Effect of Government Actions on Technological Innovation for SO_2 Control

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The relationship between government actions and innovation in environmental control technology is important for the design of cost-effective policies to achieve environmental goals. This paper examines such relationships for the case of sulfur dioxide control technology for U.S. coal-fired power plants. The study employs several complementary research methods, including analyses of key government actions, technology patenting activity, technology performance and cost trends, knowledge transfer activities, and expert elicitations. Our results indicate that government regulation appears to be a greater stimulus to inventive activity than government-sponsored research support alone, and that the anticipation of regulation also spurs inventive activity. Regulatory stringency focuses this activity along particular technical pathways and is a key factor in creating markets for environmental technologies. We also find that with greater technology adoption, both new and existing systems experience notable efficiency improvements and capital cost reductions. The important role of government in fostering knowledge transfer via technical conferences and other measures is also seen as an important factor in promoting environmental technology innovation.

Introduction

Throughout history, technological innovation has played an essential role in economic development and the creation of wealth. For this reason it has also been the subject of scholarly research to better understand the factors and forces governing the innovation process. Less well studied has been the role of innovation as it affects environmental technologies, whose use or application stems in part from government policies or regulations as opposed to fully from “natural” market forces. Understanding the impacts of government actions on environmental technology innovation is important because such insights can help shape policies that reduce the costs and improve the effectiveness of future environmental control measures.

This paper presents findings from a study of the effects of government actions on innovation in SO_2 control technology, particularly flue gas desulfurization (FGD) systems that achieve high levels of SO_2 control at coal-fired power plants and industrial boilers. Because much of the world’s electricity is generated from the combustion of coal, emissions from coal-fired power plants have been the subject of substantial scrutiny and attention in the United States and elsewhere. Until recently, the primary focus has been on pollutants directly linked to adverse human health effects, namely, particulate matter, sulfur dioxide, nitrogen oxides, and air toxics, especially mercury. Today, power plant emissions also are the subject of intense study in the context of a new environmental problem—global climate change. This issue centers primarily on emissions of carbon dioxide (CO_2), a greenhouse gas widely linked to global warming and climate change impacts. In looking prospectively at potential technological options and costs for abating power plant CO_2 emissions, historical experience for other environmental technologies can serve as a plausible guide to future trends in ongoing assessments of options such as CO_2 capture and storage technologies.

We begin with a brief summary of the history of public concern and government actions to control SO_2 emissions in the United States. We then describe the industry responses to government policies and the subsequent impacts on technological innovation with respect to SO_2 control. Our results and findings are discussed in the context of the technology innovation literature and past treatments of environmental technologies. Throughout the paper, we also include brief descriptions of relevant methodologies, more detailed treatments of which are found in ref *1*.

Historical Context for SO_2 Control

There is a long history of public concern about SO_2 because of its negative effects on human health and ecosystems. SO_2 is an eye, nose, and throat irritant, which in the extreme has contributed to infamous air pollution incidents such as the killer smogs in Donora, Pennsylvania, in 1948 and London, England, in 1952 (*2*, *3*). SO_2 emissions also are the major culprit (along with nitrogen oxides) in acidic deposition, with resulting damage to lakes, streams, plants, and forest growth. More recently, SO_2 emissions have been linked to the formation of fine particles associated with increased human mortality (*4*).

Table 1 summarizes the key legislative and regulatory actions undertaken by the U.S. government in response to public concern regarding SO_2 emissions. These actions over several decades have set the stringency of emission reduction requirements, defined the flexibility and time constraints for regulatory compliance, and established markets for suppliers of SO_2 abatement equipment. In addition, the U.S. government has funded research, training, and technical assistance programs for SO_2 control, including demonstration projects, grants to pollution control vendors, and technology transfer opportunities such as national conferences. All of these measures have directly affected the design, deployment, and operation of SO_2 control equipment.

In the United States, the main source of SO_2 emissions is the combustion of coal at electric power plants (*5*). Measures to reduce these emissions fall into two general categories: switching to lower-sulfur or sulfur-free fuels (such as low-sulfur coal or natural gas), or installing control technology to capture SO_2 before it is emitted to the atmosphere. The latter measure is the primary focus of this paper.

