical and biological pre-combustion technologies exist that can also remove some of the organic sulfur from coal for a greater overall SO₂ emission reduction, but these processes are costly and exist only in non-commercial stages. None of these pre-

² Sub-bituminous and lignite coals, found primarily in easily surface-mined deposits in the western U.S., are typically lower in both heat and sulfur content. Bituminous and anthracite coals, found primarily in deposits that are deep-pit mined in the eastern U.S., are typically higher in heat and sulfur content (Laitos and Tomain, 1992, p. 450).

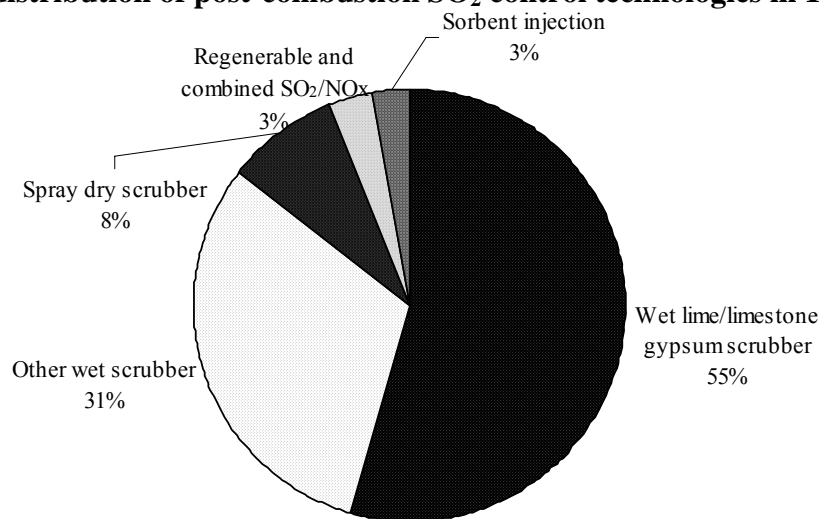
³ Tall gas stacks that disperse SO₂ from local areas were once promoted by the electric power industry as an effective method of controlling SO₂ emissions from existing generation processes. These are no longer relevant because of regional concerns about SO₂ and acid rain.

combustion technologies, however, removes as much SO₂ as post-combustion control technologies.

These technologies, which are installed on roughly 90 gigawatts (or about one-third) of U.S. electrical capacity, can be grouped under such names as “flue gas desulfurization” (FGD) systems or “scrubbing” technologies. FGD systems involve contacting a post-combustion gas stream with a base reagent in order to remove SO₂. These systems can be categorized as wet, dry, or other, following an article by Jozewicz et. al., in 1999. Wet FGD processes include wet throwaway and gypsum by-product processes involving reagents like limestone, lime, dolomitic lime, sodium carbonate, and seawater. Dry FGD technologies include the throwaway processes of spray drying, sorbent injection into the furnace, boiler, or downstream duct, and circulating fluidized bed. Other FGD processes include regenerable processes with reagents such as sodium sulfite (Wellman-Lord) and magnesium oxide, as well as combined sulfur oxide/nitrogen oxide technologies. Figure 1 demonstrates the distribution of installed post-combustion SO₂ control technologies around the world.

FIGURE 1

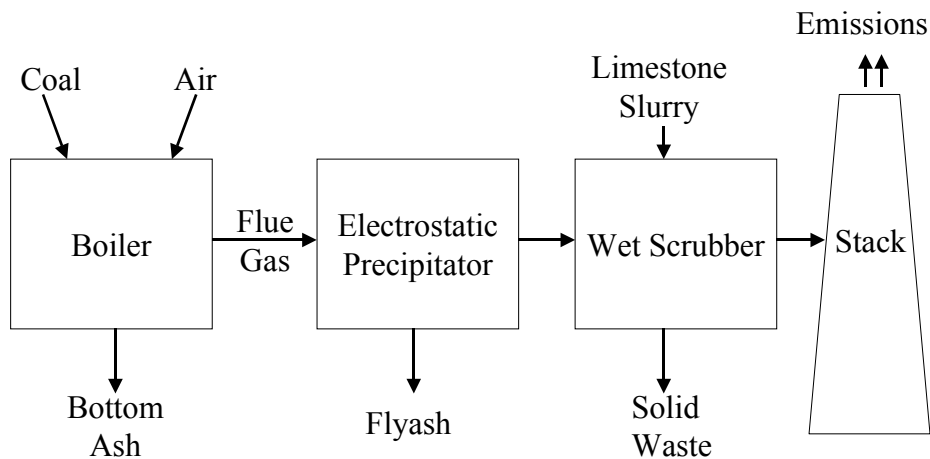
World market distribution of post-combustion SO₂ control technologies in 1994, by type.



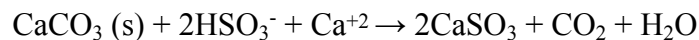
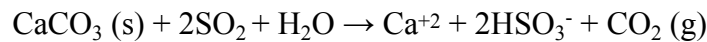
Source: Soud (1994)

The dominant wet FGD systems use limestone as the scrubbing reagent and today achieve reliable, 95%+ SO₂ removal efficiencies.⁴ Figure 2 shows a simple schematic of a wet limestone FGD system. In the wet scrubber in this figure, limestone slurry is typically contacted with flue gas in a gas absorber where SO₂ is absorbed, neutralized, and partially oxidized to calcium sulfite and calcium sulfate.⁵ Equation 1 displays the overall stoichiometry of the limestone SO₂ absorption process, and Figure 3 demonstrates the diffusion over time of wet scrubbers of the lime or limestone type around the world.

FIGURE 2
Schematic of a typical wet limestone FGD system.



EQUATION 1
Stoichiometry of the limestone SO₂ absorption process.



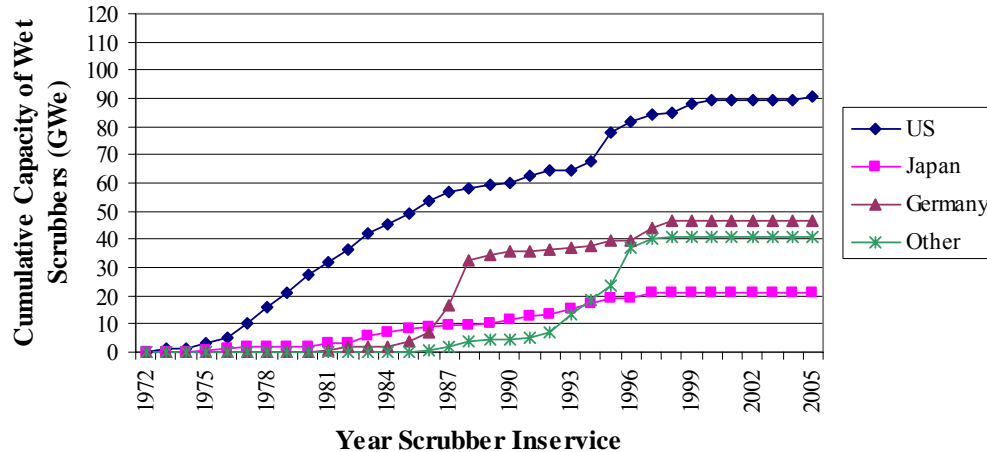
Source: (Cooper and Alley, 1994, p. 454)

⁴ Wet limestone scrubbing is dominant in the worldwide utility FGD market in part because limestone is inexpensive and widely available

⁵ Absorber devices include packed towers, plate or tray columns, venturi scrubbers, and spray chambers (Barbour et. al., 1995).

FIGURE 3

Cumulative installed GWe capacity of wet scrubbers using lime or limestone as the reagent in the U.S., Japan, Germany, and the rest of the world. Years after 1993 were under construction or firmly planned as of 1994.



Source: Soud (1994)

B. SO₂ Regulation in the U.S.

Focusing on the case of FGD in the United States, it appears that although a range of government actions influenced innovation in SO₂ control technologies, the adoption pattern for FGD technologies was largely set by national legislative/regulatory events related to SO₂ control. The national market for FGD in the U.S. was effectively established by the 1970 Clean Air Act Amendments (CAA) and their associated 1971 New Source Performance Standards (NSPS). Both the 1970 CAA and the 1971 NSPS were flexible regarding the technological alternatives viable for attainment, but the standard required for emissions control (and the limited availability of low-sulfur coal in the early 1970s) provided a particular incentive for the development of post-combustion control technology such as FGD. The CAA was amended again in 1977, and the NSPS requirements that accompanied these amendments in 1979 established stringent SO₂ emission reduction levels (e.g., 70 to 90 percent removal) which were based on existing FGD system capabilities. In effect, the 1979 NSPS implicitly mandated the use of FGD for new coal-

fired power plants. Scholars often call such a phenomenon "technology forcing" in that the stringency of regulation forced the development and use of new technology. In 1990, the U.S. revised the CAA again in light of the issue of acid deposition, which had warranted a major ten-year study by the U.S. government as well as high-level diplomatic pressure by the Canadian government. The 1990 CAA employed a national emissions "cap-and-trade" system that reduced emissions from existing and new sources in phases. The first phase of the 1990 CAA did not capture the entire set of U.S. coal-fired power plants, but instead focused on the "dirtiest" existing plants and required them to meet emissions levels that were twice as lax as the 1979 NSPS was for new sources.

C. SO₂ Control Innovation Evidence: Patents

Taylor (2001) linked national legislative/ regulatory events pertinent to SO₂ control to the innovation process of invention through a detailed patent analysis. This analysis was the basis of much of the work done to date on this project, although we have extended the patent analysis to 1999. It is based on an established line of innovation research that uses patents as a measure and descriptive indicator of inventive activity (for a review of patent research, see Griliches, 1990). Patents provide publicly accessible and detailed technical and organizational information for what can be assumed to be non-trivial inventions over a long period of time. Studies have shown that patenting activity parallels R&D expenditures and can also be linked to events external to the firm.

In Taylor (2001), patent activity analysis involved four main sources of data: an interview with the primary U.S. Patent and Trademark Office (USPTO) examiner of FGD technologies (see Straub, 1999), the USPTO patent database from 1887-1997, International Energy Agency (IEA) data on the world FGD market (see Soud, 1994) and patent lists from

companies accounting for over one-third of the U.S. FGD market in 1973-93. First, the USPTO classes the examiner used to develop legal prior art were elicited and used to generate a time-series of 2,681 patents relevant to SO₂ control from 1887-1997 (see Table 1 for the classes considered). To check the commercial relevance of this dataset, these patents were compared to the patent lists from prominent FGD vendors as determined through analysis of the IEA dataset. This “SO₂ class-based” patent dataset was consistent for over 100 years and, therefore, could be compared to the timing of government actions related to SO₂ control, such as government R&D funding in the 1950s.

TABLE 1
U.S. patent classes and subclasses that comprise the SO₂ class-based dataset

USPC Class/ Subclasses	Definition of USPC Class/Subclasses
423/242.1-244.11	Class 423, the “chemistry of inorganic compounds,” includes these subclasses representing the modification or removal of sulfur or sulfur-containing components of a normally gaseous mixture.
095/137	Class 095, “gas separation processes,” includes this subclass representing the solid sorption of sulfur dioxide or sulfur trioxide.
110/345	Class 110, “furnaces,” includes this subclass representing processes to treat fuel combustion exhaust gases, for example, in order to control pollution.
44/622-5*	Class 044, “fuel and related compositions,” includes these subclasses to treat coal or a product thereof in order to remove “undesirable” sulfur.

Source: U.S. Patent and Trademark Office (2000)

Patent classes are a relatively broad method for identifying specific technologies, however, so Taylor (2001) also developed and analyzed a second, more commercially relevant dataset of 1,593 patents that was based on electronic searches of the abstracts of patents granted between 1976-96. These dates were used because keyword searching is only consistently possible for the subset of USPTO patents beginning with grant dates in 1976. Content analysis was performed on this “SO₂ abstract-based” dataset to eliminate irrelevant patents and assign

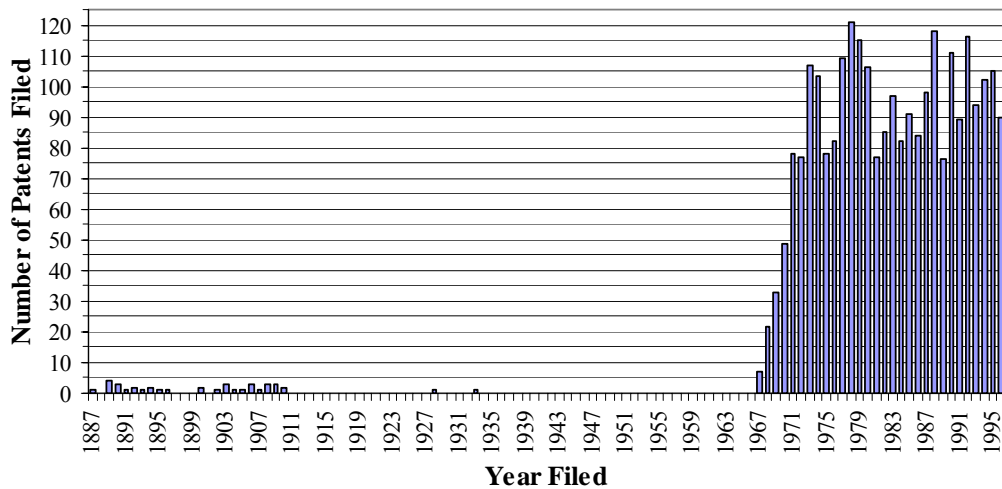
derived variables to these patents. The final abstract-based dataset contained 1,237 “SO₂ relevant” patents. The SO₂ relevant dataset captured 75% of the patents from the three companies that held over 40% of the U.S. FGD market between 1973 and 1993, a considerably greater percentage than was captured by the SO₂ class-based dataset (54%). Patent activity in the SO₂ relevant dataset was considered in the context of various government actions through a number of statistical techniques, econometric analysis, and the interpretation of experts in Taylor (2001).

