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The Effect of Government Actions on Technological Innovation for SO2 Control

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The Effect of Government Actions on Technological Innovation for SO_2 Control

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ABSTRACT

This paper examines innovation in sulfur dioxide (SO_2) control technologies for electric power plants. Innovation in these technologies has been influenced by government actions, ranging from government-sponsored R&D and pollution-control demonstration programs to regulation of emissions.

Our analysis employs several complementary methods with which to understand innovation in SO_2 control technologies. Innovative activities were investigated using: analysis of patenting activity; analysis of the technical content of conferences held for over twenty years to promote innovation in SO_2 control technologies; analysis of the researcher networks formed by co-authorship in that conference; analysis of learning curves for U.S. power plants; and structured interviews of experts spanning a range of roles in SO_2 control technology. Innovative outcomes were investigated through: analysis of observed improvements in newly installed technologies over time; evaluation of historic cost studies on standardized systems; and expert interviews.

Several policy-relevant findings result from this research. (1) The existence of national government regulation stimulated inventive activity more than government research support alone. (2) Regulatory stringency directs the focus of inventive activity. (3) Increased requirements for SO_2 control helped stimulate the formation of communication channels important to technology diffusion. (4) The existence and anticipation of government regulation appears to spur inventive activity. (5) Federal funding of a conference to support technology transfer in SO_2 control was extremely valuable to innovation. (6) The regulation-forced adoption of SO_2 control technologies led to significant cost savings based on operating experience. The rate of these cost savings is comparable to learning curves found in many other industries, and is likely to be useful in predicting improvements in future environmental control technologies. (7) Notable SO_2 removal efficiency improvements and capital cost reductions for new systems occurred as the technology became more widely adopted. These findings are currently being expanded to assess other emerging areas of environmental control.

INTRODUCTION

When the New Source Performance Standards for the 1970 Clean Air Act were issued in December 1971, only three commercial SO_2 scrubber units were operating in the United States. In hearings held in 1973, 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 reliability problems and low SO_2 removal efficiencies. A 1976 study reported that SO_2 removal efficiencies ranged from 40 to 90% during the 1970 to 1976 period.[1]

These early problems notwithstanding, Figure 1 and Figure 2 demonstrate how dramatically SO_2 control technologies have matured and diffused since those early days. These figures quantify the outcomes of the innovative activities of the interconnected organizations involved in the "SO_2 industrial-environmental innovation complex." These organizations include utilities, FGD vendors, government, universities, EPRI, and others.

Figure 1. Improvements in SO_2 removal efficiency of commercial FGD systems as a function of cumulative installed FGD capacity in the U.S. (Based on government reports.[2, 3])

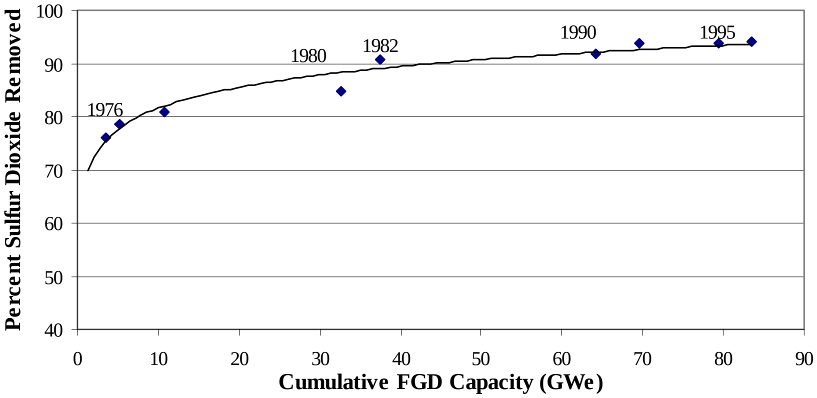
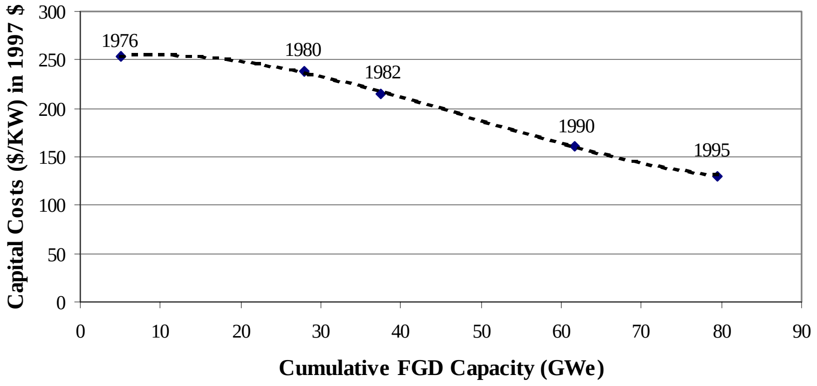


