Regulation as the Mother of Innovation: The Case of SO_2 Control*

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This paper explores the relationship between government actions and innovation in an environmental control technology—sulfur dioxide (SO_2) control technologies for power plants—through the use of complementary research methods. Its findings include the importance of regulation and the anticipation of regulation in stimulating invention; the greater role of regulation, as opposed to public R&D expenditures, in inducing invention; the importance of regulatory stringency in determining technical pathways and stimulating collaboration; and the importance of regulatory-driven technological diffusion in contributing to operating experience and post-adoption innovation in cost and performance. A number of policy implications are drawn from this work.

I. INTRODUCTION

Environmental technologies—a range of products and processes that either control pollutant emissions or alter the production process, thereby preventing emissions altogether—are distinguished by their vital role in maintaining the “public good” of a clean environment. Unfortunately, the common finding in the economics of innovation literature that industry tends to under-invest in research, development, and demonstration (RD&D) generally, is enhanced for environmental technologies because their public good characteristic also indicates that there are weak incentives for private investment. Thus, environmental technologies are developed not just in response to competitive forces; they are also advanced, to a considerable extent, by specific government actions.[1] These actions include: creating (and destroying) demand for various technologies through regulation; conducting and supporting

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RD&D activities in support of environmental goals; promoting technologies through subsidy; and facilitating knowledge transfer between government, regulated firms, and outside environmental equipment suppliers through everything from the patent system to industry-specific conferences, publications, and collaborations.

This article seeks to contribute empirically to the long-standing debate about how policy instruments can best be used to induce innovation in environmental technologies (early papers on this topic include Kneese & Schultze 1975; Magat 1978; Orr 1976; Rosenberg 1969). This is a debate of growing importance in environmental policy, especially as decision makers confront such issues as climate change for which environmental technological innovation has great potential to mitigate the problem while still maintaining economic growth.

II. LITERATURE REVIEW

One of the main issues in the economics of innovation literature is the relative importance in driving technological innovation of "technology-push" (reducing price on the supply curve) versus "demand-pull" (increasing quantity on the demand curve). The literature on environmental policy instruments and innovation, however, has tended to focus less on broad types of government actions related to this issue—government "technology-push" through RD&D versus "demand-pull" through the market that regulation makes for a compliance technology, for example—than on the effectiveness in inducing innovation of specific attributes of regulatory "demand-pull" (for a critical review of this "environmental technology" literature, see Kemp 1997).[2] Although such regulatory characteristics include efficiency, flexibility, stringency, differentiation, phasing, enforcement, uncertainty, and the potential market for environmental equipment suppliers to meet, the largest body of work on this topic has dealt with regulatory efficiency, or whether the policy instrument mimics the "free market" in its allocation of private-sector resources. Other well-known work on this topic has focused on regulatory stringency and uncertainty. In this section, we review some of the major arguments in these areas, while acknowledging that there is much still to be explored in this literature, especially in the areas of government "technology-push," and some of the less-studied attributes of regulatory "demand-pull."

A. REGULATORY EFFICIENCY

The dominant viewpoint on regulation and innovation is arguably that of supporters of "economic incentives" such as emissions trading and taxes, who claim that such instruments induce innovation to a greater extent, and more continuously, than "command-and-control" regulation (see economic work on "dynamic efficiency," including Baumol & Oates 1988; Downing & White 1986;

Jaffe & Stavins 1995; Marin 1978; Milliman & Prince 1989; Orr 1976; Smith 1972; Wenders 1975; Zerbe 1970). Supporters of economic incentives link the allocative efficiency of this type of instrument to the flexibility the instrument allows firms in making compliance technology choices; the assumption is that command-and-control regulation is less flexible, and therefore provides less incentive for innovation.

Although a number of researchers disagree, Driesen (2003) provides one of the most comprehensive counterarguments to date. First, he questions the basis for the comparison itself, as the distinction between "command-and-control" regulation versus economic incentives is false. He argues that most traditional environmental regulation provides a flexible, negative economic incentive (a "stick") that induces regulated firms to innovate in a technology in order to meet a proscribed level of environmental performance at the lowest possible cost using "any adequate technology [a firm] choose[s]."[3] Second, he argues that programs such as emissions trading that aim for regulatory efficiency probably "weaken net incentives for innovation" (ibid.: 64). This is because although they provide over-compliance inducement incentives for innovation by pollution sources with low marginal control costs (selling their excess credits becomes a "carrot" for innovation), they provide an equal measure of under-compliance inducement incentives for innovation by pollution sources with high marginal control costs. Third, Driesen shows that neither traditional regulation (such as programs that prohibit additional emissions despite economic growth) nor market-based mechanisms like emissions trading (which limits the number of tradable permits despite economic growth) provides a more continuous incentive for innovation.

B. REGULATORY STRINGENCY, ANTICIPATION, AND UNCERTAINTY

Beyond the regulatory efficiency debate, the main body of literature on regulation and innovation focuses on the existence and anticipation of regulation, as well as the stringency and certainty of that regulation, as important drivers of innovation. Several studies, including an innovation survey of UK firms by Green, McMeekin, and Irwin (1994), cross-national industry interviews by Wallace (1995), a diffusion study of the Ontario organic chemical industry by Dupuy (1997), and, most famously, a review of ten cases of regulation between 1970 and 1985 by Ashford, Ayers, and Stone (1985), point to the importance of existing, and even anticipated, government regulation in driving the development and deployment of environmental technologies. In addition to these empirical studies, the "Porter Hypothesis" very prominently advances the theoretical argument that tough environmental standards which stress pollution prevention do not constrain technology choice, and are sensitive to costs, can spur innovation and thereby enhance industrial competitive advantage (Porter 1991). A body of work is growing around this hypothesis.

On the issue of stringency, Ashford, Ayers, and Stone (1985) find that "a relatively high degree of [regulatory] stringency appears to be a necessary condition" for inducing higher degrees of innovative activities (ibid.: note 36 at 429), and that is the dominant view among case studies. Two of the most prominent empirical economic studies on this relationship have contradictory results, however: Jaffe and Palmer (1997) find no statistical correlation between stringency (as represented by pollution-abatement expenditures) and innovation (as indicated by patenting activity), while Lanjouw and Mody (1996) show the two variables paralleling each other with roughly a two-year lag.[4] In both studies, reliance on aggregate data sources masks some of the complexities of environmental technological innovation.[5]

Uncertainty has not been as well studied as regulatory stringency in driving innovation, and results are currently vague. According to Wallace (1995), unpredictable and inconsistent policies thwart innovation by creating uncertainty for prospective innovators. Ashford, Ayers, and Stone (1985) take a more balanced stance, stating that too much uncertainty may stop innovation, but too little "will stimulate only minimum compliance technology" (ibid.: 426). Both studies could benefit from a more precise understanding of the various activities that comprise the innovation process.