Today, over 90,000 MW of U.S. electric power plant capacity (nearly 30% of coal-fired capacity) are equipped

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10.1021/es034223b CCC: $25.00

TABLE 1. Main U.S. Legislative/Regulatory Actions Related to SO_2 Control

government action	enactment date	summary and implications
Air Pollution Control Act Clean Air Act Air Quality Control Act	1955 1963 1967	Provided research funding and federal financial assistance to state & local governments for air pollution control.
1970 Clean Air Act Amendments (CAAA)	December 1970	Required EPA to establish national ambient air quality standards for SO_2 (affecting all sources of SO_2) and "best available technology" performance standards for major new sources of SO_2.
1971 New Source Performance Standards (NSPS)	December 1971	Maximum allowable emission rate for new and modified sources was 1.2 lbs of SO_2/MBtu heat input. This effectively required 0−85% SO_2 removal, depending on coal properties.
1977 Clean Air Act Amendments	August 1977	Directed EPA to implement new source performance standard for SO_2 based on a percentage reduction from uncontrolled levels. This was intended to promote universal scrubbing at new plants.
1979 New Source Performance Standards	June 1979	Required a 70% to 90% reduction of potential SO_2 emissions (depending on coal sulfur content and heating value) for new plants built after 1978. This sliding scale favored wet scrubbing for high-sulfur coals and dry scrubbing for low-sulfur coals.
Clean Coal Technology Demonstration Program	December 1985	$2.5 billion government cost-sharing program operated by DOE to demonstrate advanced "clean" coal technologies, including SO_2 control, at a commercially relevant scale.
Senate Attempt at 1987 Clean Air Act Amendments (CAA Try)	(1987)	Serious but unsuccessful attempt to overhaul the CAA, with particular emphasis on tightening acid rain precursor controls. Federal government would subsidize the capital cost of installing scrubbers.
1990 Clean Air Act Amendments	November 1990	Established an emission allowance trading program to achieve a cap in 2010 of 8.95 million annual tons of SO_2 in two phases. Phase I (1995−1999) applied an aggregate emission limit of 2.5 lb/MBtu to 261 existing generating units. Phase II (2000−10) applies an aggregate emission limit of 1.2 lb/MBtu to about 2,500 existing units.

with flue gas desulfurization systems (also known as scrubbers), with the dominant technology being wet limestone systems (*6*, *7*). As Table 1 shows, all new coal-fired plants built since 1978 were required to install SO_2 removal systems, with many older plants also installing FGD units to comply with state and local air quality regulations, or with federal acid rain control requirements. However, when the New Source Performance Standards for SO_2 were first issued in 1971, only three commercial SO_2 scrubber units were operating in the United States. In hearings held in 1973, FGD systems brought into service in 1972 and 1973 reported operating difficulties related to chemical scaling, demister pluggage, corrosion, reheater problems, and mechanical failures in equipment such as fans, pumps, and dryers. These early scrubbers had widespread reliability problems and SO_2 removal efficiencies as low as 40% (*8*).

Since those early days, FGD technology has matured and improved considerably, as will be shown later in this paper. The sources of innovation in SO_2 control technology included electric power producers, FGD vendors, equipment suppliers, engineering firms, government agencies, universities, and industrial researchers. Together, these organizations comprise the "SO_2 industrial−environmental innovation complex." This complex engages in innovative activities including invention, adoption, diffusion, and learning by doing. "Invention" refers to the development of a new technical idea, whereas "adoption" refers to the first commercial implementation of an invention. "Learning by doing" refers to post-adoption innovative activities that result from knowledge gained through operating experience. "Diffusion" is the process by which an adopted technology or knowledge enters widespread use, and involves communication of information among current and potential users of the technology. More detailed discussions of these concepts can be found in the technology innovation literature (for example, refs *9* and *10*). A brief review of that literature provides additional context for the present study.

Literature Review

Previous research on the effects of government actions on technology innovation can be found in two types of literature. The first, "mainstream innovation literature," traces its origins to Schumpeter (*11*) and is generally centered on technologies for which market forces have been the primary drivers. A comprehensive review of this literature can be found in Stoneman (*12*). Here, environmental technology was considered at least as early as 1969 in an article by Rosenberg (*13*) that sought historical examples of the "forces which provide inducements to technical change." Among the numerous and diverse "inducement mechanisms" to technological innovation articulated by Rosenberg was governmentally imposed environmental regulation. Rosenberg cited a case in Sweden in which newly imposed regulations on process water discharges in the pulp and paper industry had "induced" some Swedish firms to innovate, developing manufacturing processes that not only met government regulations but that also were inherently more efficient. Thus environmental regulation could serve as an inducement mechanism for technological change (innovation), leading to competitive advantage. Another early champion of the benefits of eliminating "waste" in industry was the engineer Herbert Hoover, 31st President of the United States, who cited efficiency gains and other forms of competitive advantage as inevitable byproducts of technological innovation to eliminate waste (*14*).