Figure 2. Reductions in capital cost of a new wet limestone FGD system for a standardized coal-fired power plant (500 MWe, 3.5% sulfur coal, 90% SO_2 removal). (Based on government report and historical cost studies.[2, 4-8] Reported cost results were adjusted using a power plant computer model that accounts for the influence of each cost factor on total FGD cost.[9, 10])



The innovative activities carried out by these organizations include invention, adoption and diffusion, and learning by doing. "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.[11] 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 (for a discussion, see Cohen and Levin[12]).

These innovative activities were supported and spurred on by government actions ranging from command and control regulation, to market-based regulatory approaches, to public innovative activities and technology transfer mechanisms. The case study of SO_2 control technologies (which is centered on the abatement of a single pollutant using technology with a finite set of characteristics) thus provided an excellent opportunity to investigate the ways in which government actions affect innovation in environmental control technology (herein referred to as "environmental technology"). The insights of this research, which are described more fully in Taylor,[13] should contribute to policy mechanisms that harness the forces of innovation to meet environmental goals.

LITERATURE REVIEW

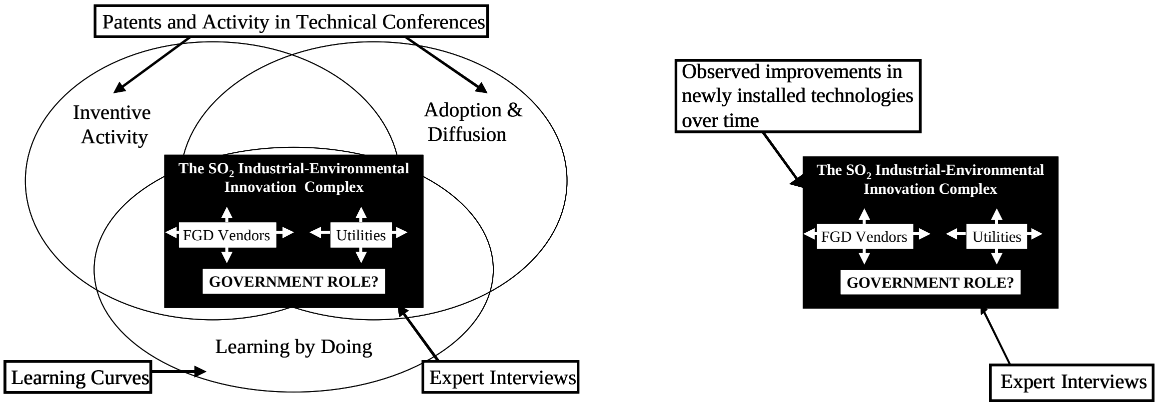
Previous research on the effects of government actions on innovative activities in environmental technology can be found in two literatures. The first, the "mainstream innovation literature," traces its origins to Schumpeter[14] and is generally centered on technologies for which market forces have been the primary drivers (for a review, see Stoneman[15]). Environmental technology, however, was considered in this literature at least as early as a 1969 article by Rosenberg that sought historical examples of the "forces which provide inducements to technical change … what Hirschman has called 'inducement mechanisms.'"[16] One of the inducement mechanisms Rosenberg found was a constraint-imposing environmental legislation that a 1948 article showed improved the competitive advantage of the Swedish sulfate producers that were able to meet it.