One of the major findings of this patent work was that the existence of national government regulation for SO₂ emissions control appeared to stimulate inventive activity more than government research support alone. This finding is supported in Taylor (2001) by several veins of evidence (of which patent evidence was most important), as well as in environmental technological literature case studies reviewed in Taylor (2001) including Ashford, Ayers, and Stone (1985). As illustrated in Figure 4, the SO₂ class-based patent dataset demonstrated that, despite the existence of government legislation dating back to 1955 that authorized research into air pollution abatement methods, patent activity in SO₂ control did not really begin until after the introduction of a regulatory regime; indeed, Figure 4 illustrates patenting activity to be a step-function divided by the introduction of the 1970 CAA.⁶ In the first period, no more than four patents were filed in a given year, while in the second period, patenting activity never fell below a minimum activity threshold of seventy-six patents per year. It is also interesting to note that the SO₂ class-based dataset demonstrated patent activity peaks in the years 1978, 1979, 1988, and 1992; the SO₂ abstract-based patent dataset also exhibited this pattern of peaks.

FIGURE 4

⁶ In this and all other figures of patent datasets here, note that the dataset, which selects only granted patents, illustrates patenting activity by file date. Since there is a two-year lag between patent file and grant dates, on average, only patents filed two years before the last date of data collection are portrayed in figures and in the text.

SO₂ class-based dataset.

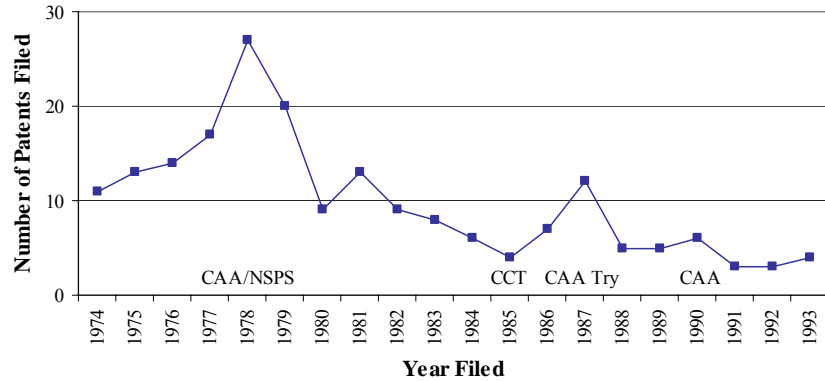


In addition to the linkage established in Taylor (2001) between overall patenting activity and the existence of legislative/regulatory actions, Taylor (2001) also explored potential linkages between the quality of these actions and patenting activity. An important finding of that work, consistent again with previous environmental innovation case studies such as Ashford, Ayers, and Stone (1985), is that regulatory stringency appears to direct the focus of inventive activity. Although other evidence in Taylor (2001) also supports this finding, the evidence of patenting activity is perhaps the most dramatic. Figure 5 shows patenting activity in pre-combustion SO₂ control technologies, which were not dominant in the SO₂ patent datasets overall and had lower levels of emissions reduction capabilities than FGD systems. In the period of time after the 1970 CAA and its 1971 NSPS, when SO₂ control standards were relatively flexible, patenting activity in these technologies grew significantly. After the CAA of 1977 and the NSPS requirements of 1979 established stringent SO₂ emission reduction levels that could only be met using an FGD system; however, patenting activity in these technologies dropped precipitously. Both statistical analysis and expert interpretation support the idea that the high stringency of the 1979 NSPS for

high-sulfur coal applications curtailed the viability of, as well as inventive activity in, pre-combustion control technologies.

FIGURE 5

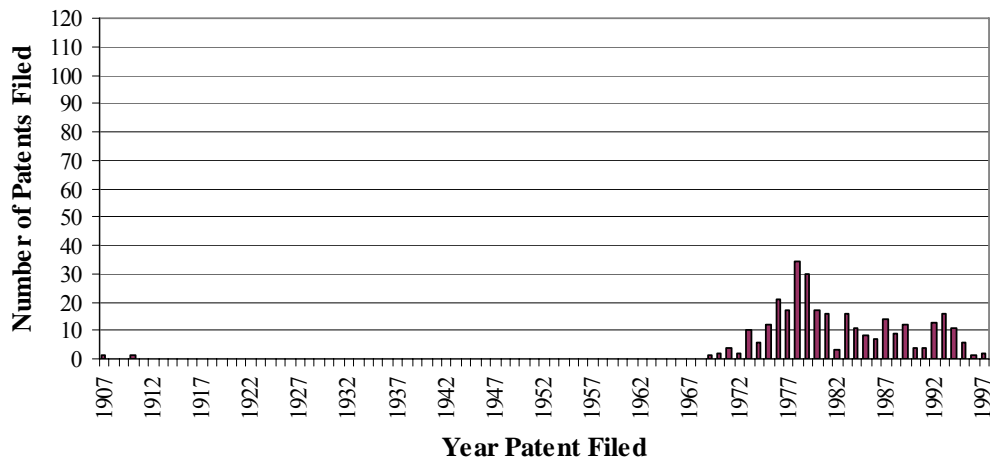
Trend in pre-combustion patents identified in the SO₂ relevant dataset.



In addition, a recent analysis of the SO₂ class-based dataset shows a similar pattern for the class 044 subclasses pertinent to the treatment of coal or a product thereof in order to remove “undesirable” sulfur, as seen in Figure 6. This pattern also supports the overall finding about regulatory stringency.

FIGURE 6

Patent activity in class 044, subclasses 622-5. These subclasses are pertinent to the treatment of coal or a product thereof in order to remove “undesirable” sulfur.



Finally, patents reveal a considerable amount of descriptive information about inventive activity. Figure 7, for example, displays the proportion of the U.S. SO₂ relevant dataset held by inventors from various nations. Figure 8 looks at these proportions in a normalized way, by tracing the patent activity indices of various countries (the patent activity index is here defined as the ratio of a country's proportion of SO₂ relevant patents in a given year divided by its proportion of all U.S. patents in that year). A patent activity index greater than 1.0 indicates that a country patents more frequently in a given subset of U.S. patents than in the overall U.S. patent system. Note that Germany has a particularly high patent activity index in SO₂ control technology in the mid-to-late 1980s. This time period in Germany was marked by an extremely rapid adoption of FGD systems (35,000 MWe capacity was installed in four years) as a result of a major government acid rain control program.⁷

FIGURE 7

U.S. SO₂ relevant dataset by inventor nation of origin.

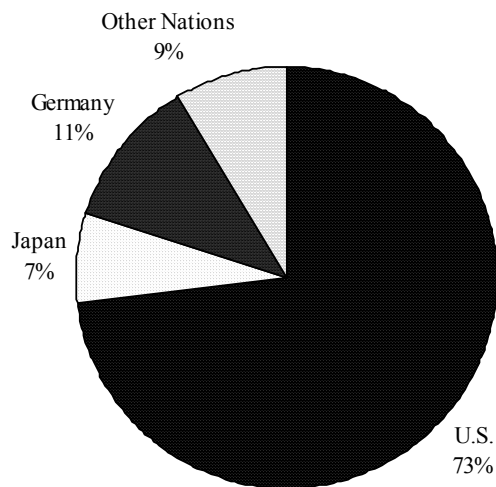
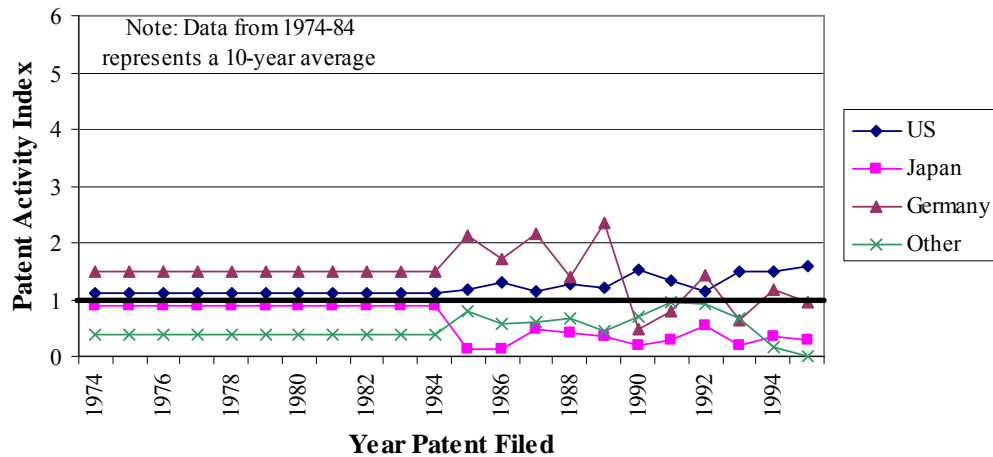


FIGURE 8

Patent activity indices over time.

⁷ It is interesting to note that only 33% of these systems were licensed from U.S. companies, which were the major early players in the FGD market.

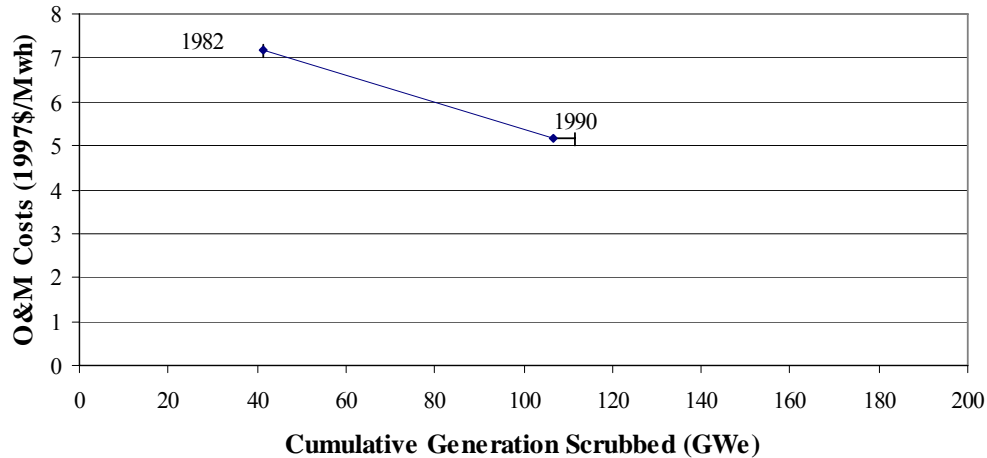


D. SO₂ Control Innovation Evidence: Experience Curves in FGD

Innovation in SO₂ control technologies has had measurable outcomes in improvements in operating and capital costs, as well as in SO₂ removal efficiencies. Taylor (2001) demonstrated improvements in important operating costs of the SO₂ control technology of wet limestone flue gas desulfurization (FGD) systems, based solely on the effects of the innovative activity of learning-by-doing. Econometric analysis of twelve years of operating experience with installed FGD systems at electric power plants demonstrated that as the cumulative power generation treated with FGD in the U.S. over time doubled, FGD labor and maintenance costs declined to 83% of their original values. This percentage decline, known as the learning curve “progress ratio,” is comparable to findings in many other industries. In addition, a review of the operating and maintenance costs of two historical studies of FGD economics, when compared with the cumulative capacity of wet scrubbers of the lime or limestone type in the U.S., Germany, and Japan, shows that overall operating and maintenance costs declined to 72% of their original

value within the 1982-1990 period, as displayed in Figure 9 (McGlamery et.al., 1980; Keeth et. al., 1991).⁸

FIGURE 9
Operating and maintenance costs of FGD technologies according to cumulative capacity of wet scrubbers in the U.S., Germany, and Japan, with error bars indicating the capacity in the rest of the world.



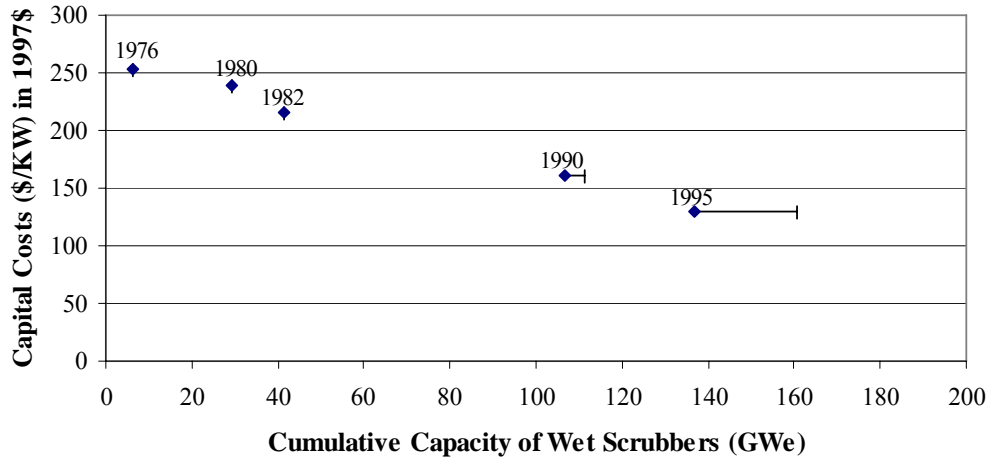
Sources: McGlamery et.al. (1980); Keeth et. al. (1991)

More significant, in order of magnitude, were reductions in FGD capital cost (see Figure 10) and improvements in the SO₂ capture efficiency (see Figure 11) of new generations of FGD equipment that resulted from the combined processes of innovation. These “experience curve” improvements are not “cost-free” as learning curve improvements generally are, as they result from expenditures in areas such as R&D and capital. However, these curves are very important for policy-makers interested in projections of future technological change to be aware of, as they (as well as learning curves) demonstrate the technological improvements that accompany the increasing adoption of control technology.