The work of most scholars dealing with environmental technological innovation, however, is part of a second body of work that we call the "environmental technology literature." This literature is considerably smaller than the mainstream innovation literature, and is diverse and interdisciplinary in nature. Kemp (*15*) provides a useful review and critique. In this literature, the observation that competitive advantage sometimes accrues to firms able to meet environmental constraints was popularized in the 1990s by debate on the "Porter Hypothesis." This emerged from an

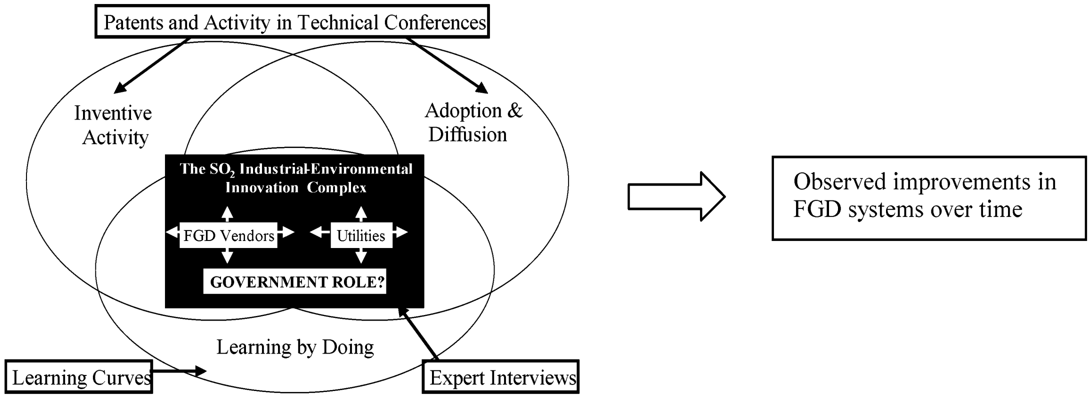

FIGURE 1. Methods used in this research to study environmental technology innovative activities (left) and the outcomes of these activities (right).

influential 1991 essay by strategy expert Michael Porter (*16*), who argued that tough environmental standards which stress pollution prevention, do not constrain technology choice, and are sensitive to costs could spur innovation and enhance competitive advantage. Underlying this hypothesis is the long-standing debate in the environmental technology literature of how best to design the specifics of environmental standards in order to spur innovation. Throughout this literature the need for detailed case studies is emphasized as especially critical for developing and supporting defensible hypotheses relating environmental technology innovation to government actions and policies. Thus, the present study is intended to contribute to a better understanding of how the forces of innovation can be harnessed to help meet environmental goals.

Research Methods

A number of different methods have been used in the past to study technology innovation. Cohen and Levin (*10*), and Schmoch and Schnoring (*17*) discuss the strengths and limitations of different methodological approaches. As depicted in Figure 1, our study integrated several established research methods (both quantitative and qualitative) to investigate innovative activities and outcomes in the SO_2 industrial—environmental innovation complex. This approach provides a more realistic and robust understanding of innovative processes than any single method would offer. Each of the methods depicted in Figure 1 is briefly described below, with additional details provided in ref *1*.

Patent Activity Analysis. Researchers have long used patents as a measure and descriptive indicator of inventive activity (*18*). Patents provide detailed and publicly accessible technical and organizational information for inventions over a long period of time. In addition, studies have shown that patenting activity parallels R&D expenditures by firms; this relationship is particularly useful when detailed R&D information for an industry is unavailable. In addition, studies have shown that patenting activity can be linked to events external to a firm. This attribute of patents also is especially useful for studying the effects of SO_2-related government actions on inventive activity in SO_2 control technology.

Our patent activity analysis drew on four main sources of data: the U.S. Patent and Trademark Office (USPTO) patent database from 1887 to 1997, an interview with the primary USPTO examiner of FGD technologies (*19*), International Energy Agency (IEA) data on the world FGD market (*7*), and patent lists obtained from three companies that together supplied nearly 40% of the U.S. FGD capacity between 1973 and 1993. First, the USPTO classes used to develop prior art—earlier patents whose claims are legally determined by the patent examiner to be closely related to the claims in the citing patent (*20*)—were elicited from the patent examiner, then used to generate a time-series of 2,681 patents issued from 1887 to 1997 that were relevant to SO_2 control. This “class-based” patent dataset was consistent for over 100 years and thus could be used to relate patenting trends to the timing of past government actions related to SO_2 control.

Patent classes are a relatively broad method for identifying specific technologies, however. Thus, a second dataset of 1,593 patents was generated based on an electronic search for relevant keywords in the abstracts of all patents granted from 1976 to 1996. These dates were used because systematic electronic keyword searching is possible only for USPTO patents granted after 1975. Content analysis was then performed on this “abstract-based” dataset by reading each abstract to eliminate irrelevant patents. The final yield was 1,237 relevant patents. Patent activity in this dataset was later analyzed in the context of various government actions through econometric analysis and the interpretation of experts, as discussed later in this paper.

To check the commercial relevance of both the class-based and abstract-based datasets, the patent lists obtained from prominent FGD vendors were compared to those in each dataset to see if the screening had identified them. Both datasets included a high percentage of these commercially relevant patents, with the abstract-based dataset showing better overall performance. Inferences drawn from these patent datasets also are discussed later in this paper.