The work of most scholars dealing with environmental technological innovation, however, is considered part of a second literature, the "environmental technology literature." This literature, while considerably smaller than the mainstream innovation literature, is diverse and interdisciplinary (for a useful review and critique of much of this literature, see Kemp[17]). In this literature, the observation made by Rosenberg, among others, that competitive advantage sometimes accrues to firms able to meet environmental constraints, has been popularized in the last ten years by debate on the "Porter Hypothesis." This hypothesis emerged from an influential essay by the corporate strategy expert Michael Porter in 1991. In this essay, he argues that tough environmental standards that stress pollution prevention, do not constrain technology choice, and are sensitive to costs can spur innovation and enhance industrial competitive advantage.[18] 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. Our research drew in particular on work in this literature concerning the role of regulatory stringency, flexibility, and uncertainty in driving environmental innovation.

RESEARCH METHODS

As depicted in Figure 3, our study integrated several established quantitative and qualitative research methods in order to investigate innovative activities and outcomes in the SO_2 industrial-environmental innovation complex. This is important for two reasons. First, this methodological approach provides a more realistic understanding of innovative processes than any single method would be able to provide (for a useful review of methodological issues in the study of technological innovation, see Cohen and Levin[12] and Schmoch and Schnoring[19]). Second, the fact that these methods are well-established and repeatable increases the likelihood that the insights of this research will be able to be synthesized with those of similarly-conducted future case studies. These insights could then have a more generalized impact on policy discussions related to innovation, particularly in the environmental area.

Figure 3. Methodologies used in this research to explore innovative activities (left) and innovative outcomes (right).



Each of the analyses depicted in Figure 3 required several research tasks. Our research methods are described below.

Patent Activity Analysis

Researchers have long used patents as a measure and descriptive indicator of inventive activity (for a review of patent research, see Griliches[20]). For scholars of innovation, 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. In addition, studies have shown that patenting activity parallels R&D expenditures; this relationship particularly benefits researchers who are unable to obtain detailed R&D information in an industry.[20] Finally, studies have shown that patenting activity can be linked to events external to the firm. It is this advantage of patents that particularly suggested their use in this study of the effects of SO_2-related government actions on inventive activity in SO_2 control technology.

In our study, 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,[21] the USPTO patent database from 1887-1997, International Energy Agency (IEA) data on the world FGD market,[2] 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 SO_2 control from 1887-1997. 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.

The "class-based" patent dataset was consistent for over 100 years and, therefore, could be compared to the timing of past government actions related to SO_2 control, such as government R&D funding in the 1950s. Patent classes are a relatively broad method for identifying specific technologies, however. Thus, a second, more commercially relevant dataset of 1,593 patents was generated 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 "abstract-based" dataset to eliminate irrelevant patents (the final yield was 1,237 relevant patents) and to assign derived variables to these patents. Patent activity in this dataset was considered in the context of various government actions through econometric analysis and the interpretation of experts.

Activity in Technical Conferences

One source of data – the SO_2 Symposium conference proceedings from 1973 to 1995 – inspired two types of analysis in our research. The first, technical content analysis, was conducted in order to document the changing emphasis of the research community on various technology areas over time. This evolving emphasis was compared to the timing of major government legislative and regulatory actions. Such technical content analysis is in the research tradition that examines a variety of indicators of innovative activity, including journal articles and advertisements in trade publications (for a brief review of literature-based innovation research see Santarelli and Piergiovanni[22]).