⁸ These data points were drawn from the studies in 1984\$ and 1990\$, then adjusted through the use of a composite index of 1/3rd labor and 2/3rd a standard GDP deflator (to handle the non-labor component of O&M). This index was derived for the purpose of this study from many back issues of *Chemical Engineering*.

FIGURE 10

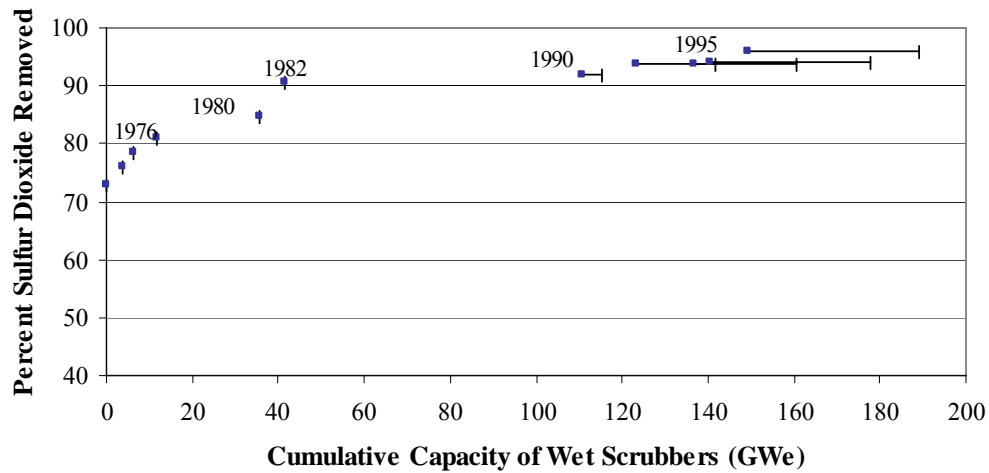
Reductions in capital cost of a new wet limestone FGD system for a standardized coal-fired power plant (500 MWe, 3.5% sulfur coal, 90% SO₂ removal). Cumulative GWe capacity based on wet lime/limestone scrubbers in the U.S., Germany, and Japan, with the error bars including the rest of the world.⁹ Reported cost results were adjusted using a power plant computer model that accounts for the influence of each cost factor on total FGD cost. See Rubin, et. al. (1995) and Rubin, et. al. (1997).



Source: Based on data from Soud (1994), McGlamery, et. al. (1980), Laseke, et. al. (1983), Keeth, et. al. (1986), Keeth, et. al. (1990), and Keeth, et. al. (1991).

FIGURE 11

Improvements in SO₂ removal efficiency of commercial FGD systems as a function of cumulative installed FGD capacity in the U.S., Germany, and Japan (the error bars indicate the rest of the world).²



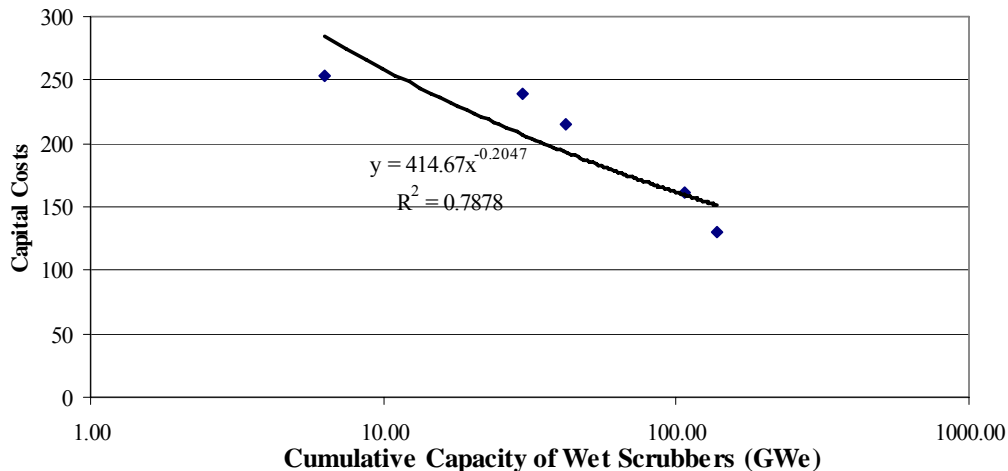
Source: Data from Soud (1994) and Energy Information Administration (1999)

⁹ Data in which the FGD unit's start date is unknown were excluded from the analysis.

For the purposes of this project, Figure 11 was considered in greater detail, as it could be directly linked to aspects of integrated assessment models such as IIASA's. For the purposes of incorporation into IIASA's model, Figure 12 was created. This figure is a variation of Figure 11, but on a log-normal scale with a power function fitted to the data points. As in Figure 11, the x-variable of each data point is based on the cumulative capacity of wet scrubbers of the lime or limestone type in the U.S., Germany, and Japan (the rest of the world was not taken into consideration). The simple power function here shows that as cumulative output of scrubbed power doubles, capital costs decline to about 87% of their original value.¹⁰

FIGURE 12

Capital costs on a log-normal scale for a standard 500 MWe plant with 3.5% sulfur coal.



In summary, the SO₂ control technology case thus provides evidence that links government actions to the innovation process of invention (see Figure 4 and Figure 5). The case also demonstrates quantifiable improvements in capital costs and performance improvements resulting from the entire innovation process (see Figure 10 and Figure 11). For the integrated assessment of global climate change, both of these lines of evidence are useful for enhancing the

¹⁰ Note that this “experience ratio” has the same mathematical concept as the progress ratio, although the innovation processes it captures are slightly different.

portrayal of technological change in larger models. In the first half of the current DOE project, particular attention was paid to modifying the second of these lines of evidence for capital cost reductions for immediate incorporation into larger integrated assessment models (see Figure 12).

E. Use of SO₂ Case as a Carbon Control Scenario in IA models

During the report period, we conferred extensively with our collaborators at IIASA regarding that institution's integrated assessment modeling framework and how that framework deals with technological change among a number of scenario drivers. The IIASA group has been in the forefront of climate modelers who have tried to build technological learning-by-doing phenomena into their energy systems engineering models (see, e.g., Messner, 1995; Riahi and Schratteholzer, 2001). The group has constructed three scenarios, based on the IPCC-Third Assessment Report, which incorporate technological learning rates for a set of more than 400 technologies. One of these scenarios incorporates a set of investment cost curves versus cumulative installed capacity for an array of energy technologies. Labeled the "A1B-550 (IIASA-TAR) scenario (1990-2100)," it estimates carbon capture cost reductions with increasing cumulative installed capacity of power plants that capture carbon (through "technological learning"). The group used this learning scenario to estimate the contribution of carbon capture technologies to total carbon reduction to achieve stabilization of global atmospheric carbon concentrations (at 550 ppm) in 2100. The IIASA group also developed two other scenarios for carbon mitigation to achieve stabilization of world carbon levels in which the costs and performance of all technologies employed in the three scenarios improved more moderately over time and in which carbon scrubbing costs in particular remained static [A2-550 (IIASA-TAR) and B2-550 (IIASA-TAR)]. IIASA reported to us the results of their three-scenario runs and

analyses in their First Draft Report (Riahi and Schratteholzer, 2001), which is attached as Appendix A.

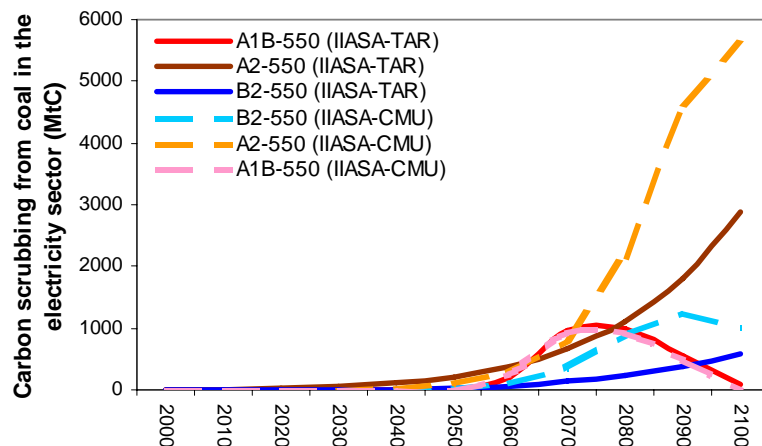
Following the IIASA group's first report to us, we supplied them with estimations of long-term technological performance (i.e., scrubbing with technological learning in capital, operating, and maintenance costs and performance improvements with increasing cumulative output of flue gas scrubbed) extracted from our SO₂ case as proxies for endogenous change in carbon-capture technologies.¹¹ Using the same methods they had employed in their earlier runs, the IIASA group ran the same three above-mentioned mitigation scenarios but this time employing our data for carbon scrubbing. They conveyed their results in the Second Draft Report (Riahi, Schratteholzer, and Zhu, 2001), which is attached as Appendix B.

Although not a substitute for our IIASA collaborators' full Second Draft Report, Figure 13 from that report suggests the significance of using the empirically derived experience curves from SO₂ control technologies as proxies for a scenario for experience with carbon-capture scenarios under particular regulatory regimes.

FIGURE 13

Figure 9 from Second Draft Report: Carbon scrubbing in coal power plants (MtC) in the IIASA-TAR and IIASA-CMU scenarios.

¹¹It should be borne in mind that, as is discussed in the Second Draft Report, IIASA's linear-programming-based model requires that endogenous technological change or learning be introduced into the model as iterative, "ex post" exogenous technological change. Hence, in their discussion of technological change related to Carnegie Mellon's data on technological change in sulfur dioxide control (which we deem endogenous), our IIASA collaborators use the term, "exogenous learning," when such experience data is applied in their model.



As the figure shows, the A1B scenarios for carbon scrubbing from the IIASA-TAR and IIASA-CMU, both assuming technological learning for carbon capture technologies, are roughly the same. But the CMU learning data result in significantly greater amounts of carbon being scrubbed from coal in the electricity sector in the other two CMU data scenarios than in the IIASA-TAR scenarios, which as noted above contained static costs of carbon scrubbing.

Our IIASA collaborators' seven main findings of their scenario analysis using CMU data and comparing their runs with those reported earlier (i.e., non-CMU technological change data) are as follows:

- the contribution of CCTs [Carbon Capture Technologies] to the emissions reduction is considerably higher under exogenous learning assumptions;
- the introduction of exogenous cost improvement for CCT leads to S-shaped diffusion curves for market penetration;
- the diffusion cycle (from initial introduction to saturation) of CCTs is about five decades, which is very similar to the life cycles of other technologies observed in the past;
- the timing of the diffusion for CCTs depends strongly on the socio-economic and technological assumptions in the baseline, leading to early deployment in A1B (2020), and comparatively late diffusion in A2 and B2;
- the price of electricity increases just moderately in case of a 550 ppmv stabilization, particularly under the assumption of technological change for CCTs;
- the GWP [Gross World Product] losses (macroeconomic costs) of stabilization are low compared to the total GWP increase of the scenarios, and do not differ significantly in the case of exogenous technological learning;

- CO₂ taxes (to meet the 550 ppmv carbon concentration constraint) depend strongly on the baseline assumptions, and are between 2 and 20 percent lower in the case of exogenous learning for CCT by 2100.

III. The Case of NO_x Control Technologies

A. Overview

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

As in the case of SO₂, environmental control strategies pertinent to control NO_x emissions can generally be divided into two categories: primary measures or combustion modifications and post combustion NO_x flue gas treatment processes. Primary measures for NO_x control, such as burner optimization, air staging (over-fired air or two-stage combustion), flue gas circulation, fuel staging, and low NO_x burner, generally require relatively little capital investment and do not entail the use of the additives. Post combustion NO_x processes reduce the NO_x in the flue gas into nitrogen and water downstream of the furnace, using reagents such as ammonia or urea by selective catalytic (SCR) or non-catalytic reduction (SNCR). The reduction capabilities of NO_x control range 30-60% for primary measures, 30% to 50% for SNCR and 70-90% removal efficiency for SCR systems.