FGD Performance and Cost Analysis. Key outcomes of the innovation process for FGD technology include improvements in the reliability, performance, and cost of new and existing systems over time. Analysis of the rate of technical improvements for new FGD systems was conducted using the concept of a learning curve (or experience curve) (*21*), in which a performance variable such as cost is displayed as a function of total cumulative production of the technology; in this case, total installed FGD capacity in the United States. First, the improvement in SO_2 removal efficiency of new wet limestone systems was characterized using the DOE/EIA Form 767 dataset (*22*) to determine the average removal efficiency of new FGD units coming online each year. In a second analysis, improvements in FGD capital cost were analyzed based on a benchmark 500-MW power plant burning a high-sulfur coal, as analyzed by five historical studies and adjusted to 1997 dollars. It was important to investigate costs based on a benchmark plant because FGD capital costs depend on a variety of site-specific factors. Implicit in the FGD cost analysis was a high degree of system reliability relative to early designs.

Cost reductions from “learning by doing” at existing FGD units also were analyzed in a manner consistent with other studies of organizational learning (*23*). This analysis again drew on the DOE/EIA Form 767 dataset (*22*), this time for operating experience from 1985 to 1997 at 88 U.S. power

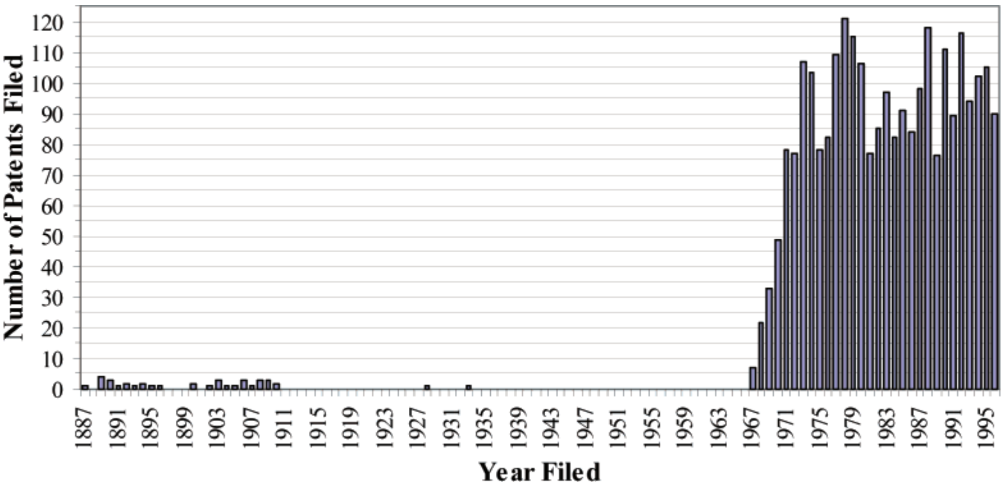

FIGURE 2. U.S. patents relevant to SO_2 control technology (based on the patent class dataset).

plants with FGD systems that were in operation over this entire 12-year period (no data were available prior to 1985). Results of the performance and cost analyses are presented later.

Analysis of Knowledge Transfer Activity. As noted earlier, the diffusion of information is an important component of the innovation process. To study the influence of government activity in this area, we conducted two additional types of analysis centered on the government-sponsored SO_2 Symposium that was held on a regular basis from 1973 to 1995. This prominent national conference brought together all elements of the SO_2 industrial–environmental innovation complex, and was widely regarded as a critical activity in the development of SO_2 control technology.

First, a technical content analysis of each conference proceedings was conducted to examine changes in emphasis on various SO_2-related technology areas over time, and their relationship to the timing of major government legislative and regulatory actions. Technical content analysis of this type is in the research tradition of examining a variety of indicators of innovative activity, including journal articles and advertisements in trade publications. Santarelli and Piergiovanni (*24*) provide a brief review of such literature-based innovation research.

The second type of analysis examined researcher coauthorship networks. This analysis was conducted to capitalize on previous innovation research showing that networked organizations have better opportunities to benefit from knowledge transfer (*23*), and that technical conferences and consortia are among the important knowledge transfer mechanisms (*25*). In this research, network analysis of the changing coauthorship patterns at the SO_2 Symposium provided a proxy for the channels of inter-personal and inter-organizational information exchange (relevant to the diffusion process) that were facilitated by the conference.

To carry out these analyses, each technical paper in seventeen conference proceedings was coded by year, session topic, paper number, title, coauthors, organizations, “organization types,” and geographic location. For the content analysis, paper sessions were grouped by technical category. For the researcher coauthorship network analysis, the overall network was considered according to organization type, whereas a more refined analysis considered the interactions among “important” organizations and coauthors that presented in at least half of the conferences. Ref *1* provides additional details of these methods.