The second type of analysis, researcher co-authorship network analysis, was conducted to capitalize on previous innovation research results that state that networked organizations have better opportunities to benefit from knowledge transfer (see discussion in Argote[23]). In our research, network analysis of the changing co-authorship patterns in the SO_2 Symposium provided a proxy for the channels of interpersonal and inter-organizational information exchange (relevant to the communication process of diffusion) that were facilitated by the conference as the legislative/regulatory context of SO_2 control changed over time. Note that technical conferences and consortia have been previously considered as knowledge transfer mechanisms in such studies as Appleyard[24] and Browning, Beyer, and Shetler[25].

To carry out both analyses, each paper in seventeen conference proceedings was coded by year, session topic, paper number, title, co-authors, affiliations, "affiliation type," and geographic location. For the technical content analysis, paper sessions were grouped by technical category. For the researcher co-authorship network analysis, the overall network was considered according to affiliation type, while more refined analysis considered the interactions among "important" affiliations and co-authors who presented in at least half of the conferences considered.

Learning Curves

Analysts of technological change have in recent years focused on a phenomenon termed "learning by doing." The earliest studies of learning by doing centered on aircraft-production, both before and during World War II, and on the fabled wartime manufacture of Liberty Ships. Scholars found that, simply by the accumulation of production (that is, without additional inputs of capital or labor), costs of production dropped in an ordered fashion. Indeed, both scholars and production managers came to observe this "learning by doing" in terms of a mathematical function or "learning curve," as defined in Equation 1 (for a review of organizational learning studies, see Argote[23]).

Equation 1. The classical form of an organizational learning curve.

$y_i = ax_i^{-b}$

where:
y = the number of labor hours required to produce the ith unit
a = the number of labor hours required to produce the first unit
x = the cumulative number of units produced through time period i
b = the learning rate
i = a time subscript

In our research, learning curve analysis of FGD system operations was conducted based on a DOE Energy Information Administration (EIA) 767 form dataset of operating experience in 1985-97 of 154 U.S. power plants with FGD system inservice dates between 1971 and 1997.[3] For 88 plants with at least twelve years of continuous operating data, Equation 1 was estimated for the null hypothesis in which $b \geq 0$. The y-variable chosen for analysis was the labor, maintenance, and supervision costs of FGD units as adjusted for inflation using *Chemical Engineering* cost indices. The x-variable analyzed was the cumulative kilowatt-hours of electricity produced by a power plant that was treated with FGD.

Improvements in Newly Installed Technologies over Time

Analysis of the rate of technical improvement of FGD technologies over time was conducted using three datasets: the DOE EIA 767 form dataset, IEA data on the world FGD market, and five historical cost studies. Two main analyses were performed using basically the same format as the learning curve analysis, but with the x-variable based on total installed U.S. FGD capacity (from the IEA dataset). First, improvement in FGD SO_2 removal efficiency was considered using the average of the reported removal efficiencies (at the annual operating factor) of each year's class of inaugural FGD units (from the EIA dataset). Second, improvement in FGD capital costs was considered using a benchmark 500 MWe power plant burning a high sulfur (3.5%) coal as analyzed by five historical studies and adjusted to 1997 dollars. It was important to investigate costs based on a benchmark plant since FGD capital costs depend on a variety of site-specific design factors.

Expert Interviews

Finally, a dozen experts from a variety of organizational affiliations in the SO_2 industrial-environmental innovation complex were interviewed. These experts were identified based on the length and level of their participation in the SO_2 Symposium. In structured two-hour interviews, these experts were asked about numerous aspects of the SO_2 industrial-environmental innovation complex. FGD performance trends were elicited from them in order to cross-calibrate expert responses. FGD technological developments and SO_2-related government actions considered significant over time were also elicited, as was the organizational context of the industrial-environmental innovation complex. In addition, experts were asked about the importance of patents and the SO_2 Symposium to the industry and technology, and they were asked to give their interpretation of patenting trends.