III. RESEARCH APPROACH

This section uses the economics of innovation literature that dates back to Schumpeter (1942) to provide that understanding. This literature has provided much of the academic thought on the definitions and metrics of the innovation process, as well as the interplay between innovation and such things as market structure and firm size. The innovation process can be pictured as a set of activities—invention, adoption, diffusion, and learning by doing—that overlap each other and allow feedback between the activities.[6] Figure 1 depicts the role of government actions on these innovative activities in the case of an environmental technology, with arrows illustrating the primary innovative activity each type of government action affects. These arrows are labeled either government "technology-push" or regulatory "demand-pull," an indication that this article will duly treat regulatory characteristics as they come up, yet it considers a broader set of government actions than the standard literature. Note that all the innovative activities in Figure 1 are enclosed in a circle, which demarks the full innovative process; the outcomes of innovation are manifest outside this circle.

The case analyzed in this article—the set of technologies that control sulfur-dioxide (SO_2) emissions from electric power plants—has a long history of government action, as well as technical and organizational characteristics that can be documented and compared/contrasted with those of other end-of-pipe technologies—both past and present—in the electric power sector. It is particularly important to understand the organizational context of this SO_2

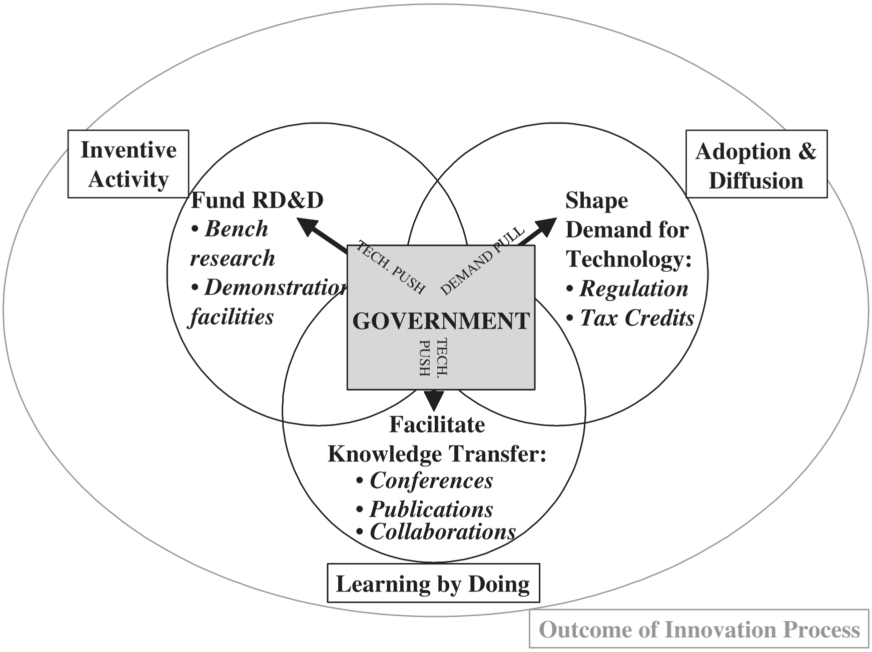


Figure 1. The Role of Government Actions on the Innovation Process in an Environmental Technology.

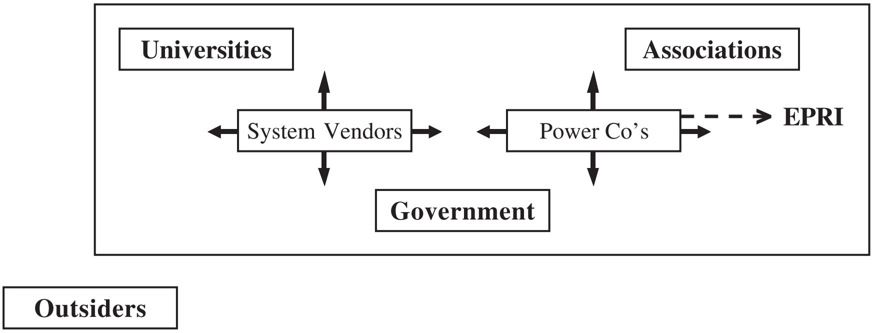


Figure 2. Sources of Innovation in the Characteristic "Industrial-Environmental Innovation Complex" of Energy-Related Environmental Technologies in the U.S.

control study, as it frames the multifaceted innovation process described above. Figure 2 depicts the various sources of innovation in the SO_2 control "industrial-environmental innovation complex," which can also be considered a model of the typical organizational context of energy-related environmental technologies in the U.S. The most important sources of innovation in this complex are the system vendors—in many cases boiler manufacturers and architectural and engineering firms—and the users of their products, the power companies. These actors are embedded in standard business relationships with suppliers, buyers, competitors, and substitutes, as represented by arrows without endpoints in Figure 2. The single dashed arrow in the figure is between power companies and a very special and important innovative actor, the Electric Power Research Institute (EPRI), which is the U.S. utility sector's non-profit cooperative research, development, and demonstration (RD&D) consortium. Organizations without arrows are highlighted because of their innovative importance; their connections to the other organizations are not as easily delineated as in the case of the power company-to-EPRI tie. Lastly, the "outsiders" in this figure refer to industries outside this box of the industrial environmental innovation complex that have technical relevance to the specialties involved inside it.

The complexity of the innovation process in environmental technology—in terms of activities, government actions, and actors—poses methodological challenges. This article begins to confront these challenges by focusing on the full history of SO_2 control technology (particularly in the U.S.); this allows diverse government actions related to this single pollutant to be studied, while limiting the variety of environmental technology features—such as those articulated in Kemp (1997)—which could undermine possible insights. In addition, the article integrates several repeatable quantitative and qualitative techniques that are well established in the economics of innovation literature to arrive at its insights. This approach provides a more realistic understanding of the innovation process than any single method would be able to provide (for useful reviews of methodological issues in the study of technological innovation, see Cohen & Levin 1989; Schmoch & Schnoring 1994). Figure 3 illustrates the variety of analyses conducted for this article and indicates the primary innovative activities they speak to. The data used in these analyses are: (a) U.S. patents in SO_2 control technology, (b) government research laboratory expenditures, (c) SO_2 control technology conference proceedings, (d) market, performance, and cost trends (for calculating learning and experience curves), and (e) interviews with influential experts.