Expert Elicitations. Finally, we conducted extensive interviews with twelve experts representing a variety of organizational backgrounds and affiliations involved in SO_2 control technology development. These experts were identified on the basis of the length and level of their participation in the SO_2 Symposium and the range of perspectives they provided (including those of industry, government, and academia). In structured two-hour interviews, they were asked about numerous aspects of the SO_2 industrial–environmental innovation complex. FGD performance trends were elicited from them in order to calibrate other expert responses. Key technological developments and government actions considered significant also were elicited. In addition, experts were asked about the importance of patents and the SO_2 Symposium to the industry and SO_2 control technology development, and they were asked to give their interpretation of observed patenting trends.

Results and Discussion

The key findings from this study are organized into three main areas. In general, the results and conclusions in each area are drawn from more than one of the methodological approaches described above.

Effect of Regulation on Inventive Activity. Figure 2 shows the level of inventive activity in SO_2 control technology as reflected by patenting activity over more than 100 years using the class-based dataset. Patenting levels can be portrayed as a step-function dividing two time periods. Prior to the late 1960s, there was little or no activity (no more than four patents per year), despite government legislation dating back to 1955 that authorized research into air pollution abatement methods (see Table 1). The onset of SO_2-related patenting activity is seen to coincide with adoption of the 1970 Clean Air Act Amendments (CAAA) and the 1971 New Source Performance Standards (NSPS), which effectively established a national market for FGD technology in the United States. After 1970, patenting activity never fell below 76 per year. Thus, the patenting trend in Figure 2 suggests that the adoption of stringent national regulations for SO_2 emissions control stimulated inventive activity more than government-sponsored research support alone. This indication that national regulation was a more effective stimulant of inventive activity than federal research funding alone is supported by other veins of evidence in our research, notably the technical content analysis of the SO_2 Symposium and the testimony of experts interviewed. It is also consistent with findings from case studies of other environmental technologies (*26*).

The anticipation of government regulation also appears to have spurred inventive activity as reflected by patent filings. Trends in the abstract-based patent dataset (Figure 3), together with expert testimony, support this hypothesis (see ref *1* for modeling details). The data in Figure 3 (as well as the class-based dataset in Figure 2) show “bursts” of patent

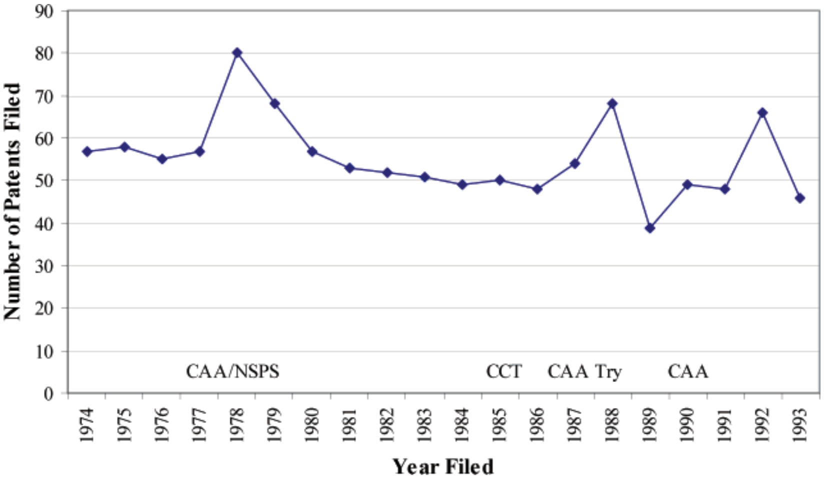

FIGURE 3. Trend in U.S. patents relevant to SO_2 control technology as identified in the abstract-based dataset. (See Table 1 for descriptions of the government actions shown on the *x*-axis at different points in time.)

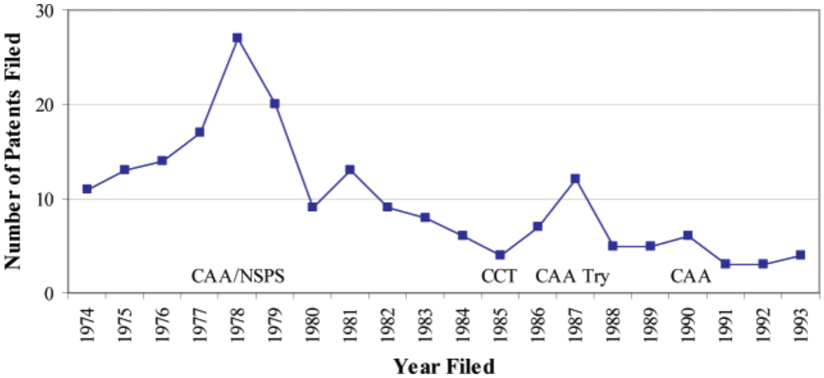

FIGURE 4. Trend in precombustion SO_2 control technology patents identified in the abstract-based dataset.