RESULTS AND DISCUSSION

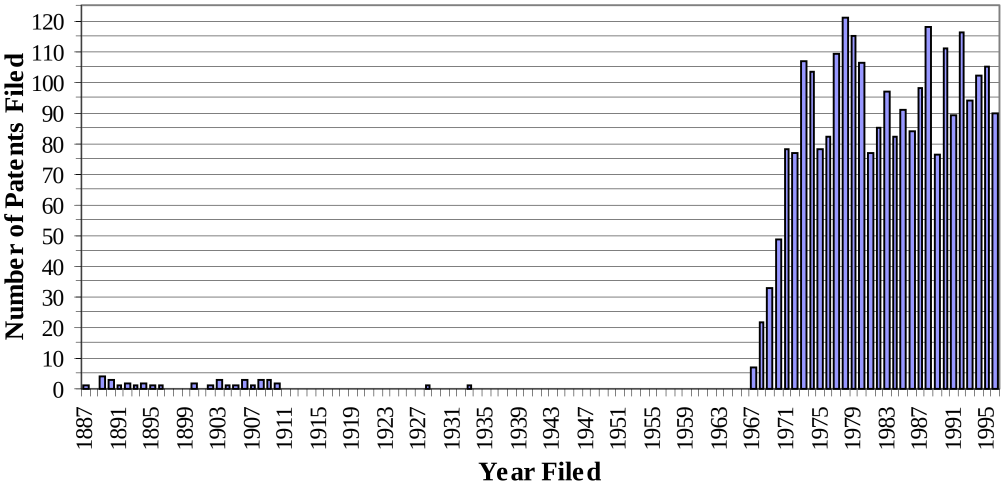
The key findings from this study are summarized below. Results are organized into seven main conclusions.

The existence of national government regulation for SO_2 emissions control stimulated inventive activity more than government research support alone.

This finding is supported by several veins of evidence in our research, as well as by a collection of environmental technological literature case studies analyzed in Ashford, Ayers, and Stone.[26] The primary evidence for this finding in our research comes from patent analysis, although technical content analysis of the SO_2 Symposium and expert testimony also support it. The 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 SO_2 control did not really begin until after the introduction of a regulatory regime.

As illustrated in Figure 4, patent activity levels for this dataset can be portrayed as a step-function dividing two main periods. In the first period, no more than four patents were filed in a given year, while in the second period, 1971 to 1996, patenting activity never fell below a minimum activity threshold of seventy-six patents per year. The onset of patenting activity corresponds to the 1970 Clean Air Act Amendments (CAA) and their associated 1971 New Source Performance Standards (NSPS) (which effectively established a national market for FGD in the U.S.). The class-based dataset also demonstrated that patent activity in the second period peaked in the years 1978, 1979, 1988, and 1992. The abstract-based patent dataset also exhibited this pattern of peaks.

Figure 4. U.S. patents relevant to SO_2 control technology as identified with the patent class method.



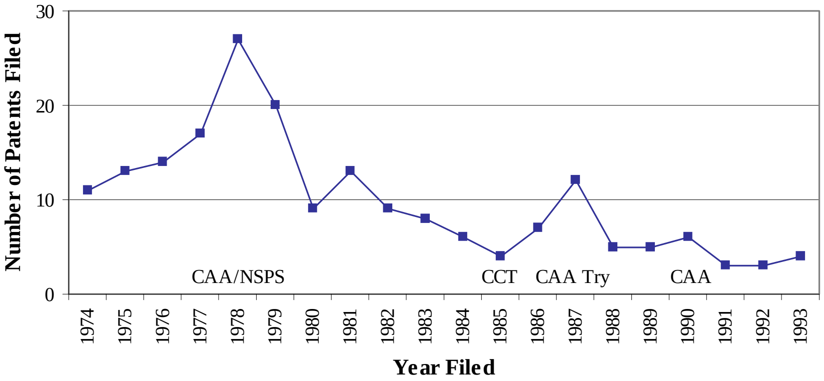
The indication that national regulation of SO_2 was a more effective stimulant of inventive activity than legislated research funding alone with no regulatory requirements (as was the case prior to 1970), may well be germane to environmental policy-makers today. For example, no regulatory stimulus exists in the area of global climate change policy today in the U.S., although the U.S. government does provide research funding in this area.