Note that nothing in Figure 3 speaks to only one innovative activity. Patents, for example, measure inventive activity, but they are also important to the understanding of adoption and diffusion, as inventors typically file patents because they expect to market their inventions. Research laboratory activity speaks mainly to RD&D funding, but is also important for understanding the ways government facilitated knowledge transfer in the SO_2 industrial-environmental innovation complex. Technical conferences provide a forum for all the various innovative activities; they also provide a data set for understanding changing researcher networks over time. Learning curves and experience curves both reflect diffusion (market trends), but also speak separately to learning-by-doing and the full innovative process, respectively. Lastly, expert interviews provide insight into all the various innovative activities, as well as into the outcomes of innovation. For more details on

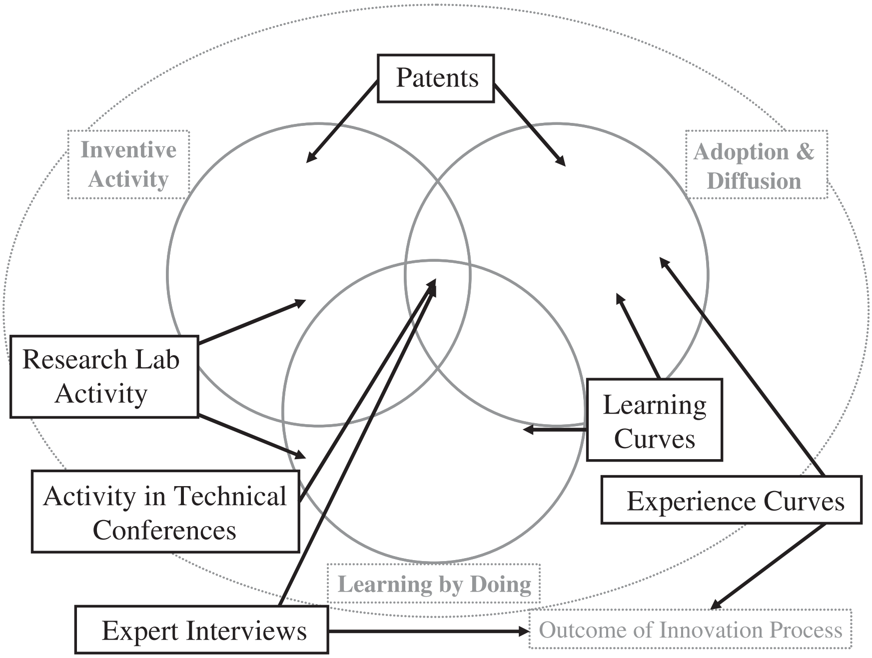


Figure 3. Indicators and Research Methods Used in this Paper to Understand the Innovative Process in SO_2 Control Technology.

these research methods, see Taylor, Rubin, and Hounshell (forthcoming) and Taylor (2001).

IV. OVERVIEW OF GOVERNMENT ACTIONS AND SO_2 CONTROL TECHNOLOGY DEVELOPMENT

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 case has contributed to such infamous air pollution incidents as the killer smogs in Donora, Pennsylvania, in 1948 and London, England, in 1952 (Cooper & Alley 1994; Snyder 1994). 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 (U.S. Environmental Protection Agency (EPA) 1997). SO_2 is primarily emitted to the atmosphere as a byproduct of the combustion of fossil fuels necessary to many long-standing economically productive processes. Electricity generation is the main U.S. emissions source, accounting for an average of 67 percent of SO_2 emissions since 1970.

A. TECHNOLOGY STRATEGIES FOR SO_2 CONTROL

An important issue in the economics of innovation literature is path dependence, in which technologies can be locked-in "by historical events" so that one succeeds when another fails (seminal articles on this are David 1985, and Arthur 1989). Government actions would appear to be prime candidates for such historical events, so in order to be aware of any technology "winners" from government actions and path dependence, it is important to understand the range of technological responses that have developed in the area of SO_2 emissions control. Four main technology strategies have been pursued by the electricity industry: (1) tall gas stacks that disperse emissions away from immediate areas; (2) "intermittent controls," which involve routine operational adjustments to reduce power plant SO_2 emissions in response to atmospheric conditions; (3) pre-combustion reduction of sulfur from fuels (commercial technologies remove less than 30 percent of the sulfur); and (4) removal of SO_2 from the post-combustion gas stream. Although the Battersea, Bankside, and Fulham power stations in London employed this fourth, post-combustion removal technology strategy as far back as 1926, power-plant air pollution control strategies through the 1960s generally emphasized either the first three strategies, or switching to naturally lower-sulfur fuels. Since that time, the focus has shifted to post-combustion control technologies—the focus of this article—as well as fuel switching.

Post-combustion control technologies, otherwise known as "flue gas desulfurization" (FGD) systems or "scrubbing" technologies, contact a post-combustion gas stream with a base reagent (or "sorbent") in an absorber in order to remove SO_2. Commercially available FGD technologies can be classified first as "once-through" versus "regenerable" processes, and then as "wet" or "dry" systems, depending on the moisture level of the waste material and the flue gas leaving the absorber.[7] Whereas wet systems comprise roughly 87 percent of world FGD capacity and dry systems comprise another 11 percent of world capacity, only a few regenerable FGD processes are in use today (about 2 percent of world capacity, calculated from Srivastava 2000). This market dominance by wet systems is despite the fact that they are considerably more expensive than dry systems; their dominance results from their higher removal efficiencies, the larger capacity of their typical applications, and the interplay of these factors with government actions. Wet once-through FGD systems using limestone as the scrubbing reagent dominate internationally (about 72 percent of world capacity). The limestone forced oxidation process is preferred; it makes possible reliable, 95 percent + SO_2 removal efficiencies. The leading dry FGD system is the lime spray drying process (about 8 percent of world capacity); today's model makes possible 80–90 percent SO_2 removal efficiencies. Note that the costs of both wet and dry systems are higher in "retrofit" application to "existing" power plants, as opposed to "new" application to new power plants. In this paper, when "FGD" systems are used without additional technical details, the systems in question should be understood as once-through wet limestone FGD systems.

B. GOVERNMENT ACTIONS REGARDING SO_2 CONTROL

There were nine major federal legislative/regulatory events in the U.S. that helped to shape the U.S. demand for FGD systems. These government actions generally occurred every few years, with the first occurring in 1955 and the last in 1990. In addition to these legislative/regulatory "demand-pull" events, the federal government also pushed the technology ahead through RD&D funding and by facilitating technology transfer, all as part of the national effort to reduce SO_2 emissions from power plants. Table 1 provides an overview of relevant demand-pull government actions. Table 2 provides an overview of relevant technology-push actions.

C. MARKET FOR WET SCRUBBERS

Figure 4 presents the cumulative international demand for wet FGD systems in the U.S. and internationally, according to International Energy Agency (IEA) Coal Data publications (Soud 1994). It also presents the annual percentage of U.S. FGD units that are new, as opposed to retrofit, applications, in order to tie the figure to the discussion in Table 1 concerning the FGD market implications of the various demand-pull government actions over time. Note that in the 1970s, the stringency of the New Source Performance Standards (NSPS), the limited availability of low-sulfur coal, and the tight deadline for attainment of primary SO_2 emissions standards provided an important incentive for the development of FGD technology in the U.S. The vendor industry responded to this demand with rapid entry: the number of U.S. scrubber vendors went from one to sixteen in the 1970s. Considerable exit, mergers, and acquisitions also occurred in the industry, however. In the 1980s, although demand grew, it did not do so as quickly as had been expected during the legislative process preceding the 1979 NSPS. Similarly, the scale of demand expected as a result of the 1990 Clean Air Act Amendments (CAA) was not realized in the 1990s. As in other environmental technologies, notably wind turbines, U.S. system vendors compensated for periods of unexpectedly low domestic demand by helping to serve growth in the European and other markets (Figure 4, for example, shows the very rapid advent of full scrubbing in Germany, which was later followed by other European countries).