filing activity in 1978, 1979, 1988, and 1992 that are indicative of changes in external events relevant to the technology (*18*). The experts in our study also believed that the pattern of peaks observed in Figure 3 was due to contemporary national legislative and regulatory events identified in Table 1. For example, as an explanation for the 1988 peak, nearly all the experts mentioned a heightened public and legislative awareness of acid rain in the mid- to late-1980s and the anticipation of legislation that would have overhauled the Clean Air Act. The result of that anticipation, they explained, was an intensification of research, technology demonstrations, and testing of moderate-removal SO_2 control technologies that would have fit contemporaneous Congressional proposals (see Table 1) which ultimately did not get enacted. The idea that *anticipated* regulation has the ability to drive innovation is not new to this study; Ashford, Ayers, and Stone (*26*), for example, drew a similar conclusion from studies of other industries. This study shows, however, that the direction and nature of innovative activity can be affected significantly by the anticipated and actual requirements of environmental regulations.

Evidence that regulatory stringency directs the focus of inventive activity is seen in Figure 4, which shows patenting activity in precombustion SO_2 control technologies, which are primarily coal cleaning processes. Although these technologies were not dominant in the overall patent datasets, in the early 1970s patenting activity in this area grew significantly. At that time, SO_2 emission standards allowed low-sulfur coals to play a prominent role as a compliance strategy for both new and existing sources, and precombustion sulfur removal was of significant interest. However, after the 1977 CAAA required New Source Performance Standards to be tightened (based on the technological capabilities of both wet and dry FGD systems), patenting activity in coal cleaning technologies dropped precipitously. Both statistical analysis and expert elicitation support the conclusion that the stringency of the 1979 NSPS (requiring 70 to 90% sulfur removal) curtailed inventive activity in precombustion technologies, as these technologies were no longer as central an option in SO_2 control for new plants as the postcombustion control technologies.

Conversely, the stringency of the 1979 NSPS for low-sulfur coals was an important driver of innovation in dry FGD technology in the 1980s, according to both expert interviews and the content analysis of papers presented at the national SO_2 Symposium (*1*). Dry FGD technology was the basis for the 70% removal floor of the 1979 NSPS, and the technology matured and diffused quite rapidly in the utility FGD market as a result. The 1990 CAAA, however, although initially predicted to increase demand for FGD systems, eroded the market potential for both dry and wet FGD system applications at existing power plants when the SO_2 allowance trading market returned low-sulfur coal to its importance in SO_2 control. [Of those plants specifically required to participate in Phase I of the 1990 CAAA, 62% chose fuel switching and blending as a compliance option while only 10% chose FGD (*27*).] As a result, research in dry FGD technology declined significantly (*1*). In this case, the flexibility provided by the 1990 acid rain regulations discouraged inventive activity in technologies that might have had broader markets under the traditional command-and-control regimes in place prior to 1990.

Overall, our results regarding the effects of regulatory stringency and market scope on environmental technology innovation are consistent with one of the strong conclusions of the mainstream innovation literature, namely that the

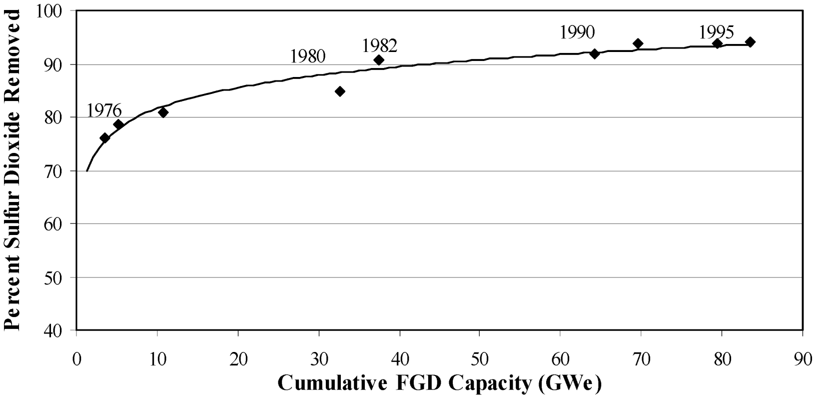

FIGURE 5. Improvements in SO_2 removal efficiency of commercial FGD systems as a function of total installed FGD capacity in the United States.