Regulatory stringency directs the focus of inventive activity.

Again, this conclusion is consistent with the Ashford, Ayers, and Stone case studies, which found that "a relatively high degree of [regulatory] stringency appears to be a necessary condition" for inducing higher degrees of innovative activities.[26] Our research further shows that regulatory stringency can affect the specific technologies that innovative activity focuses on.

Figure 5 shows patenting activity in pre-combustion SO_2 control technologies (which were not dominant in the patent datasets overall). In the period of time after the 1970 CAA and its 1971 NSPS, when SO_2 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 SO_2 emission reduction levels (e.g., 70 to 90 percent removal) that could only be met using an FGD system, 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, this pre-combustion control technology.[13]

Figure 5. Trend in pre-combustion patents identified in the SO_2-relevant abstract-based dataset.



Meanwhile, papers at the SO_2 Symposium and expert testimony point to the stringency of the 1979 NSPS, even for low-sulfur coal applications, as an inducement for innovation in dry FGD technologies that could achieve low- to mid-level removal efficiencies at relatively low costs. With the relatively less stringent 1990 CAA, coupled with the lower cost of non-technological alternatives (i.e., switching to low-sulfur coal or natural gas), this area of innovative activity has declined.

Increased requirements for SO_2 control appear to have helped stimulate the formation of communication channels important to knowledge transfer and diffusion.

Analysis of the SO_2 Symposium from 1973 to 1977 reveals that in the wake of the technologically flexible 1970 CAA, when FGD systems had considerable operating difficulties, not every type of innovating organization reached beyond its boundaries for research paper co-authorship. Those organizations that did cross affiliation boundaries did so at lower levels in conferences held in the 1973 to 1977 time period than in later years.

Following the implementation of the more stringent 1979 NSPS, which affected a larger number of utilities than the 1971 NSPS (thereby creating a larger market for FGD in the U.S.), the innovative audience for knowledge about SO_2 control technologies grew. The decade beginning in 1979 saw a major increase in the number of papers that were presented and the number of organizations and authors that contributed to the SO_2 Symposium. This period also corresponded to growth in concern (and anticipation of regulations) for acid deposition as a major new problem related to SO_2 emissions.

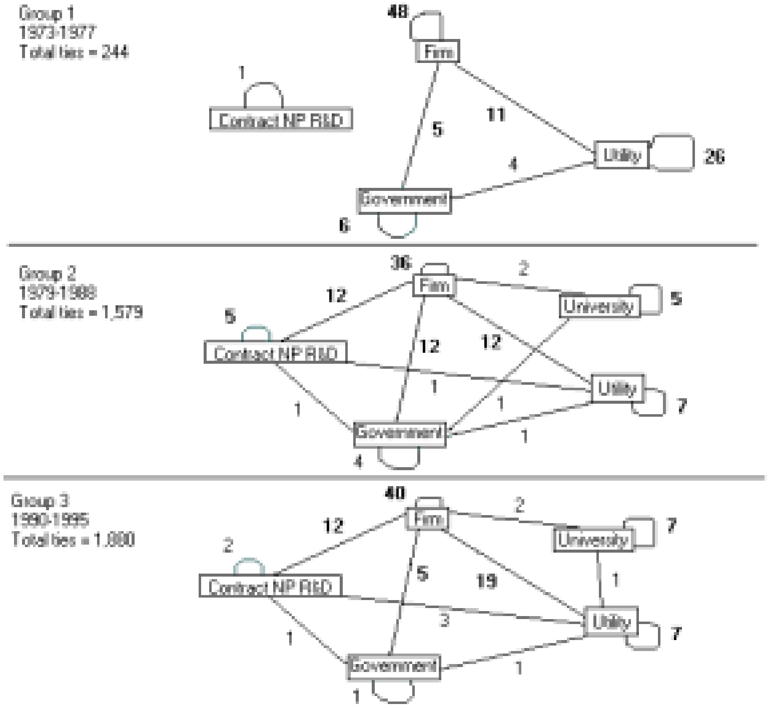
The substantial growth in cross-affiliation paper co-authorship in the SO_2 Symposium conferences held between 1979 and 1995 is evidence that a denser communication network emerged after 1979 for knowledge transfer relevant to the diffusion of SO_2 control technologies. Figure 6 demonstrates the evolution in co-authorship among types of organizations in three time periods defined by the legislative/regulatory events of the 1977 CAA (with its 1979 NSPS) and the 1990 CAA. The unit of analysis here is the "tie" between paper authors, which is defined in Equation 2.