(delete a paragraph) In response to government regulations, NO_x control technology has been passing through various phases as the regulatory and commercial climate has changed since the early 1970's. During the decade of the '70's, boiler manufactures focused on developing and field-demonstrating NO_x control technologies to meet the New Source Performance Standards of 1971 and 1979. In the 1980s, with the reduced need for new utility generating capacity,

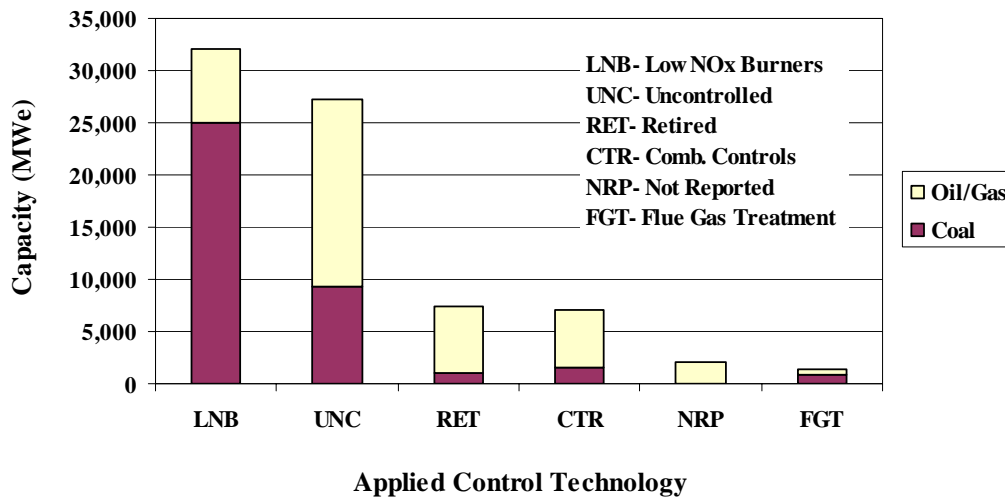
emphasis shifted to retrofittable technologies to meet acid rain control legislation. In the 1990s, more rigorous reductions in NO_x emissions were required for both new and existing source. Until recently, federal and state requirements for NO_x emission reductions from power plants have been quite modest, and standards such as Title IV Acid Rain NO_x program could generally be met by combustion modification technologies (Figure 14). Only in response to recent ozone attainment has the more expensive option of post-combustion NO_x control technology been introduced into the U.S. power generation market. Greater NO_x reductions are needed for the third phase of the Ozone Transport Commission (OTC) trading program, NO_x State Implementation Plan (SIP) Call and Section 126 regulations. This will require the use of advanced NO_x control technologies, especially selective catalytic reduction (SCR), to achieve 75 to 90 percent of the total reductions needed (State and Territorial Air Pollution Program Administrators and the Association of Local Air Pollution Control Officials, 1994; Krolewski and Mingst, 2000; NESCAUM, 2001).¹² Furthermore, several NO_x trading programs are expected to provide flexible, yet stringent incentives to achieve lower NO_x emissions. Evidence suggests that these NO_x trading programs will provide economic incentives (selling NO_x allowances) for a unit to go well beyond its required annual emission limit. Recent experience has also provided a better indicator of what post-combustion control technologies are capable of achieving beyond present regulations (Krolewski and Mingst, 2000; NESCAUM, 2001). The early history of NO_x control in stationary power plants is an example of weak technological response to initially weak regulatory demands in the U.S. The adoption of the OTC in 1994 and

¹² EPA regulatory impact analyses predicted that SCR retrofits would be installed at 142 utility units, representing approximately 72,900 MW in order to achieve overall NO_x SIP call/Section 126 compliances (U.S. EPA, 1999). Another study by DOE estimated that to achieve the required reduction in NO_x emissions in SIP call area, it is projected that SCR would be selected for about 500 fossil-fired boilers, totaling about 180 GWe, and SNCR would be selected for about 200-300 units, totaling about 20-35 GWe. OF these, 98% of the NO_x removal is from coal-fired units, and 93-98% of all NO_x removal is achieved by SCR (U.S. DOE, 1999).

subsequent, more stringent NO_x regulations have elicited a strong technology response, mainly advanced post-combustion technologies. The strong technology response had achieved a doubling of the reduction levels typically achieved over the two decades before 1995 (NESCAUM 2001).

FIGURE 14

1996 Ozone Transport Region (OTR) utility total utility (coal and oil/gas) boiler capacity by applied control technology.



Source: (NESCAUM, 2001)

Innovation in NO_x control technologies stimulated by government regulations is again verified in this study. We show that, in the case of Japan, Germany, and U.S., innovations in NO_x control technologies, as measured by the number of new patents related to NO_x control technologies, did not occur until stringent government regulations were in place, therefore “forcing” innovation. We also demonstrate the reductions in capital cost and levelized cost of new generations of SCR equipments are consistently associated with the increasing adoption of the control technology (measured by the world total installed capacity). The experience of learning in SCR technology is largely driven by lower cost of catalyst and the improvement of

catalyst life, due to market competition, economies of scale, redesign, and technological advancement.

B. NO_x Regulation

The Clean Air Act of 1970 and subsequent amendments set National Ambient Air Quality Standards (NAAQS) for seven pollutants, including NO_x, to protect public health and welfare. The New Source Performance Standards of the CAA set standards for utility boilers that strictly regulated emissions for new sources and were revised in 1987. However, the specification of national NO_x emissions limits for existing power plants did not begin until the passage of the 1990 Clean Air Act Amendments (CAAA) that required NO_x emissions reductions under Title I and Title IV. Title I of the CAAA required NO_x reductions from all source types to achieve attainment with ambient air quality standards for NO_x and ozone. Title IV required NO_x reductions from coal-fired units in order to reduce acid rain precursors. The control technology requirements for Title I were based on Reasonably Available Control Technology (RACT), with emissions levels being set by individual states based on local conditions. RACT was defined to include the following NO_x control technologies: low NO_x burners, selective non-catalytic reduction (SNCR), and selective catalytic reduction (SCR).

In addition to the conventional command and control rules that set emission limits or dictated control technologies for NO_x reduction, the South Coast Air Quality Management District (SCAQMD) started the Regional Clean Air Incentives Market (RECLAIM) on January 1, 1994. States in the northeast U.S. cooperatively designed a regional NO_x cap and trade program [Ozone Transport Commission (OTC) NO_x Budget Program] to control transport of ground-level ozone. Moreover, EPA's NO_x State Implementation Plan (SIP) Call in 1998 and Section 126 of the Federal NO_x Budget Trading Program in 1999 are also market-based

mechanisms for reducing NO_x pollution. These programs are designed to offer greater flexibility and a financial incentive to reduce air pollution beyond what clean air laws and traditional command-and-control rules require.

C. NO_x Control Innovation Evidence: Patents

In our research to date, we have created two datasets in order to conduct patent analysis that could link inventive activity in NO_x control technologies to government actions. The first step in creating both datasets was an exploration of a few highly relevant NO_x control technology patents based on iteratively conducted, small-scale patent searches. For the “NO_x-class based dataset,” a list of potential class and subclass combinations was developed from these preliminary searches, and interviews were conducted with the various patent examiners responsible for the art units that encompassed these classes. More interviews had to be conducted for NO_x control patents than SO₂ control patents because of the technical range of solutions to NO_x emissions from stationary sources. The resulting class/subclass combinations that emerged from these interviews are displayed in Table 2, and the NO_x class-based dataset that resulted from searching these class/subclass combinations over time encompassed 5,863 patents.

TABLE 2
U.S. patent classes and subclasses that comprise the NO_x class-based dataset.

USPC Class/ Subclasses	Definition of USPC 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, 180,	Class 431, “combustion” includes these subclasses representing a

183-4, 187-8, 351	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. It also encompasses apparatus including (180) a row of fuel dispersers extending from one wall to another of a combustion chamber; (183) spaced fins coaxial with the disperser to whirl air; (184) pivotally adjustable fins to direct air; (187) devices to discharge feeds coaxially; (188) an air chamber with inlet control surrounding disperser at a wall. Finally, it includes this subclass for a protective flame enclosing or stabilizing structure (351) including the means for feeding air directly to burning gases at spaced points along the combustion region in the direction of flame flow as it passes along or through a shield, tunnel, or chamber.
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Source: U.S. Patent and Trademark Office (2000)

As in Taylor (2001), a second abstract-based patent dataset was developed next in order to more narrowly capture relevant technologies. The preliminary searches conducted earlier were analyzed for frequently occurring keywords within the patents' titles and abstracts, and the resulting keywords and their likely variations were used to run further searches on patents in a limited number of years (dispersed over time). These search results were then analyzed for relevant keywords and the process was repeated for a few more iterations until the combination of keywords selected appeared to maximize the number of relevant patents and minimize the number of irrelevant patents that were captured with each search. This successful search was then run on the entire USPTO database, although it was only consistent for patents granted after January 1, 1976, since only patents granted after this date are considered completely electronically coded for the abstract field that the searches were run on. The resulting "NO_x abstract-based dataset" totaled 3,717 patents granted between the years of 1976 and March of 2001.

In order to carefully follow the methodology established in Taylor (2001), two further tasks are necessary to refine this NO_x abstract-based dataset. First, these patents have to be

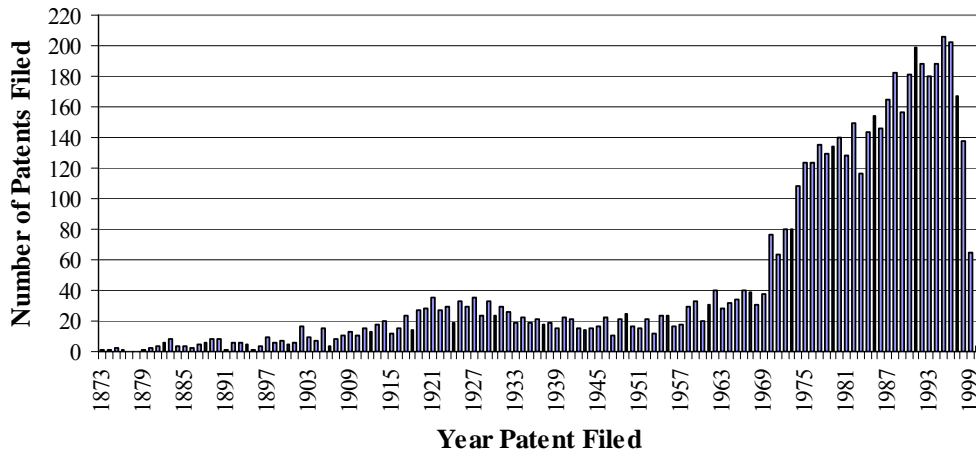
coded and irrelevant patents discarded. To date, this has been done for the sample of these patents that were filed in 1976, 1980, 1984, 1988, 1992, and 1996, which will be referred to here as the “partial relevant NO_x dataset.” During these years, 850 patents were filed; only 455 of these were deemed relevant to this study, for a total of 54%. Work is continuing on completing this coding process for the remaining abstract-based patents.¹³ The second task that needs to be accomplished is to complete the process of identifying and contacting the primary vendors of SCR technologies in order to solicit their commercially relevant patents related to SCR in order to confirm the strength of our datasets.

Figure 15 displays the full NO_x class-based dataset over time, and it is interesting to note the differences between this figure and the similar figure for SO₂ control, Figure 4, above. In Figure 4, patenting activity in the SO₂ class based dataset occurs as a pronounced step function which spikes from less than or equal to four patents a year before 1967 to no less than 76 patents per year starting in 1971. Our interpretation of Figure 4 primarily focused on the existence of national government actions related to SO₂ control after 1970, as opposed to the existence of only research in SO₂ control between 1955 and 1970, in order to explain this pattern.

In the case of Figure 15, however, the pattern of patenting activity appears to occur in three phases, rather than two. In the first phase, which occurred before 1970, patenting activity averaged 16.46 patents per year. In the second phase, which occurred between 1971 and 1986, patenting activity averaged 119.53 patents per year. In the final phase, which occurs from 1987 to the end of the dataset, patenting activity averaged 179.42 patents per year. Thus, patenting activity increased over seven times between the first and second phases, then increased another 1.5 times between the second and third phases.

¹³ Since this task is not yet complete, the partial relevant NO_x dataset will not be discussed further in this report.

FIGURE 15
NO_x class-based dataset.



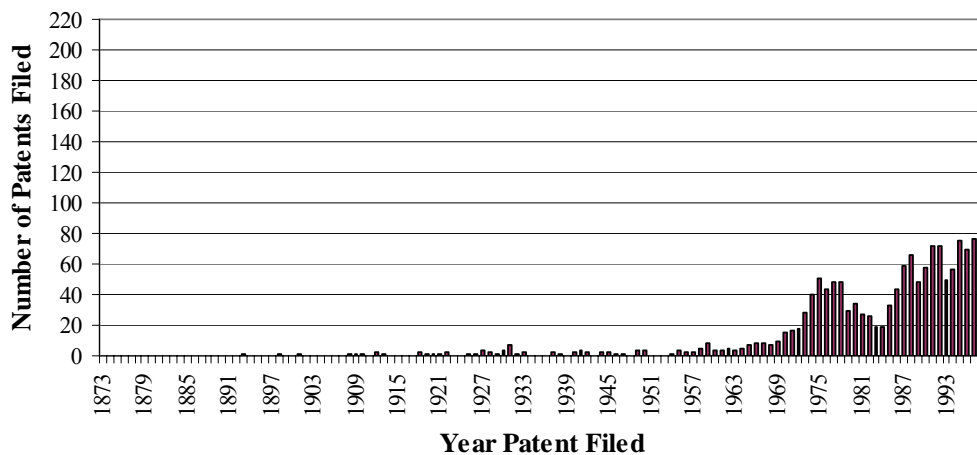
Note that the years separating these phases are the years of major national government actions relevant to control of the pollutant, as was the case for SO₂. These actions for NO_x control are the 1970 CAAA (as was the case for SO₂) and the 1987 revised New Source Performance Standard that dramatically increased the stringency of NO_x control for new sources. This second action created, for the first time, a potential market for higher percentage removal technologies in the U.S. that were technically more demanding (and likely to be patented). This de facto market niche for SCR and SNCR technology only came to exist seventeen years after the passage of the 1970 CAAA, whereas the technologically demanding FGD technology had a similar de facto market niche as early as nine years after the 1970 CAAA.

This point is further supported by Figure 16, which depicts patenting activity in the class/subclass combinations of 423/235 and 423/239.1. These two class/subclass combinations were mentioned by patent examiners as particularly pertinent to SCR and SNCR technology (see Table 2 for a more detailed description). The pattern of patenting activity in three phases is even more prevalent in Figure 16 than in Figure 15. In the pre-1970 first phase, patenting activity averaged 1.84 patents per year. In the 1971 to 1986 second phase, patenting activity averaged

32.75 patents per year, or 17.76 times the activity level of the first phase. In the third phase, from 1987 to the end of the dataset, patenting activity averaged 62.17 patents per year, or 1.90 times the activity level of the second phase.

FIGURE 16

Patent activity in class 423, the subclasses 235 and 239.1 of the NO_x class-based dataset. These subclasses are pertinent to the removal of nitrogenous components of a normally gaseous mixture through use of a solid sorbent, catalyst, or reactant and represent the primary classes for SCR and SNCR technology.