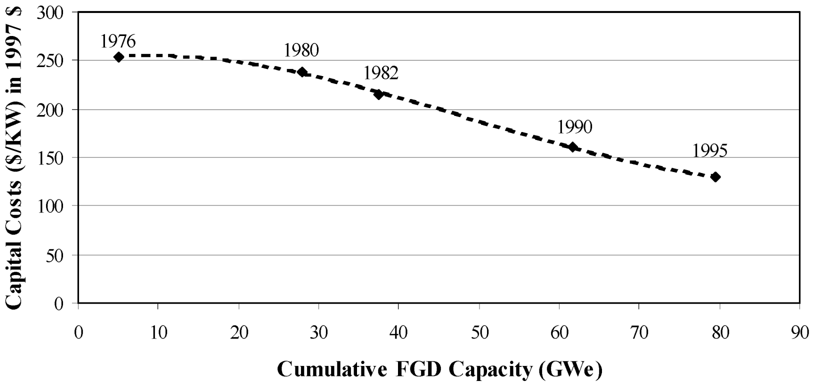

FIGURE 6. Reductions in capital cost of a new wet limestone FGD system for a standardized coal-fired power plant (500 MW, 3.5% sulfur coal, 90% SO_2 removal) as a function of total installed FGD capacity in the United States.

demand for a technology is a major driver of innovation (*28*). In the context of environmental technologies, the demand for various types of pollution control equipment is almost inseparable from the details of environmental legislation (*15*).

Innovation Impacts on Performance and Cost. The most tangible outcomes of technology innovation in SO_2 control over the past several decades have been the improvements in reliability and SO_2 removal efficiency of FGD systems relative to those of early designs of the 1970s, as well as substantial reductions in the cost of this technology. Figures 5 and 6 show the results of the performance and cost analyses described earlier for wet limestone FGD systems at new U.S. power plants. Figure 5 first shows the average SO_2 removal efficiency of new units coming online each year. The improvements seen reflect advances in FGD process design stemming from continued research and development and operating experience (*1*). Today, new FGD systems are routinely designed for SO_2 removal efficiencies in the range of 95 to 98% or more. Reliability has not been an issue for over a decade because of design changes now embodied in this technology.

Figure 6 illustrates the dramatic reduction in capital cost that has been achieved since FGD systems were first deployed in the U.S. The costs shown here are for a new wet limestone system doing the same "job" at different points in time, i.e., 90% SO_2 removal at a standardized 500 MW plant burning high-sulfur coal. Over the 20-year period shown, capital cost decreased by a factor of 2. While many factors contributed to this overall cost reduction (including competition among equipment suppliers), a careful look at the evolution of this technology (*1*) indicates that technological innovations stemming from experience and investments in R&D (by both the public and private sectors) were the dominant factor in realizing these gains.

Our research also found that many of the utilities that installed FGD systems over the past three decades realized significant reductions in the operating cost of these systems through "learning by doing." Analysis of the operating data for 88 plants with at least twelve continuous years of wet limestone FGD operation indicated that the total adjusted labor cost for FGD operation, maintenance, and supervision was reduced, on average, to 83% of its original value for each doubling of cumulative power generation at the plant (*1*). This value of 83% is known as the progress ratio in organizational learning curve analysis, and this particular value is comparable to those found in studies of many other industries (*21*, *23*). In some cases, the benefits or knowledge gained from learning by doing can be passed on to others. The role of government in facilitating such knowledge transfer is illustrated by our findings for SO_2 control, as discussed below.

Influence of Knowledge Transfer Activities. Government support of the national SO_2 Symposium as a technology transfer and knowledge diffusion mechanism played a key role in the evolution of SO_2 control technology, according to strong agreement among the diverse set of experts interviewed for this research. In addition, experts credited the conference with fostering cooperation between utility operators and technology developers and researchers, as it brought together all the major technological actors in SO_2 control to try to advance the technology. The patterns of coauthorship between these technological actors approximate the knowledge transfer routes facilitated by the conference. To explore these patterns through network analysis, we began by dividing the conferences into three time periods based on real or anticipated government actions; the 1979 NSPS and 1990 CAA, both of which represented important changes in the stringency and scope of SO_2 control require-

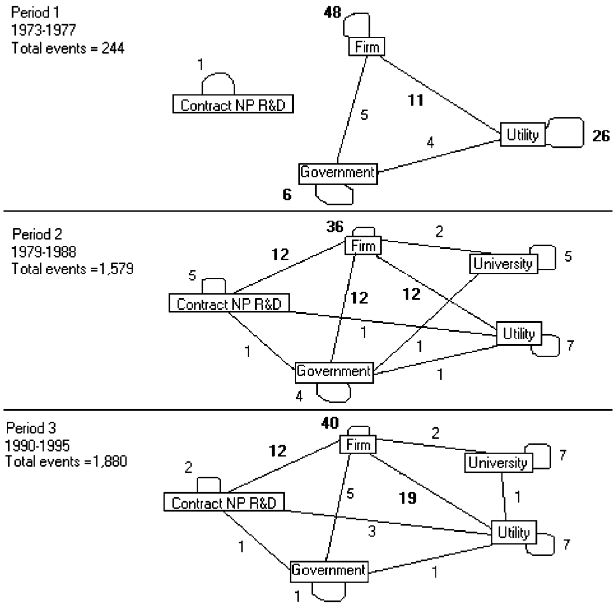

FIGURE 7. Evolving coauthorship ties between organization types for three time periods; numbers are percentages of total ties in each period. "NP R&D" = nonprofit research and development organizations; "Firm" includes FGD vendors and architect−engineering firms.

ments, were chosen as the period-defining government actions.