Equation 2. Ties between paper authors.

$$Ties = \frac{n*(n-1)}{2}$$

where
n = the number of authors on a paper

Figure 6. Evolving co-authorship ties between affiliation types for three time periods. Numbers are percentages of total affiliation type co-authorship ties in each period. Numbers in bold are strong ties (greater than 10% of affiliation type ties). The "Contract NP R&D" label is an abbreviation for "contract non-profit research and development organizations," which include organizations like EPRI. The "Firm" label indicates companies such as FGD vendors and architect and engineering firms that do not fit in the other types of organizations given.



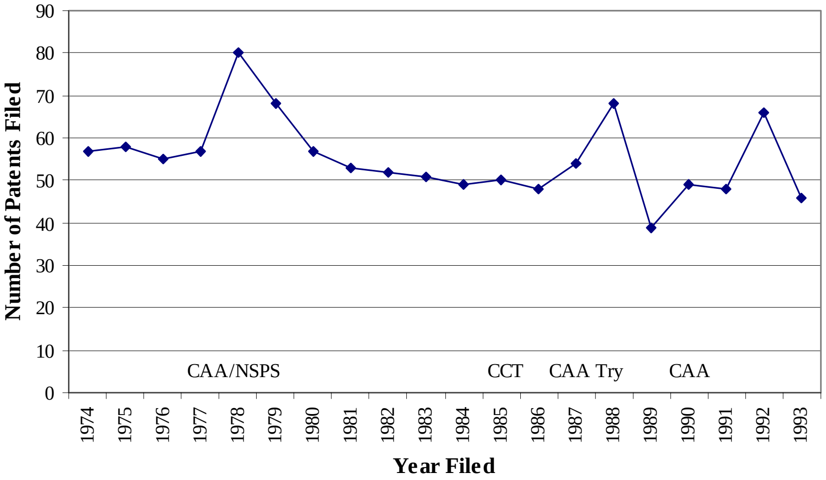
These findings about the effects of regulatory stringency and scope on innovation are consistent with one of the strong conclusions of the mainstream innovation literature, namely that demand is a major driver of innovation (see Mowery and Rosenberg[27]). In an industrial-environmental innovation complex, the demand for various types of pollution control equipment is almost inseparable from the details of environmental legislation (see Kemp[17]).

The existence and the anticipation of government regulation appear to spur inventive activity, as captured by patents.

Analysis of the abstract-based patent dataset and interview testimony support this correlation, although the relatively sparse dataset precludes a rigorous statistical analysis.[13] Figure 7 displays the trend of the abstract-based patent dataset (which includes patents granted between 1976 and 1996). Along the x-axis are abbreviations representing the various government actions considered in the analysis of the influence of external events on patenting activity. Thus, along the x-axis are: the CAAs, which occurred in 1977 and 1990; the NSPS that occurred in 1979; the "CCT" that began in 1985 (the DOE's Clean Coal Technology Demonstration program); and the "CAA Try" that occurred in 1987 (the serious but unsuccessful attempt in the Senate to overhaul the CAA with emphasis on acid rain precursor controls).