V. RESULTS

As Table 1 and Table 2 show, from the late 1940s to the 1990s, government employed a number of policy instruments that provided demand-pull and technology-push incentives for the development of SO_2 control technologies. This section addresses the effects of these government actions on the innovative activities described in Figure 1, using the research methods and indicators depicted in Figure 3. The first subsection discusses findings

Table 1. Chronology of Government Legislation/Regulation in SO_2 Control, with Implications for the FGD Market

Government Action	**Summary and Implications for FGD Market**
Air Pollution Control Act Public Law 84-159 July 1955	*Summary*: Authorized funds for demonstration projects, grants to state and local air pollution control agencies, and research by the Department of Health, Education, and Welfare (HEW). More a technology-push than a demand-pull, the Act was based on the principle that the federal government should protect the right of states and local governments to control air pollution while supporting and aiding research and developing abatement methods. *FGD Market Implications*: First federal signal of interest in air pollution control, so first potential market for control technology. Demand signal weak: provided no stringency requirements, timeframe, or national demand.
Clean Air Act Public Law 88-206 December 1963	*Summary*: Expanded research funding and federal financing of state and local governments for air pollution control. Provided first limited enforcement powers to Secretary of HEW, who could take legal action against interstate polluters. *FGD Market Implications*: Negligible change in incentives from previous act due to limited enforcement power and continued decentralized market.
Air Quality Control Act Public Law 90-148 November 1967	*Summary*: Required the HEW National Air Pollution Control Administration (NAPCA) to designate air-quality control regions, establish air-quality criteria, and issue associated reports on available control technology. States were directed to set ambient air quality standards and propose implementation plans, with federal intervention an option if states did not comply within fifteen months. The HEW Secretary was authorized to act against stationary sources of air pollution only in times of "imminent and substantial" danger to public health *FGD Market Implications*: This act contained signals that the FGD market was likely to become national: (1) drafts of the bill had national (versus state) ambient air quality standards, and (2) the intervention provision for state compliance failures elevated the federal role in air pollution control. Still, the final version of the act continued the incentives for a decentralized FGD market. Also, NAPCA was slow to fulfill its enforcement and other responsibilities.
1970 Clean Air Act Amendments (1970 CAA) Public Law 91-604 December 1970	*Summary*: Required the newly formed Environmental Protection Agency (EPA) to establish national ambient air-quality standards for SO_2 from all sources without consideration of economic or technical feasibility. Each state was required to develop a state implementation plan (SIP) for controlling existing stationary sources and submit it for EPA approval. *FGD Market Implications*: SIPs were submitted in 1972, and almost all called for continuous reduction of SO_2 emissions, which required utilities to use low sulfur fuels, pre-combustion treatment, or FGD systems, rather than intermittent controls.Utilities sued and lost at the level of the Supreme Court in 1976. The act's strong enforcement power, national standards-based market signal, technological flexibility,and post-Supreme Court legal certainty were very conducive to creating an FGD market in the U.S.

Table 1. *Continued*

Government Action	**Summary and Implications for FGD Market**
1971 New Source Performance Standards (1971 NSPS) December 1971	*Summary*: The 1970 CAA required EPA to create these "best available technology" performance standards for major new sources of SO_2. There was a "technology basis" underlying the NSPS: EPA had to stipulate which control technologies were adequately demonstrated for use by utilities in SO_2 control. *FGD Market Implications*: The maximum allowable emission rate for new and substantially modified sources was 1.2 lbs of SO_2/MBtu heat input (2.2 kg/Gcal), a rate that effectively required 0–85 percent SO_2 removal, depending on coal properties. This standard was technologically flexible, as it could be met through the use of low sulfur fuels, pre-combustion cleaning, and FGD systems. Utilities sued on the grounds that FGD systems were demonstrated enough; EPA was concerned that the technology basis would not hold up to repeated legal tests. Thus, legal uncertainty weighed against other market-inducing characteristics of the NSPS.
1977 Clean Air Act Amendments (1977 CAA) Public Law 95-95 August 1977	*Summary*: Directed EPA to implement new source performance standard for SO_2 based on a percentage reduction from uncontrolled levels. *FGD Market Implications*: Intended to promote universal scrubbing at new plants.
1979 New Source Performance Standards (1979 NSPS) June 1979	*Summary*: Required a 70–90 percent reduction of potential SO_2 emissions (depending on coal sulfur content and heating value) for new plants built after 1978. *FGD Market Implications*: For new and substantially modified sources, the "sliding scale" guaranteed a market for wet FGD for high-sulfur coals and dry FGD for low-sulfur coals. This was not technologically flexible. The demand for FGD prompted by the passage of the 1979 NSPS was not as high as expected, as utilities had an incentive to rely on existing power plants rather than build new ones or modify existing plants beyond the limits of either their willingness to install FGD or bet on the EPA's enforcement capabilities.
Senate Attempt at 1987 Clean Air Act Amendments (CAA Try)	*Summary*: The most serious of the repeated unsuccessful attempts to overhaul the CAA in the 1980s due to heightened concern about acid rain precursors. *FGD Market Implications*: Contributed to an expectation that low-cost, moderate-removal FGD (dry FGD and sorbent injection systems) would be required at all power plants. One version of this legislation required the federal government to subsidize the capital cost of installing scrubbers.
1990 Clean Air Act Amendments (1990 CAA) Public Law 101-549 November 1990	*Summary*: Established an emission-allowance trading program to achieve a cap in 2010 of 8.12 million annual tonnes of SO_2 in two phases. Phase I (1995–1999) applied an aggregate emission limit of 2.5 lb of SO_2/MBtu heat input of coal (4.5 kg/Gcal) to 261 existing generating units, while Phase II (2000–10) applies an aggregate emission limit of 1.2 lb/MBtu (2.2 kg/Gcal) to about 2,500 existing units.

Table 1. *Continued*

Government Action	Summary and Implications for FGD Market
	FGD Market Implications: The act brought existing sources back as potential players in the FGD market after avoiding the 1979 NSPS. The aggregate emission limits are not particularly stringent, and could be met through the use of low sulfur fuels, pre-combustion cleaning, and FGD systems. The act killed the expectation of a large market for dry FGD, and resulted in a smaller-than-expected market for wet FGD.This is because the dominant response to the act was to meet aggregate limits by fuel switching (low-removal) at many of a utility's plants while installing a few offset wet FGD systems (high-removal).

related to inventive activity, the second subsection discusses findings related to learning-by-doing, and the third subsection discusses the SO_2 Symposium findings, which speak to the nexus where the three innovative activities of Figure 1 overlap. Lastly, the fourth subsection discusses the quantifiable outcomes of innovation in SO_2 control technology.