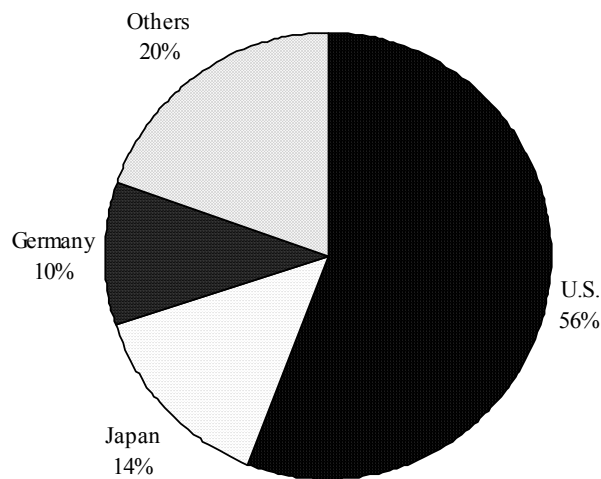


Further quantitative analysis and expert interpretation of these findings have not yet been completed, but these preliminary results appear to support the major finding of the SO₂ control case that the existence of government action is important to support innovation in an environmental control technology. In addition, these findings appear to imply that government standards of high stringency have a noticeable effect on inventive activity in advanced pollution control technologies capable of meeting these standards.

Of course, the U.S. implementation of higher stringency NO_x standards in 1987 followed the experience of Japan and Germany with advanced technologies capable of meeting high stringency standards. This is slightly different than in the case of SO₂ control; in that case, the U.S. was more of a world leader in the 1970s in adopting higher stringency standards and control

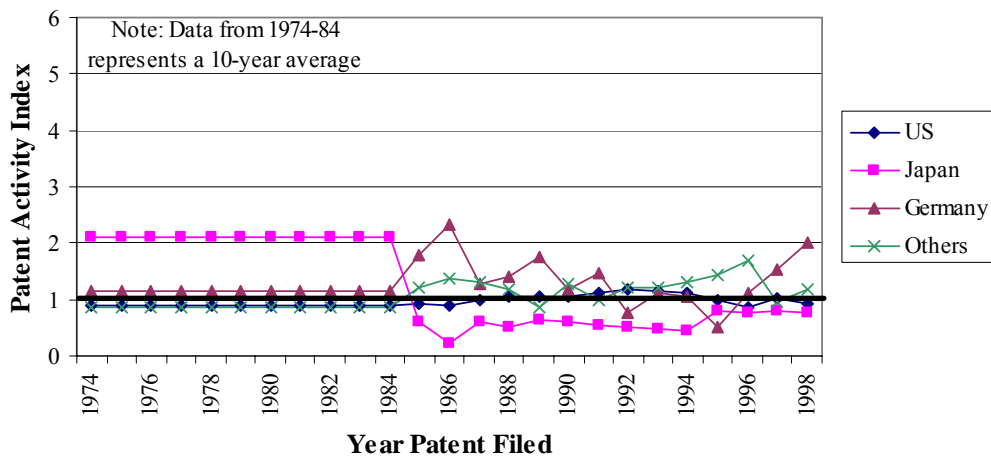
technology. The importance of other nations in the NO_x innovation story is evident in Figure 17, especially when compared to the similar figure for SO₂ control, Figure 7. In Figure 7, the U.S. held 73% of all patents in SO₂ control, while in Figure 17, it only holds 56%. In Figure 7, Japan held 7% of all patents in SO₂ control, while in Figure 17, it holds twice as many patents (14%). In Figure 7, other nations held 9% of all patents in SO₂ control, while in Figure 17, other nations hold more than twice as many patents (20%). It is interesting to note, however, that Germany holds roughly the same proportion of SO₂ and NO_x patents, at 11% and 10%, respectively.

FIGURE 17
NO_x class-based dataset by inventor nation of origin.



The importance of international innovators in NO_x control is reflected in Figure 17; Figure 18, however, shows the importance to innovators of various countries of NO_x control versus the rest of their national patent portfolio in the U.S. Comparing trendlines between the similar graph in SO₂ control, Figure 8, and Figure 18 shows that while the U.S. consistently patents at a slightly higher rate in SO₂ control technology than it does in the overall USPTO database, in NO_x control it patents at about the USPTO level or slightly beneath that level.

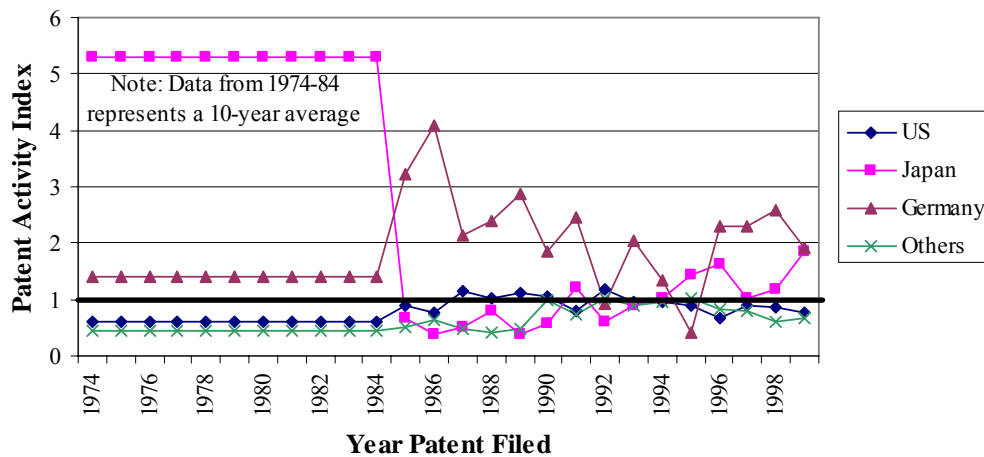
FIGURE 18
Patent activity indices for the overall NO_x class-based dataset.



More interesting than the slight differences seen in the U.S. patent activity levels between Figure 8 and Figure 18 is the importance to Japan of patenting in NO_x control technologies. Whereas in SO₂ control, Japan patented at about the same rate as in the overall USPTO before 1984, after 1984 it patented at a much lower rate in SO₂ control. In the NO_x case, however, before 1984 Japan patents at a remarkably higher rate in NO_x control than in the overall USPTO, which is especially remarkable considering Japan's innovations in other areas during this time. After a major decline in comparative patenting activity in 1985-1990, Japan's level of patenting activity in NO_x control returns to levels above its USPTO patenting activity in the 1990s (although at a much lower level than before 1984).

Germany, on the other hand, had higher proportions of SO₂ control patents than its proportion of the entire USPTO dataset, especially in the years 1985-1989. Germany's proportion of NO_x patents, when compared to overall USPTO patenting activity, is higher still. This is especially clear when one considers only patenting activity in classes identified by examiners to be likely to contain SCR and SNCR patents, as in Figure 19.

FIGURE 19
Patent activity indices for patents in the main SCR and SNCR classes of the NO_x class-based dataset.



For both Germany and Japan, it is clear that the SCR and SNCR patent classes accentuate the trend seen earlier in the overall NO_x class-based dataset. It is also clear, however, that the U.S. is not at all as active in SCR and SNCR patenting than it is in patenting in the USPTO in general.

In many ways, these results appear to reflect the market within each country for SCR and SNCR technology. The U.S. has not implemented SCR technologies to a great extent to this day, preferring instead to use a combination of other technologies such as low NO_x-burners, overfire air, and fuel staging to meet its NO_x control needs. Japan, on the other hand, was the first major innovator in SCR technology as it applied the technology to oil-fired power plants in the 1970s and worked on the first early coal systems. This is supported in both archival evidence and interviews with experts who ascribe to Japan the role of a very important licensor of these technologies to the rest of the world. Finally, Germany, as in the case of SO₂ control, did not get particularly involved in SCR technologies until after the passage of the major government acid rain control program in 1985. Then it had a rapid implementation of FGD and SCR technologies until these and other pollution control technologies were installed on coal-fired power plants across the country within five years. Note that Germany's highest comparative patenting activity

levels occurred in both SO₂ and NO_x control in the period 1985-1989 (although quite high patenting levels continue in NO_x control throughout the 1990s, whereas they drop off in SO₂ control).

These findings about the geographic origin of patenting activity in NO_x control technologies, and especially in SCR and SNCR technologies, lend further support to the idea that regulatory stringency has an important impact on innovation in an environmental control technology.

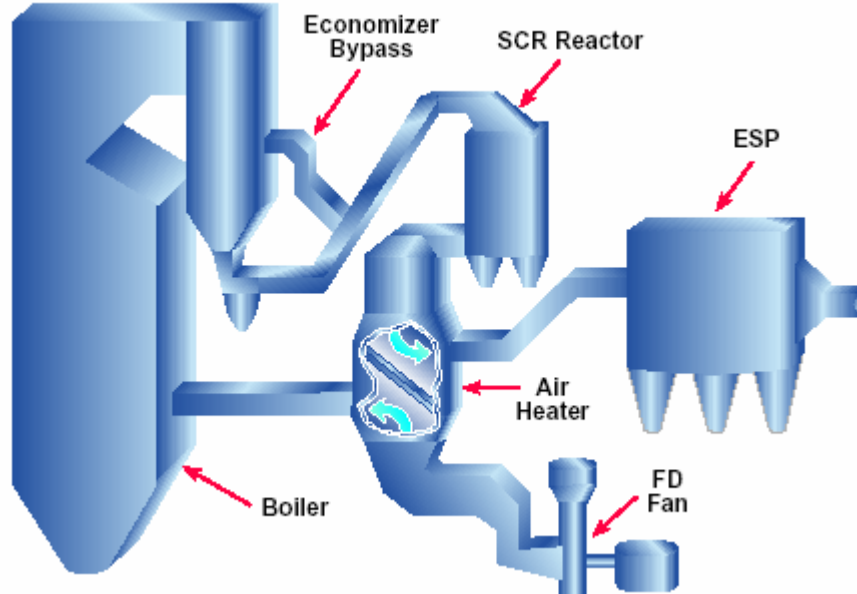
D. NO_x Control Innovation Evidence: Experience Curves in SCR

Selective Catalyst Reduction (SCR) is a process for controlling emissions of nitrogen oxides from stationary sources. The basic principle of SCR is the reduction of NO_x to N₂ and H₂O by the reaction of NO_x and ammonia (NH₃) within a catalyst bed.¹⁴ Several different catalysts are available for use at different exhaust gas temperatures. In use the longest and most common are base metal catalysts, which typically contain titanium and vanadium oxides, and which also may contain molybdenum, tungsten, and other elements. The mechanical operation of an SCR system is quite simple. It consists of a reactor chamber with a catalyst bed, composed of catalyst modules, and an ammonia handling and injection system, with the ammonia injected into the flue gas upstream of the catalyst (see Figure 20).

FIGURE 20

¹⁴ $4\text{NO} + 4\text{NH}_3 + \text{O}_2 \rightarrow 4\text{N}_2 + 6\text{H}_2\text{O}$
 $2\text{NO}_2 + 4\text{NH}_3 + \text{O}_2 \rightarrow 3\text{N}_2 + 6\text{H}_2\text{O}$

Schematic flow diagram of a typical high-dust SCR system

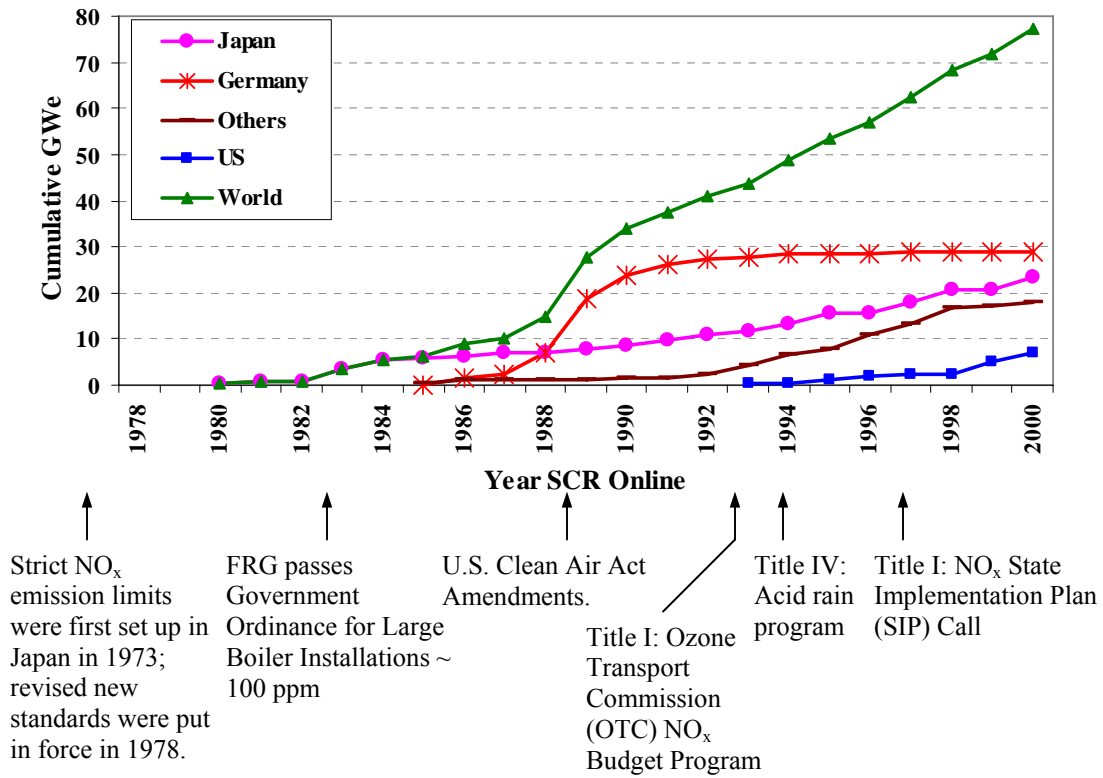


Source: {U.S. DOE, 1997 #52}

SCR was first developed and commercialized in Japan in the 1970s and later in Germany in 1980s. Even as late as the 1980s, SCR had not found commercial acceptance in the United States. The principle reasons were given the regulatory requirement, its high costs on all fuel applications and potential technical problems with U.S. coal ash (Damon, Ireland et. al., 1987). In spite of these concerns, interest in SCR technology grew because of the low NO_x emissions achievable by this technology. The U.S. experience has benefited to some degree from the two prior generations of design. The world total SCR annual installed capacity (GWe) from 1980 to 2000 is shown in Figure 21. The first SCR was installed in Japan in 1980 after Japan's stringent NO_x emission limits in 1978. Right after its first NO_x legislation in 1984, Germany has its first SCR installed in 1985. Similarly, U.S. did not have its first SCR installed until 1993, 3 years after the 1990 CAA. The adoption patterns for SCR technology once again show a clear relationship with national legislative/regulatory events related to NO_x control.