Figure 7 shows ties among authors of symposium papers by type of organization, where a "tie" is calculated as the total number of independent links between any two coauthors (e.g., a paper with three coauthors represents three ties; four coauthors yields six ties, etc.). Each organization type is connected either to the same organization type or to other organization types for at least 1% of all the coauthorship ties in each of the three time periods. [Because they do not account for 1% of the ties in each period, trade associations do not appear in this figure.] The numbers shown in this figure are the percentages of all coauthorship ties (the total number of ties in each period is labeled the number of "events" on the side of each diagram) that occurred between researchers in the tied organization types of "firm," "government," "nonprofit R&D organization," "university," and "utility" during each time period. The numbers in bold highlight strong ties accounting for more than 10% of the total in each period.

The organization type network in the Group 1 conferences is quite different from that in the Group 2 and 3 conferences. In the Group 1 conferences (1973 to 1977), not every organization type is connected to others through authorship ties on papers. This is perhaps to be expected in this time period, which was marked by litigation between regulated utilities and government, as well as by a particularly competitive SO_2 control market in which FGD systems were being deployed on a limited scale. [The contemporary perception of the scrubber market, which had experienced a 10-fold increase in commercial scrubber unit installations between 1971 and 1976 and a low but growing profitability between 1976 and 1978, was that it would continue to improve due to new regulatory initiatives. This was an impetus to FGD equipment and services industry acquisitions and new entry (the number of firms in the utility FGD market between 1971 and 1977 increased from one to thirteen).] Most of the papers presented at the early SO_2 Symposia reflected ties within the utility industry or within other firms; only 20% of the ties involved links across different types of organizations.

In the organization type network in the Group 2 conferences (1979 to 1988), there were substantial increases not only in the total number of paper coauthorship ties, but in the percentage of ties across organization types. This provides evidence of the formation of a collaborative community of researchers that appeared just after the implementation of the 1979 NSPS, a stringent technology-based standard that applied to all new and substantially modified coal-fired plants, and during a period in which acid rain was under intense study and new SO_2 control requirements were widely anticipated.

In the third period (1990−1995), cross-organizational ties at the SO_2 Symposium remained stable, and the number of ties in the network continued to grow following implementation of the 1990 CAAA. By this period, FGD systems had largely matured (see Figures 5 and 6), and the relatively lax stringency of the new act was unlikely to drive the research community to work together more closely across organizational types. The high demand anticipated (but not realized) by the scrubber industry for new FGD installations resulting from the act, however, was likely to drive more overall interest in the industry, just as each major new national regulatory event had prompted new entry by firms into the market (see ref *1* for more details).

Ref 1 provides additional analyses of the SO_2 Symposium and its role in knowledge and technology transfer. The key implication of these findings is that government actions played an important role not only in establishing markets for environmental technologies (via the emission reduction requirements imposed), but also in stimulating the formation of communication channels important to knowledge transfer and diffusion, as well as overall technological innovation.

Concluding Remarks

The methods used here to study technology innovation for SO_2 control are being extended to case studies of other environmental technologies to provide a larger empirical basis for generalized insights about the influence of government actions on environmental technological innovation. Our hypothesis, based on the present study and other supporting literature, is that the stringency, flexibility, market size, and time allowed to achieve mandated emission reductions are among the key factors that affect the nature and pace of environmental technology innovation. Our preliminary analysis of the history of innovation in selective catalytic reduction (SCR) technology for NO_x control is consistent with the findings presented here for FGD systems (*29*).

Improved understanding of how government actions affect environmental technology innovation will be particularly important in the context of future policy decisions such as those regarding global climate change. Continued research into how such actions can most effectively promote environmental technology innovations that reduce the cost of environmental compliance can thus have a major impact on this and other areas of environmental policy.

Acknowledgments

Support for this research was provided by grants from the National Science Foundation to the Carnegie Mellon University Center for Integrated Study of the Human Dimensions of Global Change (Grant SBR-9521914), and from the Office of Biological and Environmental Research, U.S. Department of Energy (Grant DE-FG02-00ER63037). The authors alone, however, are responsible for the content of this paper.

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Received for review March 13, 2003. Revised manuscript received June 16, 2003. Accepted July 1, 2003.

ES034223B