A. INVENTIVE ACTIVITY

1. *RD&D Expenditures*

Figure 5 consolidates three different types of data into a forty-year time-series of public RD&D in SO_2 control (private sector RD&D expenditures were impossible to obtain for the purposes of longitudinal analysis). The public RD&D data in Figure 5 are adjusted to 2003 dollars using the Consumer Price Index for all Urban Consumers, and come from a number of agencies: the Department of Interior's Bureau of Mines (BoM); the Department of Health, Education, and Welfare (HEW); the Environmental Protection Agency (EPA) research laboratory (EPA Lab) successor to the National Air Pollution Control Administration (NAPCA); and the Department of Energy's (DOE) Office of Fossil Energy (OFE). Sources include congressional hearings, personal interviews, summary budget documents, internal agency reports, and agency spreadsheets and graphs. Note that although the Tennessee Valley Authority (TVA) was a long-standing and important funder of RD&D in SO_2 control, the money it spent on this RD&D came from its non-public resources, so it is not included in Figure 5. For more details on the data set underlying Figure 5, including its uncertainties, see Taylor, Rubin, and Hounshell (2005).

The most important takeaway from Figure 5 is the volatility of public RD&D over the years. As explained in Table 2, EPA accelerated its RD&D program in the mid-1970s in an effort to demonstrate conclusively the technical and economic feasibility of wet limestone scrubbers, because of

Table 2. Chronology of Public RD&D Highlights

Decade	**Main Public Actors**	**Highlights**
1950s	The Tennessee Valley Authority (TVA);[a] the Department of Interior's Bureau of Mines (BoM); the Department of Health, Education, and Welfare (HEW)	• Before 1955, TVA studied wet scrubbing systems; used a pilot plant to demonstrate ammoniacal liquor scrubbing. • Before 1955, BoM and HEW did general work on the nature and control of pollutants from fuel combustion. • In 1957, BoM and HEW started investigating sorbents for dry scrubbing technologies.
1960s	TVA, BoM, HEW's National Air Pollution Control Administration (NAPCA)	• BoM and HEW did bench-scale research into lower cost sorbents, including organic agents and transition metal complexes, while continuing bench and pilot work on the alkalized alumina process. • In 1967, as part of the Air Quality Act, NAPCA became the agency with primary responsibility for management of the engineering RD&D work related to SO_2 control; NAPCA's RD&D levels for SO_2 control were increased significantly in Fiscal Year (FY) 1968 in comparison to previous years. • In 1969, TVA participated with NAPCA on a full-scale demonstration of a dry limestone injection system.
1970s	TVA, the Environmental Protection Agency (EPA) research laboratory successor to NAPCA (EPA Lab),[b] and the Department of Energy (DOE) Office of Fossil Energy (OFE)	• In 1971, TVA built a 1 MW test unit for wet limestone FGD at the Colbert facility near Muscle Shoals, Alabama. • In 1972, EPA funded the construction by Bechtel of three 10 MWe prototype scrubbers as the "Alkali Wet Scrubbing Test Facility" at TVA's Shawnee Steam Plant; this facility was key to the development of the FGD technology in use today around the world. • The EPA established its own 0.1 MW wet limestone pilot plant at the EPA lab facility in Research Triangle Park, North Carolina; it funded repeated SO_2 control technology evaluations; and it engaged in cooperative RD&D activities with utility/vendor teams and other government agencies. • EPA began funding the SO_2 Control Symposium in 1973, and remained the sole funder until 1982, when the Electric Power Research Institute (EPRI, the utility industry's research consortium) joined in; the DOE became the third co-funder in 1991. • EPA accelerated its RD&D program in an effort to demonstrate conclusively the technical and economic feasibility of wet limestone scrubbers, due to "continued utility resistance to scrubbers and uncertainty as to whether the technology-based standard could withstand repeated legal tests" (Radian 1980) A dramatic peak occurred in EPA SO_2 control funding in FY1975. • A considerable amount of FGD research money was transferred from EPA to OFE in FY1979.

Table 2. *Continued*

Decade	Main Public Actors	Highlights
1980s	TVA, EPA Lab, OFE	• The OFE became the dominant public RD&D funder, taking on the support of the TVA Shawnee facility and, in December 1985, initiating the Clean Coal Technology Demonstration Program, a \$2.5 billion government-industry cost-sharing program established to demonstrate advanced "clean" coal technologies, including FGD, at a commercially relevant scale. • The EPA shifted its research focus from the now commercially established wet FGD systems to lower cost retrofit dry scrubbing and sorbent injection systems, "in anticipation of a major U.S. acid rain retrofit program being considered by Congress."
1990s	TVA, EPA Lab, OFE	• The DOE concluded its program by the end of 1997. • EPA basically concluded its program after 1992. • The Shawnee test facility was disassembled in 1994, and TVA discontinued further FGD research.

Notes: [a] Set up by the U.S. Congress in 1933 primarily to provide flood control, navigation, and electric power (TVA is the largest public power company in the U.S.) in the Tennessee Valley region, the TVA is unique among U.S. government agencies in that it was designed as a federal corporation.

[b] This laboratory has had many names over the years, including the Office of Energy, Minerals, and Industry for EPA's Office of Research and Development, the Industrial-Environmental Research Laboratory, the Air and Energy Engineering Research Laboratory, and the National Risk Management Research Laboratory in the Air Pollution Prevention and Control Division.

"continued utility resistance to scrubbers and uncertainty as to whether the technology-based standard could withstand repeated legal tests" (Radian Corporation 1980). Figure 5 shows a dramatic peak in public RD&D funding for SO_2 control in fiscal year 1975. After that year, public RD&D expenditures dropped, not to return to pre-1975 levels until the post-1990 CAA period (with the exception of a small spike in funding in 1980, just after the passage of the 1979 NSPS).