FIGURE 21

SCR coal-fired installed capacity by country and world total cumulative coal-fired installed capacity from 1980 to 2000.



Source: Adapted from Soud (2001)

Both the capital and operating costs of SCR in the U.S. have dropped significantly over the past decade because of technological innovation, increased manufacturing experience, and competition among manufacturers. In Japan, the levelized busbar cost of SCR decreased over a six-year period by more than a factor of 3 because of increases in catalyst life and reductions in catalyst volume requirements as a result of improved catalyst geometry and composition. In Germany the learning curve continued, dropping costs by an additional factor of 2, again largely because of technical developments: reduced catalyst installation cost; mechanized and automated catalyst manufacture; and new catalyst replacement strategies that allowed the extension of average catalyst lifetime guarantees to four years (Gouker and Brundrett, 1991). Additional progress on the learning curve toward reduced costs can be expected when SCR gains large-scale

U.S. application in anticipation of stringent NO_x reduction programs in the U.S. Decreased capital cost, successful operating experience, and tightened permit level limits have led to a sharp increase in the number of SCR systems installed or on order in the U.S.

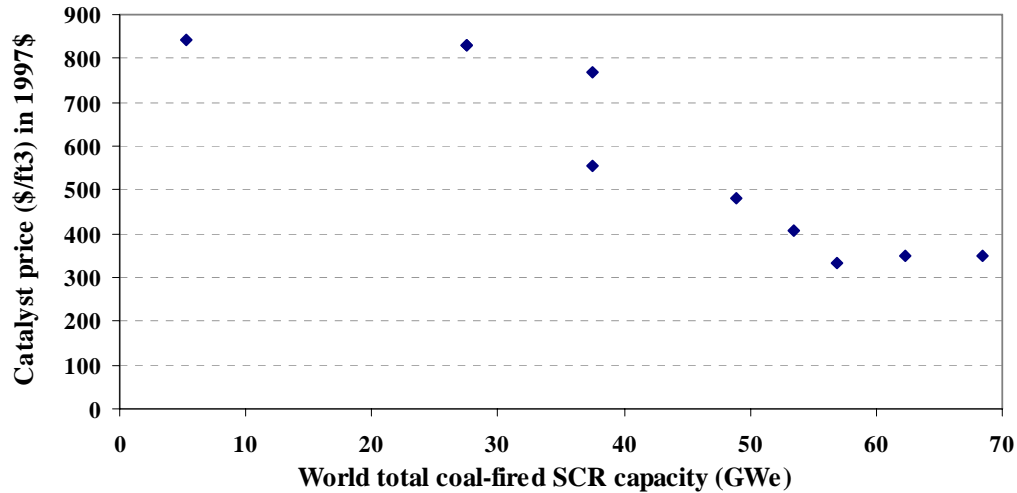
The initial catalyst cost, the catalyst replacement cost, and catalyst life are the main economic concerns and drivers of SCR process economics. Much longer catalyst lives and lower catalyst prices have contributed to the reduced operating cost (Hjalmarsson, 1990; ICAC, 1997; U.S. EPA, 1997; NESCAUM, 2001). In 1985, one study found that catalyst constitutes about 30% of the total capital requirement and 88% of the total operation and management cost (Maxwell and Humphries, 1985). The ratios dropped to 16% and 43% of the total capital cost and the total O&M respectively in 1996 (Healy, Maxwell et. al., 1996).

Historical catalyst prices in the U.S. (1987-1997) reported in published economic evaluation literatures have dropped 50% in 10-year period (Figure 22). Market competition is the main driver for the price fall. There have been no observable relationships between the prices of SCR catalyst and the prices of minerals (mainly vanadium and titanium) in the markets (U.S. Geological Survey, 2001).¹⁵ In addition, the growing demand of SCR market in the future is not expected to raise the prices of the minerals in the market.

FIGURE 22

Catalyst price reported in the historical SCR economic evaluation literatures from 1984 to 1997 and world cumulative coal-fired SCR installed capacity.

¹⁵ 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 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 (Soud and Fukasawa, 1996).



Source: Based on data from {Bauer, 1984 #18; Mobley, 1978 #24; Maxwell, 1985 #9; Damon, 1987 #17; Robie, 1991 #20; Robie, 1989 #14; Rao, 1994 #30; Healy, 1996 #2; Cochran, 1997 #21}

The expected lifetime of catalysts also improved significantly over the past twenty years. The published SCR economic evaluations in 1980s normally assumed a 1-year catalyst life (see, e.g., Damon, Scheck et. al., 1983). As more experience was gained, the catalytic operation condition improved, and their useful lifetime has increased significantly. Table 3 and Figure 23 show that the assumptions of catalyst life in the U.S. from 1978 to 1998 SCR economic evaluations and that the actual operational experiences have increased significantly for the past 13 years.

TABLE 3

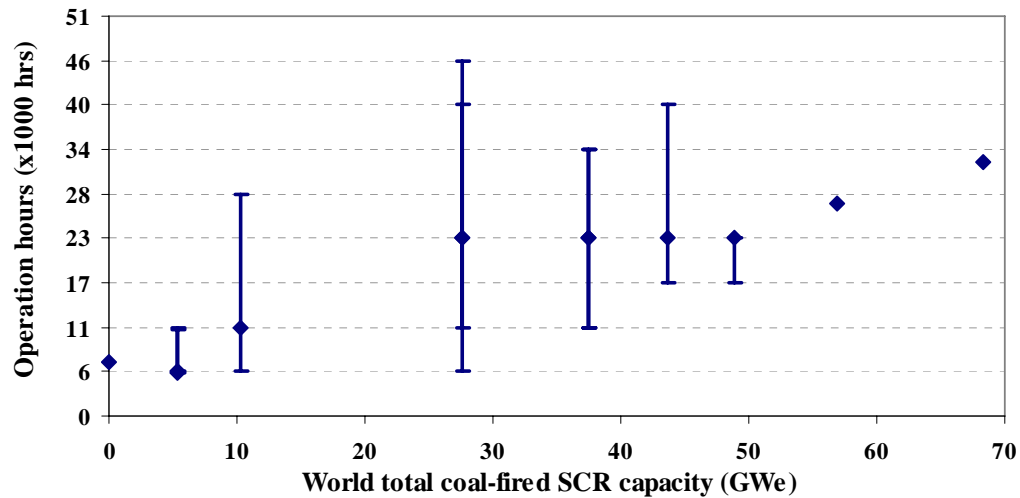
The range of catalyst lifetime assumed in the historical SCR economic evaluation literature, including values used in the base case, sensitivity analysis, and the reported actual operational experience.

Year	Source	Catalyst lifetime (operation hrs)			Actual operational experience
		Base	Low	High	
1978	Mobley	7,000			
1984	Bauer	5,694	5,694	11,388	Catalyst life guarantees are usually one year (U.S. EPA, 1983). Limited operational experience on coal-fired boilers
1985	Maxwell	5,500	5,500	11,000	
1987	Damon	5,694	5,694	28,470	Catalyst life is generally specified at one year,

					but manufacturers expect a 2 to 3 year life (Damon, Ireland et. al., 1987).
1989	Robie	22,776	11,388	45,552	
1991	Robie	22,776	5,694	39,858	A 4-year catalyst life was used in the cost development, six years of use is closer to the currently expected life (Robie, Ireland et. al., 1991).
1992	Castaldini	22,776	11,388	34,164	
1993	Eskinazi	22,776	11,388	34,164	
1994	Rao	22,776	17,082	22,776	Sophisticated management by partially replacing the catalyst can lengthen catalyst life to the range of 3 to 11 years for a coal-fired power station (Takeshita, 1995). New coal-fired boilers (e.g., Carneys Point, 1993; Logan, 1994) are securing vendor guarantees of a 10-year catalyst life (OTAG, 1996).
1997	Cochran	k/k ₀ = 0.8 after 16,000 hrs	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 to 14 years (ICAC, 1997).
1998	NESCAUM		24,000	48,000	

FIGURE 23

Catalyst lifetime used in the historical SCR economic evaluation literatures from 1987 to 1997 and world cumulative coal-fired SCR installed capacity.



Source: Based on data from {Bauer, 1984 #18; Mobley, 1978 #24; Maxwell, 1985 #9; Damon, 1987 #17; Robie, 1991 #20; Robie, 1989 #14; Rao, 1994 #30; Healy, 1996 #2; Cochran, 1997 #21}

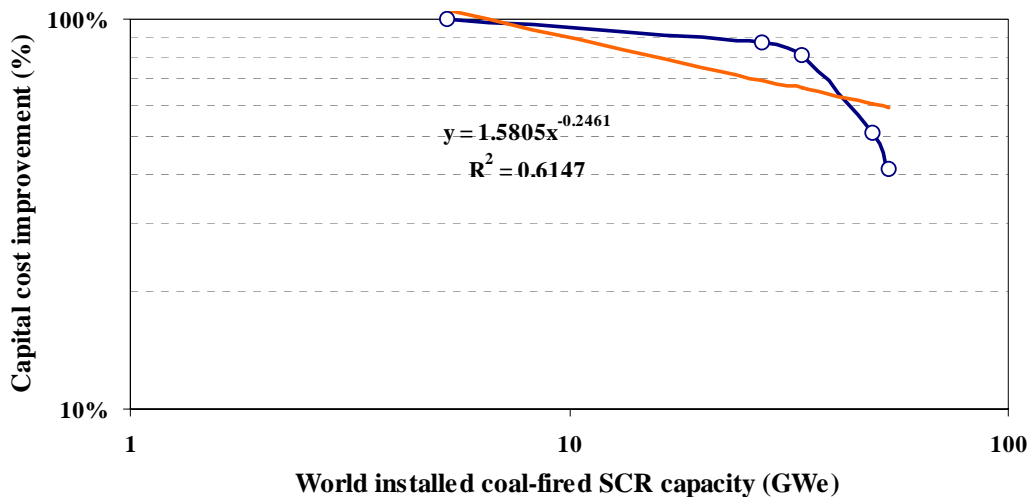
1. Capital and operating cost v. cumulative capacity findings

Decreased cost, successful operating experience, and tightened permit level limits have led to a sharp increase in the number of SCR systems installed in the U.S. Figure 24 and Figure 25 show the cost improvement (%) of new generations of SCR systems in the U.S. against world cumulative coal-fired installed capacity (GWe). Both figures show that the rates of cost improvements occurred in two stages. The first stage is the pre-commercial stage (before 1993, with world cumulative capacity < 43 GWe) where economic evaluations were based on foreign experiences (mainly Japan and Germany) and on experience from few pilot plants in the U.S. There were great uncertainties about SCR's applicability in the U.S., and therefore the cost estimates were relatively conservative and showed little rate of progress. Far more significant cost reduction rates are observed after the first U.S. SCR commercial installation and after SCR went into the commercial phase (with world installed capacity at 43 GWe). At the same time period, catalyst prices dropped (Figure 22) and expected catalyst life increased (Table 3 and

Figure 23) at a much faster rate as demand and market competition increased from foreign and domestic companies and experience accumulated both abroad and domestically. Other technological improvement accompanying with the increasing adoption of control technology also contributes to the reduction of the capital cost, such as efficient catalyst design that led to reducing the size and cost of the support structures; sophisticated catalyst management practices contributed to improve operation and cost reduction in SCR technology; and advanced flow modeling allows uniform gas flow and NH_3/NO_x ratios reduces required catalyst volumes.¹⁶

FIGURE 24

Capital cost (mills/kWh) improvement for SCR control units for a coal-fired power plant (500 MWe, 80% NO_x removal) over cumulative installed capacities. The cost decrease corresponds to a learning-by-doing rate of about 16 percent.