Analysis suggests that anticipation of an overhaul of the CAA was more relevant to patenting in SO_2 control than the research support provided in the CCT. The idea that *anticipated* regulation has the ability to drive innovation is not new to this study. Ashford, Ayers, and Stone similarly found that "anticipation of regulation stimulates innovation," and that while "excessive regulatory uncertainty may cause industry inaction, too much certainty will stimulate only minimum compliance technology."[26]

Figure 7. Trend in U.S. patents relevant to SO_2 control technology as identified in the abstract-based dataset.



Federal funding of the technology transfer and knowledge diffusion mechanism of the SO_2 Symposium was extremely valuable to innovation, according to experts in SO_2 control technologies.

More specifically, these experts cited the conference's fostering of cooperation among utility operators and outside researchers as particularly important to FGD performance improvements. The government facilitation of research cooperation and knowledge transfer appears to be an important aspect of a well-designed effort to drive environmental innovation.

The learning curve effect occurred in the SO_2 industrial-environmental innovation complex.

Our research demonstrated that operating experience with FGD equipment resulted in significant cost improvements. This is exemplified by the fact that a doubling of cumulative power generation treated with FGD in the U.S. over time corresponded with a decline in FGD labor and maintenance costs to 83% of their original values. This percentage decline, known as the learning curve "progress ratio," is comparable to findings in many other industries. It is likely to be useful to policy-makers and analysts in predictions of the costs and performance of future environmental technologies.

The outcomes of innovation in SO_2 control technology were notable SO_2 removal efficiency improvements and capital cost reductions as the technology became more widely adopted.

Our research documented these effects of innovation and established a set of relationships that characterized these effects as a function of technology adoption and diffusion in the marketplace (see Figure 1 and Figure 2). These relationships may be useful to policy-makers and analysts interested in predicting future trends in newly emerging environmental control technologies.

FUTURE RESEARCH

The methods used in our study of the SO_2 industrial-environmental innovation complex are being extended to similar case studies of other environmental control technologies. This will provide a larger empirical basis from which to derive more generalized insights about the influence of government actions on technological innovation, particularly in the environmental area. Two of these additional case studies, which focus on nitrogen oxide control technologies and carbon sequestration technologies, are now underway in a follow-on study funded by the USDOE Office of Science program on the Integrated Assessment of Global Climate Change Research.

Our hypothesis 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. In contrast to U.S. policy requiring stringent SO_2 reductions dating back to the 1970 CAA, stringent control of power plant NO_x emissions (i.e., reductions on the order of 80 percent or more) have been imposed on U.S. utilities only in the past few years. Up until now, federal and state requirements for NO_x emission reductions from power plants have been quite modest, and focused mainly on the use of inexpensive low-NO_x burner technology at new facilities. Only in response to recent regulations for ozone attainment has the more expensive option of SCR technology for the post-combustion control of NO_x (analogous to FGD for SO_2 control and CO_2 capture systems for carbon management) been introduced into the U.S. power generation market. Thus, we anticipate that patenting activity in SCR technology will be modest in the U.S. until recently, although there will be Japanese and German patenting of these technologies in the U.S. as a result of their respective national development and commercialization of these technologies in the 1970s (Japan) and 1980s (Germany). We also anticipate that there will be other differences in innovative behavior in NO_x control technologies, in contrast to SO_2 control technologies, because of the differences in the nature and history of the control policies and emission reduction requirements for these two pollutants.

The differences we perceive in these innovative behaviors can be used to test and expand our models of technology innovation and diffusion, and thereby increase the utility and robustness of our conclusions with respect to the influence of government actions on environmental technology innovation. This will be particularly important as we begin to consider carbon sequestration technologies, including CO_2 separation and capture systems plus carbon storage methods, which are in their infancy in the pollution control arena (although they have an established history in other industries). The results of this research will also be applicable to more immediate issues, such as the control of mercury emissions from coal-fired power plants.

ACKNOWLEDGMENTS

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KEY WORDS

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