2. *Patenting Activity*

Patents are required by law to publicly reveal the details of a completed invention that meets thresholds of novelty, usefulness, and non-obviousness. They are thus probably best thought of as an outcome of invention that has an eye to commercialization; studies have shown that they can be linked to events that occur outside the firm (see Griliches 1990 for a review).[8] There are three major challenges involved in using patents in research: (1) technical difficulties arise in both locating patents of interest and allocating these patents to relevant industrial and product groups; (2) analysis difficulties arise from

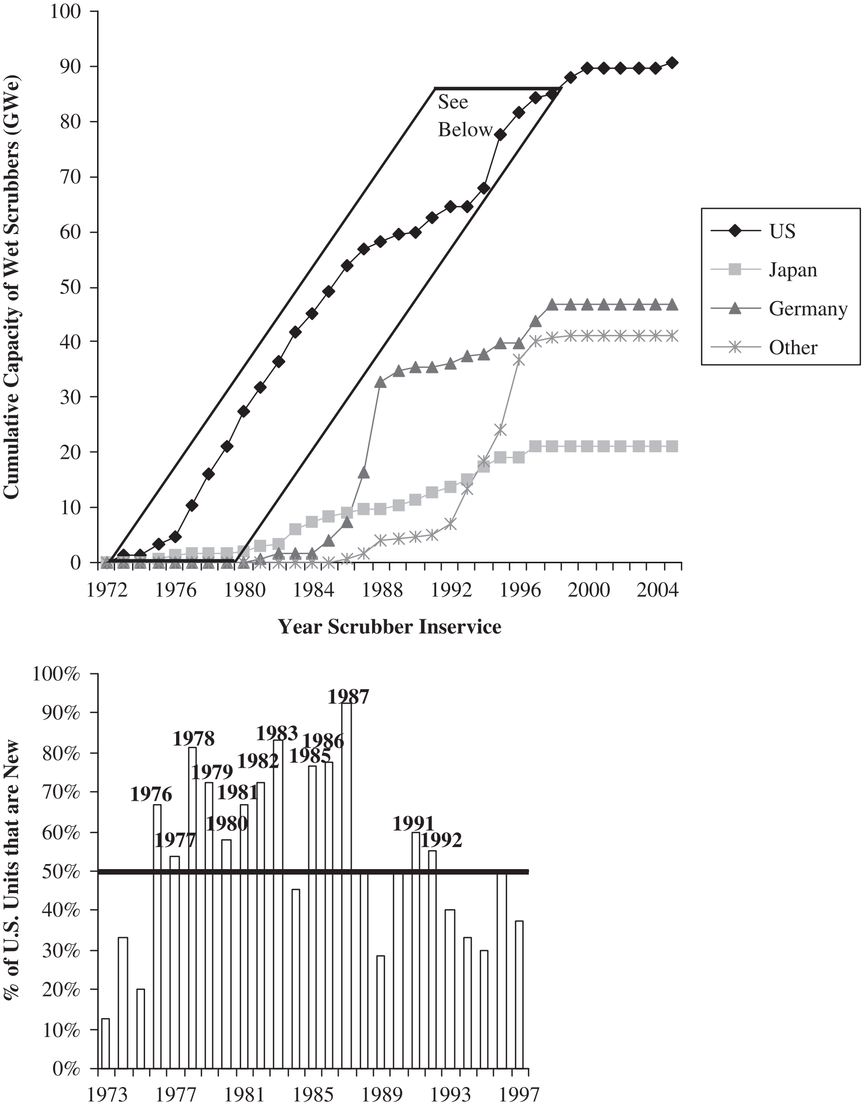


Figure 4. Cumulative GWe Capacity of FGD Units Internationally, and in the U.S. by Percentage of Units that are New Applications.

variations in the strategic decisions of entities to apply for patent protection; and (3) comparison difficulties arise because of "qualitative homogeneity" issues related to the question of whether all patents are of equal value simply because they have unique patent numbers. Challenges (2) and (3) can be dealt with using several technologies, including by treating patents as a relative, rather than an absolute, measure of inventive activity. The first challenge is more difficult: too many patents will swamp the trend one is

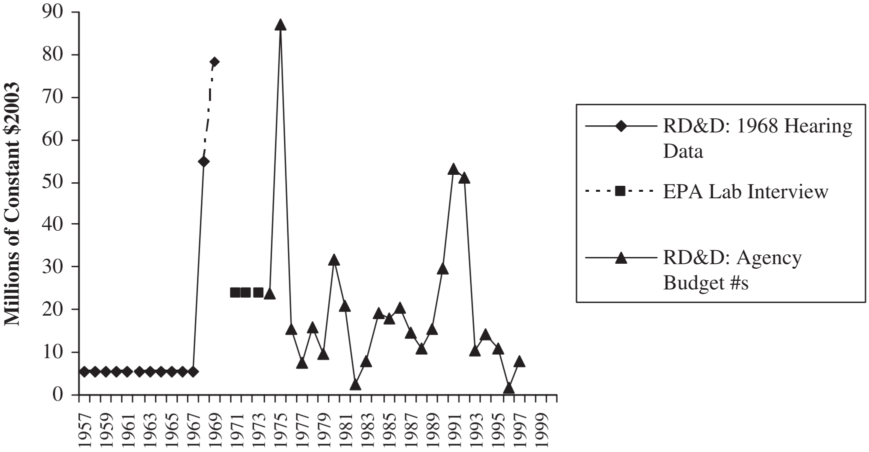


Figure 5. Estimated Combined Public RD&D Expenditures in SO_2 Control.

interested in studying, and too few will leave out relevant innovations, similarly disguising the true trend in inventive activity.[9]

This paper uses two techniques to identify relevant patents, one based on U.S. patent classes, the other based on electronic keyword searching of the title and abstracts of U.S. Patent and Trademark Office (USPTO) patents granted beginning in 1975. The advantage of the first technique is that it allows the creation of long time-series, as the USPTO technological classification dates back to 1790.[10] The advantage of the second approach is that it allows a more targeted search, as SO_2 control technologies are cross-disciplinary and are likely to appear in numerous classes.

We did not identify patent classes directly from the USPTO *Manual of Classification*, as many authors do; rather, we began by interviewing the primary USPTO examiner of SO_2 control technologies to create a list of classes based on his search procedure for establishing the legal prior art of the patents he examines.[11] The resulting “class-based” patent dataset, illustrated in Figure 6, identified 2,681 patents issued from 1887–1997 that were relevant to SO_2 control. Note that these patents are graphed by their file date, as this is the earliest date that can be attributed to the completion of an invention based on the data published in a patent.

By contrast, the “abstract-based” dataset initially returned 1,593 patents granted in 1975–1996. After discarding irrelevant patents caught in the initial search, the resulting abstract-based dataset contained 1,237 patents from 408 USPTO classes (note that this class distribution indicates how diverse SO_2 control technologies are). Figure 7 shows the abstract-based patent dataset according to file date, as well as breakdowns of this dataset according to technological and organizational category. For use in comparison with RD&D expenditures, Figure 7 portrays trend lines for patents according to two types of SO_2 technology: (1) pre-combustion treatment and (2) post-combustion