Source: Based on data from {Maxwell, 1985 #9; Robie, 1991 #20; Rao, 1994 #30; Healy, 1996 #2}

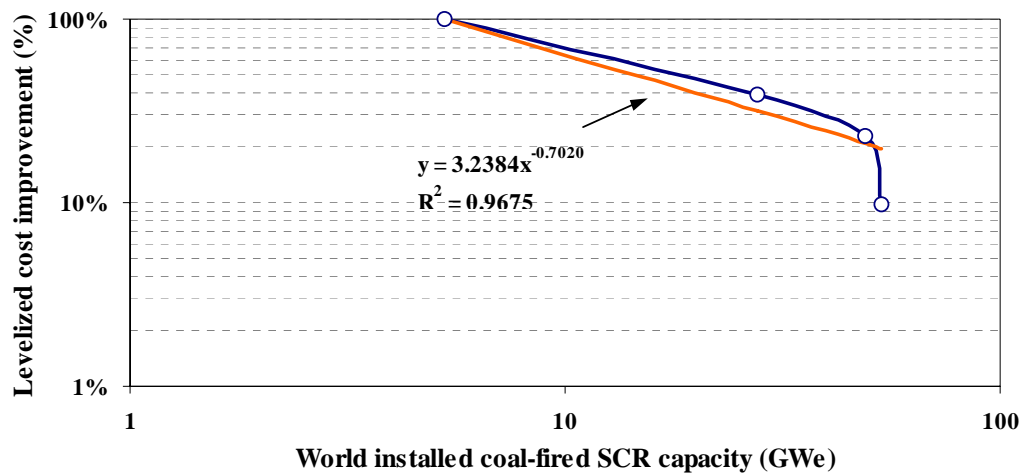
More significant rate of improvement occurred in the generational curve of levelized cost than the capital cost generational curve. The cost reductions corresponding to generational progress ratios are about 84 percent for the capital cost and 61 percent for the levelized cost (i.e., as cumulative world coal-fired SCR installed capacity doubles, capital costs and levelized cost

¹⁶ Improvement to both catalyst geometry and composition compared to earlier generation products.

decline to about 84% and 61% of their original value, respectively). The reason is simple: levelized cost (or busbar cost) is the sum of levelized first-year operating and maintenance costs + levelized capital charges. As mentioned earlier, catalyst price reduction and longer catalyst life have more impacts to the variable O&M cost than to the capital cost, therefore a greater cost improvement rate can be expected for the levelized cost generational curve.

FIGURE 25

Levelized busbar cost (mills/kWh) improvement for SCR control units for a coal-fired power plant (500 MWe, 80% NO_x removal) over cumulative installed capacities. The cost decrease corresponds to a learning-by-doing rate of about 39 percent.



Source: Based on data from {Maxwell, 1985 #9; Robie, 1991 #20; Rao, 1994 #30; Healy, 1996 #2}

E. How NO_x Contrasts with SO₂ for Carbon Control Scenarios in IA Models

NO_x regulation differed from SO₂ regulation in that, for nearly two decades before 1995, NO_x regulations were much more modest and few sources of NO_x were affected. Not until the adoption of the OTC in 1994 and subsequent stringent NO_x regulations did a strong technology response in advanced post-combustion technologies, mainly SCR, emerge. At this time, SCR technology had been commercially available in Japan, Germany, and other European countries since late 1970 due to stringent governments' actions. Steeper NO_x U.S. generational curves in

the capital and levelized cost improvements are observed when compared to the generational curve for SO₂. The following three arguments are proposed to explain the differences:

1. SCR is a much simpler technology compared to FGD. The heart of an SCR system is the catalyst. The lack of operational experience of SCR in the U.S. had initially raised concern regarding the technology's applicability when burning high-sulfur coal. Concerns regarding the use of high-sulfur coal centered on the formation of ammonium bisulfate plugs in the air heater, corrosion in other downstream surfaces, and catalyst deactivation by alkali metals and arsenic. Improvements in reducing ammonia slip, suppressing sulfur dioxide oxidation across the catalyst, and the development of poison-resistant catalysts have increased the catalyst life by 5 times or more and led to dramatic SCR cost reductions.
2. Market competition and economies of scale have reduced the catalyst price in the U.S. by 50% in 10 years. In the earlier economic assessments for several pilot projects, catalysts were imported or prices were quoted from vendors in Japan or Germany. Over the past ten years, U.S. firms have entered the market in anticipation of NO_x reduction programs in the U.S., and significant overcapacity exists as a result of the maturing of SCR markets abroad (ICAC, 1997).
3. Contrary to FGD, where it was mainly applied to coal-fired power plants, SCR systems have been commercially installed in a wide range of sources, including gas/oil/coal-fired utilities, industrial boilers, process heaters, gas turbines, internal combustion engines chemical plants, and steel mills.¹⁷ The operational experiences from other sources are hard to extrapolate to the experience of coal-fired power plants and, therefore, were not included in the generational curve that we constructed in this case study. However, these experiences should in fact contribute to the learning effect of coal-fired power plants to some degree and excluding these experiences may contribute to the steep slope of the generational curve that we found in the case of SCR.

¹⁷ In 1997, Retrofit SCR systems were in operation on 14 gas-fired utility boilers ranging in size from 147 to 750 MW in California (total of 5,482 MW) and 7 coal-fired boilers (total of 1,535 MW). SCR is also used to control NO_x emissions from more than 40 industrial boilers and process heaters and more than 176 gas turbines (approximately 7,784 MW) in the U.S. These include both field-erected and small package boilers (ICAC 1997).

IV. Preliminary Work on CO₂ Control Technologies

A. Overview

This approach involves the separation and capture of CO₂ from the gas stream of electric power plants and other industrial processes. The CO₂ would then be stored in geologic formations (e.g., deep saline reservoirs, depleted oil and gas wells, unmineable coal seams) or in other repositories including (potentially) the world's oceans. In contrast to terrestrial-based sequestration, where carbon is absorbed from the atmosphere and stored in soils or newly-grown biomass, this method of carbon management is a technology-based approach similar in principle to other types of environmental control technologies now used at power plants and other industrial facilities.

The technology for carbon capture and separation exists today, and is used commercially in some industries (for example, to produce hydrogen) (Humphrey and Keller, 1997). For power plants, CO₂ removal efficiencies of 75 to 90 percent are commonly assumed, and much higher removals (e.g. 99 percent) are achievable in some situations. The storage of CO₂ in geological formations also has been demonstrated on a limited scale, predominantly in the oil and gas industries (DOE, 1999). However, the cost of sequestration technology – especially the cost of CO₂ capture and separation – is currently prohibitive for large-scale power generation applications (Hertzog, 1999; Simbeck, 1999). But if cheaper methods can be developed to capture and reliably store the CO₂ produced by power plants and other industrial sources, the world's resources of fossil fuels could continue to be used while avoiding the potential consequences of global climate change. Such a scenario would represent a paradigm shift in the current thinking about solutions to the global warming problem.

B. CO₂ Policy Status

C. CO₂ Control Innovation Evidence: Patents

As in the other two cases, two datasets have been constructed in order to conduct patent analysis that could link inventive activity in CO₂ capture and sequestration technologies to government actions. As in the NO_x case, the first step in creating both CO₂ datasets was an exploration of a (very) few highly relevant CO₂ capture and sequestration patents based on iteratively conducted, small-scale patent searches. For the “CO₂-class based dataset,” a list of potential class and subclass combinations was developed from these preliminary searches, and interviews were conducted with several patent examiners responsible for the quite wide-ranging art units that encompassed these classes. More interviews had to be conducted for CO₂ capture and sequestration patents than for either of the other cases because of the wide-ranging nature of the technologies involved. Also unlike the other two cases, not a single patent examiner could be identified by his or her colleagues as having considerable experience with these technologies. The resulting class/subclass combinations that emerged from these interviews are more uncertain than the combinations in the other two cases; these are displayed in Table 2. The CO₂ class-based dataset that resulted from these class/subclass combinations over time encompassed 3,315 patents.

TABLE 4

U.S. patent classes and subclasses that comprise the CO₂ class-based dataset.

USPC Class/ Subclasses	Definition of USPC Class/Subclasses
423/220, 223-34, 437.1	Class 423, the “chemistry of inorganic compounds,” includes these subclasses representing the (220) modification or removal of carbon dioxide by (223-34): utilizing inorganic and organic reactants (including amine and ethanolamine); oxidizing or burning a component; suspending metal oxide or hydroxide in liquid; and utilizing a solid sorbent, catalyst, or reactant

	such as an iron oxide or carbonate (and possibly regenerating said reactant, for which process an ammonium or metal hydroxide solution may be used). It also includes this subclass (437.1) which involves products or processes wherein the product is carbon dioxide
95/51, 139, 236	Class 95, "gas separation processes," includes these subclasses representing (51) the selective diffusion of carbon dioxide or carbon monoxide gases through a substantially solid barrier; (139) solid sorption of carbon dioxide; and (236) liquid contacting process (e.g., sorption, scrubbing, etc.) in which carbon dioxide is separated
62/928	Class 62, "refrigeration," includes this subclass for recovery of carbon dioxide from a gas mixture.
166/402	Class 166, "wells," includes this subclass for the process of injecting carbon dioxide or carbonated gas
405/59	Class 405, "hydraulic and earth engineering," includes this subclass for the supply or recovery of stored fluid by a separate fluid
588/250	Class 588, "hazardous or toxic waste destruction or containment," includes this subclass for geologic marine or extraterrestrial storage and containment

Source: U.S. Patent and Trademark Office (2000)

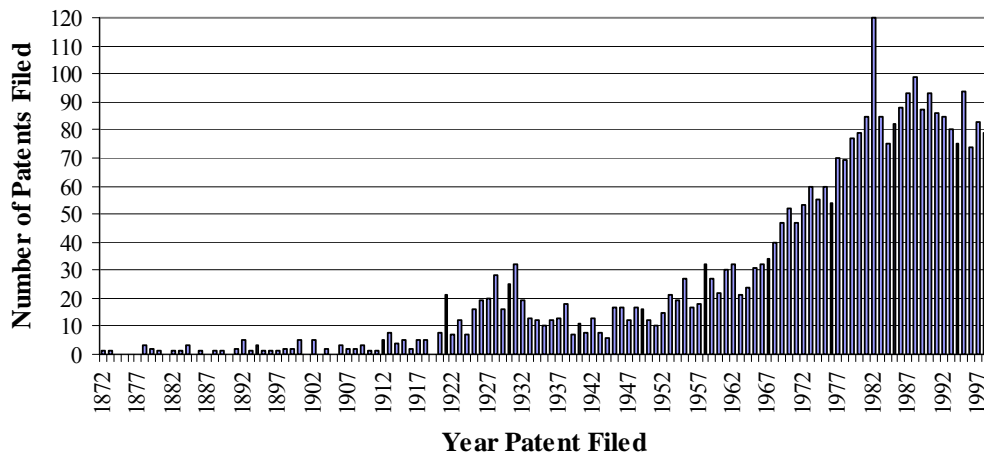
As in Taylor (2001) and in the NO_x patent work discussed above, a second abstract-based patent dataset was developed next in order to more narrowly select relevant technologies. As in the case of the NO_x abstract-based dataset construction earlier, the preliminary CO₂ capture and sequestration searches conducted above were analyzed for frequently occurring keywords within the patents' titles and abstracts. The resulting keywords and their likely variations were used to begin an iterative series of searches and analyses; these were conducted in order to arrive at a promising combination of keywords that would optimize the number of relevant and irrelevant patents selected by the final search. The optimal search derived in this process was then run on the entire USPTO database, although it was only consistent for patents granted after January 1, 1976, as discussed previously. The resulting "CO₂ abstract-based dataset" totaled 3,993 patents granted between the years of 1976 and March of 2001.

As in the NO_x case above, two further tasks are necessary to refine this CO₂ abstract-based dataset along the lines of Taylor (2001). First, these patents have to be coded and

irrelevant patents discarded, and second, the primary organizational actors responsible for CO₂ capture and sequestration technologies need to be identified and contacted in order to solicit their commercially relevant patents. Neither of these processes has been initiated yet, as we have generally followed our original research plan that involved CO₂ capture and sequestration patent analysis in the later stages of the project. One reason for this is that we believe that CO₂ capture and sequestration technologies are in their infancy and that the organizational side to innovation in these technologies is likely to change. We plan to have our final report reflect the most up-to-date patent situation possible.

Figure 26 displays the full CO₂ class-based dataset over time, and it is interesting to note the differences between this figure and the similar figures for SO₂ control and NO_x control (Figure 4 and Figure 15, respectively). The dramatically increasing slope of Figure 26 begins its ascent in about the same time (the 1960s) that the other two datasets exhibit their major increases in activity. The difference is in the shape of that increase. The most abrupt increase occurred in the SO₂ class-based dataset, a less abrupt increase occurred in the NO_x class-based dataset, and in the CO₂ class-based dataset, it appears that patenting activity increases in a much more steady way. In addition, there appears to be a single spike in the CO₂ class-based dataset that occurs in 1982, which does not appear to be consistent with the other two cases. It is probably too early in this analysis to consider what the shape of this curve and the meaning of this spike might be.

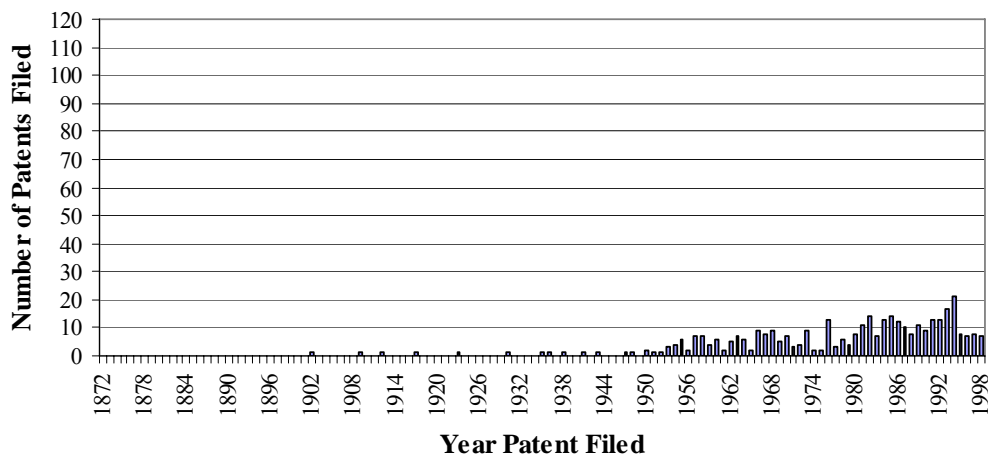
FIGURE 26
CO₂ class-based dataset.