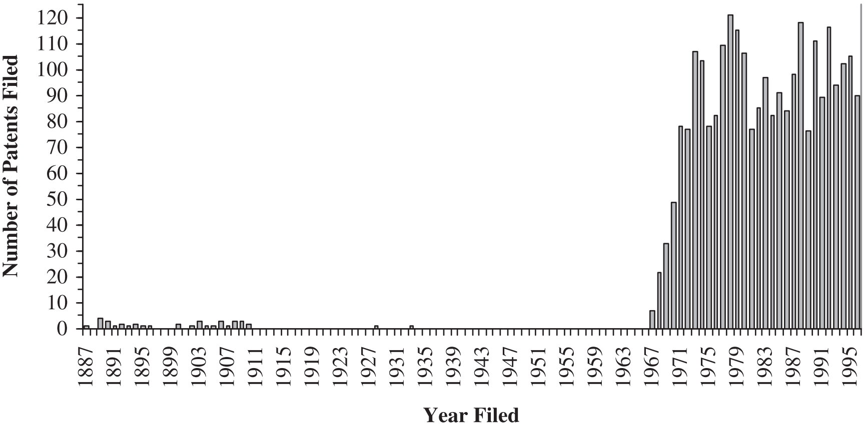
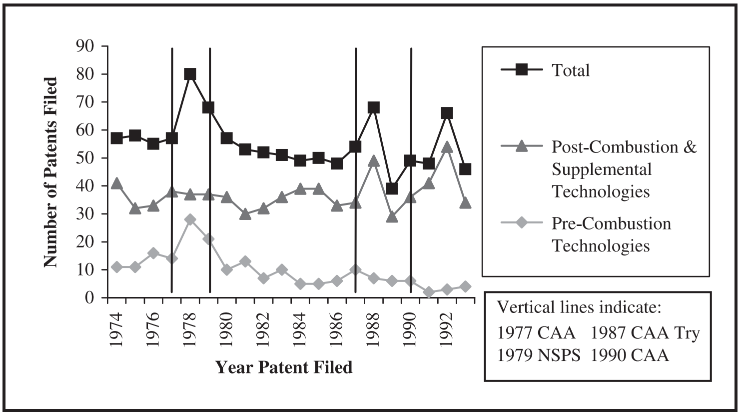


Figure 6. U.S. Class-Based Patents Relevant to SO_2 Control.



Technology	% of Patents	Organization	% of Patents
Post-Combustion Treatment	53%	Firm	76%
Pre-Combustion Treatment	17%	Individual	14%
Gassification	12%	Government	6%
Sorbent/additive development	5%	University	4%
By-product modification	5%	Consortium	3%
During-Combustion Treatment	4%		
Fluidized Bed Combustion	4%		
Measurement Technology	1%		

* = Patents are from the abstract-based dataset.

Figure 7. Demand-Pull Actions (Government Regulation) and U.S. Patents* Relevant to SO_2 Control: Total, Post-Combustion, and Pre-Combustion Patents.

and its supplemental technologies (post-combustion treatment, sorbent/additive development, by-product modification, during-combustion treatment, and measurement technology).[12] For use in comparison with environmental legislation and regulation, Figure 7 depicts important government actions with lines running to the *x* axis. Both datasets were checked against patent lists obtained from prominent FGD vendors and found to include a high percentage of commercially relevant patents, with the abstract-based dataset showing better overall performance. For more detail on the construction of both the class-based and abstract-based datasets, see Taylor, Rubin, and Hounshell (forthcoming) and Taylor (2001).

Figure 6 shows that prior to 1970, there was little or no patenting activity in SO_2 control technology (no more than four patents per year), despite public RD&D funding as well as legislative/regulatory events occurring in 1955, 1963, and 1967. Patent activity starts to pick up in 1967, the year before the large 1968 increase in public RD&D funding and the year of the 1967 Air Quality Act, which flirted with establishing national standards for SO_2 control (see Table 1 and Table 2). Patent levels after 1970—the same year the establishment of national standards was passed through the 1970 Clean Air Act Amendments (CAA)—never fell below 76 per year. National regulatory standards provided a national market for SO_2 control technology, and patenting behavior appears to reflect this regulatory demand-pull.

The more refined abstract-based dataset illustrated in Figure 7 also shows stronger correlation to government regulatory actions than to RD&D funding. The gradual post-1978 decline in patenting activity in Figure 7 is marked by significant peaks that roughly correspond to legislative and regulatory events, with the highest levels of patenting activity occurring in 1978, 1979, 1988, and 1992. These years also marked the highest level of patenting activity in Figure 6, a fact that gives weight to the likelihood that these peaks represent true "bursts" in patenting activity, which Griliches (1990) suggests is indicative of a change in external events relevant to the patented technology. In the case of SO_2 control technology, these events are likely to include enacted events such as the 1977 CAA, 1979 NSPS, and the 1990 CAA. In addition, experts interviewed for this research strongly supported the idea that anticipation of a revised CAA in the mid-to-late 1980s (1987 CAA Try) drove the inventive activity behind the 1988 patent peak.

A simple least-squares regression analysis—in which a dummy variable is "turned on" when the inventor is likely to be showing strong responses to a government action and then "turned off" when the situation returns to the status quo—was performed to test the relationship between patenting activity and these demand-pull instruments (enacted legislative and regulatory events plus the 1987 CAA Try). This analysis explains 64 percent of the variance of the total patent trend in Figure 7 ($r^2 = 0.64$). In addition, it explains 63 percent of the variance ($r^2 = 0.63$) of the post-combustion and supplemental technology trend and 73 percent of the variance ($r^2 = 0.73$) of the pre-combustion technology trend. The results are not as clean for the broader class-based data set represented in Figure 6, however; only 39 percent of the variance ($r^2 = 0.39$) is explained by enacted legislation (which also include the 1955 APCA, the 1963 CAA, and the 1967 AQA during these years) plus the 1987 CAA Try.

For each of the patent datasets, however, regression analysis shows that in SO_2 control, the demand-pull generated by legislation/regulation and the anticipation of regulation has a more direct effect on inventive activity captured by patents than governmental technology-push activities. A regression of the RD&D expenditure data underlying Figure 5 against the class-based patent dataset in Figure 6 explains only 4 percent of the variance ($r^2 = 0.04$), and similar regressions against the total abstract-based dataset and the subcategory of post-combustion and supplemental technology patents also reveal negligible correlations.[13] For more information on modeling detail and these regression results, see Taylor, Rubin, and Hounshell (forthcoming) and Taylor (2001). In addition, other evidence, including the technical content analysis of the SO_2 Symposium and the response's of interviewed experts, supports the prominence of legislative/regulatory events—notably national standards—in inducing inventive activity in SO_2 control technology (Taylor 2001). This fits well with the findings of other case studies, as discussed in the literature review above (see e.g., Ashford, Ayers & Stone 1985).