Still, it is interesting to take a preliminary look at the data, particularly in the case of the sequestration side of CO2 capture and sequestration technologies. As was mentioned above, it is expected that this aspect of the technology is only beginning to develop; Figure 27 shows that patenting activity over twenty per year in sequestration technologies only occurs for the first time in 1994. In general, the average patenting activity level for these technologies over time is 2.94. After 1970, patenting levels increase relatively steadily until 1994, with the average activity level for the dataset between 1970 and 1998 9.10 patents per year.

FIGURE 27

Patent activity in: class 166, the subclass 402; class 405, the subclass 59; and class 588, the subclass 250. These subclasses include carbon sequestration technologies.



D. CO₂ Control Innovation: Possible Experience Curves

E. Implication of CO₂ Control Scenarios for Integrated Assessments

V. Interfaces with Other IAs

A. MIT

B. Battelle

VI. Conclusions

I thought I'd help us get started by looking at the IIASA draft 2 conclusions:

The main objective of the analysis was to assess the implications and future potentials of carbon capture technologies (CCT) under a variety of assumptions concerning technology costs and climate mitigation goals. The adopted method was to assess the ranges of deployment of CCTs in a number of scenarios, developed at ECS by the MESSAGE-MACRO modeling framework, and to illustrate related impacts on economic growth, electricity prices and carbon mitigation.

In the first report of this joint study a set of three scenarios (IIASA-TAR) had been analyzed to explore the role of carbon sequestration for the long-term stabilization of carbon concentrations at 550 ppmv. The report identified carbon capture and sequestration as one of the three principal mitigation measures. However, a simplifying assumption made the first report was that the results were based on more or less static technology assumptions for carbon-capture technologies (CCT). Just one of the three scenarios (A1B-550), which were analyzed in the first report, assumed technological progress for CCTs. In the other scenarios (A2-550, B2-550), the costs and the performance over time were assumed to stay constant.

On this basis, this report analyzed the market penetration of carbon-capture technologies in the case of exogenous technological learning. For this purpose, we updated the scenario assumptions for CCTs according to technology information provided by CMU. In order to estimate the future progress of carbon-capture technologies, we took the historic cost improvement over cumulative experience (learning) for sulfur abatement technologies, and applied them to CCTs in the power sector. By doing so, we developed a new set of three GHG emissions abatement scenarios (IIASA-CMU) consistent with multiple pathways of technological learning for CCTs.

The seven main findings of the scenario analysis are that:

- *the contribution of CCTs to the emissions reduction is considerably higher under exogenous leaning assumptions;*
- *the introduction of exogenous cost improvement for CCT leads to S-shaped diffusion curves for market penetration;*
- *the diffusion cycle (from initial introduction to saturation) of CCTs is about five decades, which is very similar to the life cycles of other technologies observed in the past;*
- *the timing of the diffusion for CCTs depends strongly on the socio-economic and technological assumptions in the baseline, leading to early deployment in A1B (2020), and comparatively late diffusion in A2 and B2;*
- *the price of electricity increases just moderately in case of a 550 ppmv stabilization, particularly under the assumption of technological change for CCTs;*
- *the GWP losses (macroeconomic costs) of stabilization is low compared to the total GWP increase of the scenarios, and do not differ significantly in the case of exogenous technological learning;*

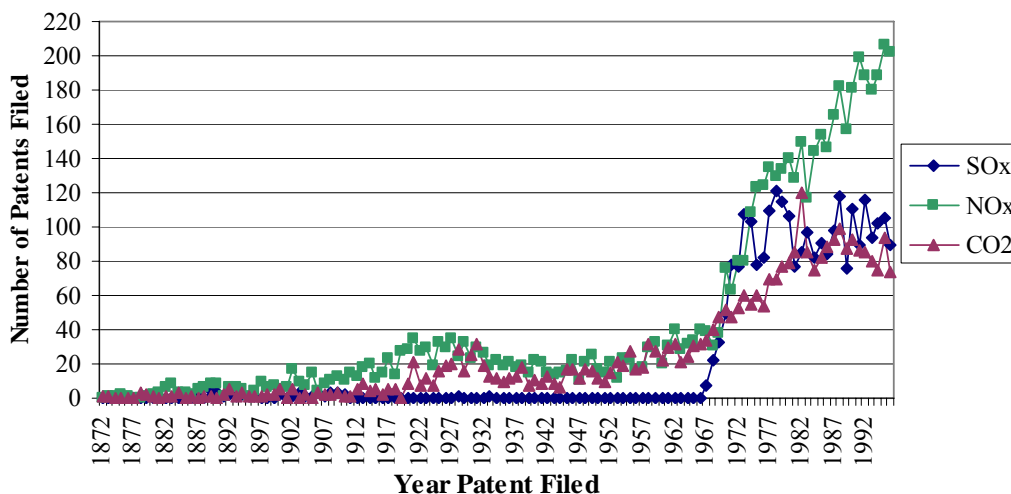
- CO_2 taxes (to meet the 550 ppmv carbon concentration constraint) depend strongly on the baseline assumptions, and are between 2 and 20 percent lower in the case of exogenous learning for CCT by 2100.

Our analysis focussed on exogenous technological learning for CCTs in the electricity sector only. One possible route of future research could therefore be a more detailed evaluation of the role of CCTs in the non-electric sectors. To do this would involve changing the model structure to better reflect the options for carbon capture during synthetic gases and liquids production. In particular, analyzing the carbon-capture during hydrogen production from various hydrocarbon sources (including biomass) seems to be a promising topic.

Another option for future research could be the advancement of the modeling framework to fully endogenize technological change for CCTs. Endogenizing technological learning leads to non-linearities and non-convexities of the optimization problem, which can not be solved with the present LP-formulation of the MESSAGE model. It is computationally infeasible for a detailed scenario that includes over 400 energy technologies and operates on 11 world regions to fully endogenize technological learning. By adopting Mixed Integer Programming (MIP), however, one could apply learning to a limited set of technologies, such as CCTs. In particular, the results from such an analysis seems to be most interesting, because it enables the quantification of CCT deployment rates fully consistent with the technological learning paradigm.

FIGURE 28

Class-based datasets for SO_x , NO_x , and CO_2 together.



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Appendix A. IIASA's First Draft Report

Appendix B. IIASA's Second Draft Report

Appendix C. History of NO_x Regulation for Stationary Sources

Year	Regulatory Agency/Regulation Act	Content
1947	California APCDs (Air Pollution Control District)	California legislature enacted a bill which allowed counties the option of establishing air pollution control districts
1955	Air Pollution Control Act	No requirements for NO _x emissions controls at that time. Still, the message was clear that NO _x emissions would be regulated in the foreseeable future. Throughout 1960s, additional supporting legislation for the Clean Air Act was passed. Yet, at the end of the decade, there were no national NO _x emissions regulations.
1969	Ventura County, CA.	The rule limited NO _x emissions from utility boilers to 250 ppm and 20 tons per day.
1970	Clean Air Act	Set National Ambient Air Quality Standards (NAAQS) , to protect public health and welfare, and New Source Performance Standards (NSPS) , that strictly regulated emissions of a new source entering an area. The long-term standard for NO ₂ was one of the original NAAQS set by EPA in 1971. This standard is set at 0.05 ppm, annual arithmetic average.
1971	Los Angeles Rule 68 San Diego APCD	Limit utility boiler NO _x emissions to 325 ppm for oil firing and 225 ppm for gas firing units having heat input rates in excess of 1775 million Btu/h.
1974 1975	San Diego APCD Los Angeles APCD	Limit utility boiler NO _x emissions to 225 ppm for oil firing and 125 ppm for gas firing units.
1977	Clean Air Act Amendments	The deadline to meet the ambient air standards was extended. Also at this time, the government made its first attempt to prevent the destruction of stratospheric ozone. This law also modified the Prevention of Significant Deterioration (PSD) policy designating regions as one of three different classes. The Amendments instruct EPA to: "Promulgate a national primary ambient air quality standard for NO ₂ concentrations over a period of not more than 3 hours unless, based on the criteria issued under section 108(c), he finds that there is no significant evidence that such a standard for such a period is requisite to protect public health." Yet no short-term standard for NO ₂ has been established. ¹⁸
1984	SCAQMD Rule 1135	Require a 90% NO _x reduction to be demonstrated on an SCE unit of at least 100 MW by January 1, 1982. Rule 1135.1 further required a 90% reduction in NO _x emissions from all units in South Coast Air Basin by either 1988 or 1990.
1990	Clean Air Act Amendments	Authorize EPA to establish standards for a number of atmospheric pollutants, including NO _x . Two major portions of the CAAA relevant to stationary source NO _x control are Title I and Title IV. Title I established National Ambient Air Quality Standards (NAAQS) for six criteria pollutants, including ozone and NO _x . Title V includes provisions designed to address acid deposition resulting from emissions of NO _x and SO ₂ from electric power plants.
1994	SCAQMD implement RECLAIM	RECLAIM replaced the previous command and control rules with a market based system of NO _x credits. RECLAIM required annual NO _x mass emission reductions of 10% relative to a predefined baseline. For SCE, who had previously installed SCR systems on their largest, most efficient units, the effect was to defer the retrofit

¹⁸ October 8, 1996 - EPA issued its decision not to set a short-term NAAQS for NO₂.

		of additional SCR systems since their annual mass emissions were already below the required levels.
1994	Title I: Ozone Transport Commission (OTC) NO _x Budget Program	Affected regions include 12 states & DC: CT, DE, MA, MD, ME, NH, NJ, NY, PA, RI, VT, VA. These reductions are in addition to previous state efforts to control NO _x emissions, which included the installation of reasonably available control technology. States have committed to developing and adopting regulations that would reduce region-wide NO _x emissions in 1999 and further reduce emissions in 2003. The NO _x Budget Program represents the Northeast's effort to control NO _x emissions in order to make progress towards attainment of the ozone health standard.
1995	Title IV: U.S. EPA acid rain program: emission standards for electric utilities	To help reduce acid rain, EPA devised a two-phased strategy to cut NO _x emissions from coal-fired power plants. The first phase, finalized in a rulemaking in 1995, aimed to reduce NO _x emissions by over 400,000 tons per year between 1996 and 1999. The goal of the second phase is to reduce emissions by over 2 million tons per year beginning in the year 2000.
1998	Title I: NO _x State Implementation Plan (SIP) Call	EPA issued a rule in 1998 that requires 22 states and the District of Columbia to revise their Implementation Plans to further reduce NO _x emissions by taking advantage of newer, cleaner control strategies. The rule does not mandate how the reductions are to be achieved, but gives each affected state a NO _x emission target. States have flexibility in determining how to reduce emissions. The goal of this rule is to reduce total emissions of NO _x by 1.2 million tons in the affected states by 2007.
1999	Title I: Section 126 Federal NO _x Budget Trading Program	For those States opting to meet the obligations of the NO _x SIP call through a cap and trade program, EPA included a model NO _x Budget Trading Program rule (Part 96). This trading program was developed to facilitate cost effective emissions reductions of oxides of nitrogen (NO _x) from large stationary sources. Part 96 provides sources with a complete trading program including provisions for applicability, allocations, monitoring, banking, penalties, trading protocols and program administration. States choosing to participate in the NO _x Budget Trading Program have the flexibility to modify certain provisions within the model rule. The allowance trading component of the NO _x SIP call provides an incentive for units to over-control if additional tons can be reduced at less cost than the market price of NO _x allowances

Appendix D. Summary of Estimated Costs of SCR Systems to New Coal-fired Electric Power Plants from 1978 to 1997

Year	1978	1984	1985	1987	1991	1991	1991	1994	1996	1997
Source	Mobley	Bauer	Maxwell	Damon	EPRI	Robie	Robie	Rao	DOE	Cochran
Technology year			1981-1983 1984	1987 dollars	1990 dollars	1989	1989	1993-1995/ 1993	1993-1995	1996
Boiler size (MWe)	500	500	500	300		500	500	500	500	460
NO _x reduction (%)	90%		80%			80%	80%	80%	80%	50%
Inlet NO _x conc.			0.6			0.4	0.4	1.01	0.35	0.32
Catalyst price (\$/ft ³), 1997\$			842			830	830	482	408	310-340
Ammonia cost (\$/ton), 1997\$			230			182	182	189	255	
Catalyst life (yrs)		1	1 (5,500 hrs)	1	2	4	4	4	K/k ₀ =0.8 at 16,000 hrs	>24,000 hrs
Type of SCR			High-dust	High-dust		Hot-side	Hot-side	Hot-side	High-dust	High-dust
Boiler Type						PC-fired	PC-fired		wall/ tangential	
Capacity factor (%)	100%		63%			65%	65%	65%	65%	
Plant life/project life (yrs)		30	30			30	30	20	30	
Outlet NO _x conc.			0.12			0.08	0.08	0.202	0.07	0.16
Ammonia slip		10 ppm		3-5 ppm		5 ppm	2 ppm	5 ppm	5 ppm	2 ppm
Coal sulfur content	3.50%	low sulfur	3.50%	medium sulfur		3.74%	3.74%	4.30%	2.70%	2.50%
Cost estimate (1997\$)										
T Capital Require. (\$/kw)	>100	86-153	128	189	94-112	98	112	65	53	48
Levelized O&M										0.42
Levelized, mills/kWh	>3.7	8.85-23.4	19.26			6.69	7.43	4.47	1.88	1.00
Cost-effectiveness (\$/ton)			8461		3324-4835	4311	4790	1136	1373	1225
Catalyst (% T. process cost)									21%	
Catalyst (% T. capital requirement)			29%						16%	
Catalyst (% variable O&M)									61%	
Catalyst (% Total O&M)			88%						43%	
Ammonium (% Variable O&M)									21%	

Ammonium (% Total O&M)			2%						15%	
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