The 1979 NSPS provides an opportunity to consider the importance of regulatory stringency to invention in SO_2 control technology. According to expert interviews and analysis of papers presented at the national SO_2 Symposium, the 1979 NSPS helped drive innovation in dry FGD systems in the 1980s (80–90 percent SO_2 removal). It also *curtailed* invention in pre-combustion technologies that "cleaned" coals (commercial technology removes less than 30 percent of the sulfur) (Taylor 2001). As seen in Figure 7, patenting in these technologies grew rapidly in the early 1970s, when standards allowed low-sulfur and cleaned coals to play a prominent role as a compliance strategy for both new and existing sources. The stringent 1979 NSPS, however, signaled that cleaned coals would no longer be sufficient for new source compliance. Patenting levels responded accordingly, as indicated in Figure 7 by the precipitous decline in pre-combustion patenting levels after that event and as supported by the regression results discussed above. It appears that researchers interested in the SO_2 control market made a decision that, based on the 1979 NSPS, RD&D dollars would be better spent on post-combustion technologies with more powerful potential SO_2 removal efficiencies.[14] The stringency of the 1979 NSPS thus affected the technology pathways considered for research. Note that the 1990 CAA did not restore patenting levels for the technology.

B. LEARNING BY DOING

According to industry analysts, FGD vendors often incorporate new ideas into new commercial installations, finding that "the jump from the idea to the full scale trial" is important to technological innovation (McIlvaine & Ardell 1978). Once an FGD system is applied to a power plant, however, the responsibility for its operation goes to the utility pollution-control operator, who often plays an important innovative role by solving post-adoption technical problems. Early scrubber challenges primarily related to extreme corrosion and reagent precipitation inside the system; precipitation caused plugging and scaling, which sometimes required taking a unit down after a few days of operations in order to shovel, jackhammer, dynamite, or otherwise clear the blockage. These challenges contributed to high operating and maintenance costs for FGD systems; for example, one expert interviewed for this paper told of a utility that regularly has a module off-line and service it within twenty-four hours, using about forty people in a shift to do different jobs such as replacing nozzles or fan blades.[15]

As experience with scrubbers grew and the process chemistry became better understood, these costs came down, in part through changes in the training and selection of operating personnel. Whereas a typical utility scrubber team in the late 1970s would have a mechanical engineer supervising boiler-operating personnel who also ran the FGD system, the same team in the 1980s would have a more specialized staff. In some cases, chemical engineers were hired, while in other cases, people who had been rotating through power plant operations were given specialized training on scrubber chemistry and operations, then given a separate job category as chemical operators.

Learning curve analysis provides a quantitative measure of improvements associated with increased operating experience with the technology. Analysis of the operating data for eighty-eight U.S. power plants with at least twelve continuous years of wet limestone FGD operation indicates that as cumulative power generation scrubbed by wet limestone FGD in the U.S. doubled, the total adjusted cost for FGD operation, maintenance, and supervision came down to 83 percent of its original value (Taylor 2001). This value of 83 percent is known as the "progress ratio," and it is comparable to progress ratios found in many other industries. Most of the other industries that exhibit a progress ratio of this size do not share the strong government role in innovation that distinguishes environmental technology (Argote 1999; International Energy Agency 2000).

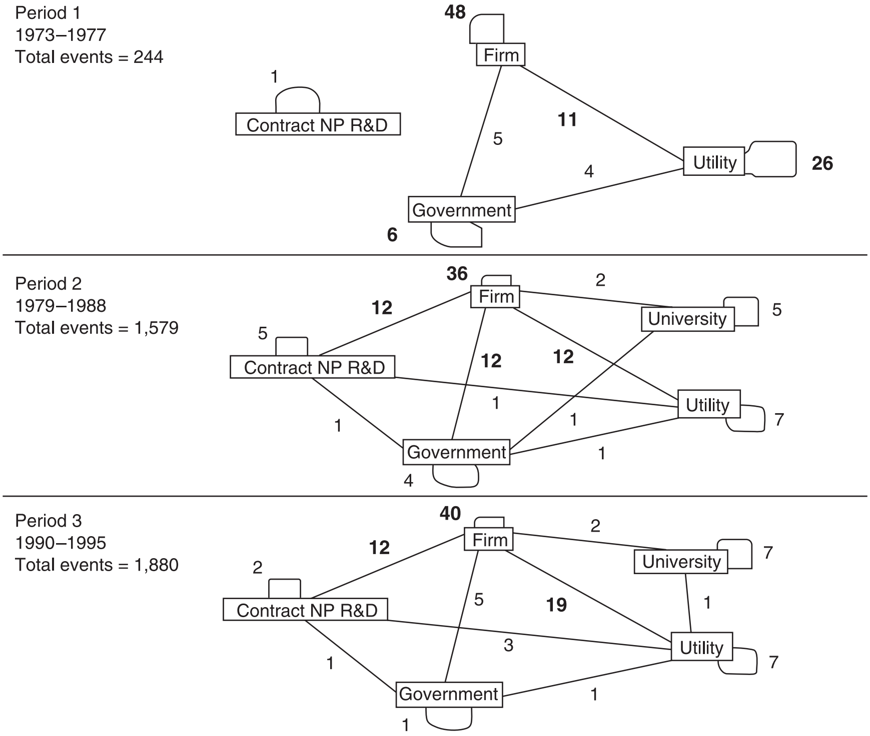
C. WHERE INVENTION, ADOPTION, AND EXPERIENCE OVERLAP

This section focuses on the SO_2 Symposium, a government-sponsored conference that the EPA began funding in 1973, remaining the sole funder until 1982 when it was joined by the Electric Power Research Institute (EPRI); this co-sponsorship arrangement lasted until 1991 when the DOE became the third co-funder. The diverse experts interviewed for this article strongly agreed that the SO_2 Symposium was essential to the evolution of FGD, as it promoted formal and informal knowledge exchange among utility pollution control operators, FGD vendors, government and university researchers, and other actors. The conference proceedings provide a rich dataset to explore new developments in FGD as they arose from invention, operating experience, and related know-how, including tacit knowledge.[16] They also provide: (1) a unique window into the policy concerns of the SO_2 community, (2) RD&D information for the government and EPRI, and (3) insight into the relationships between organizations in the SO_2 industrial-environmental innovation complex. Although content analysis on the SO_2 Symposium proceedings has been done, this section of the paper focuses instead on the co-authorship patterns of papers presented at the SO_2 Symposium (see Taylor 2001 for more detail on both types of analysis). These patterns are a proxy for the channels of interpersonal and inter-organizational knowledge flow facilitated by the conference over time.[17] As at least one expert explained in interviews for this paper, the "rubbing of noses" of researchers, both at the conference and, more importantly, after the conference, when more know-how could be transferred effectively, was more important in facilitating innovation than the technical content of the formal papers.

Figure 8 depicts how the network of technological collaborations defined by these co-authorship arrangements changed as regulatory events changed the SO_2 industrial-environmental innovation complex over time. It shows that in the period before the 1977 CAA and 1979 NSPS—a period dominated by EPA and utility tension over the FGD technology basis for the 1971 NSPS—not every organization type in the complex was connected to every other type. Utility-to-utility ties and firm-to-firm ties dominated in coauthored papers; only 20 percent of the ties brought authors from different types of organizations together. Between the 1979 NSPS and the 1990 CAA, however, there were substantial increases, not only in the total number of paper co-authorship ties, but also in the percentage of ties across organization types. This provides evidence of the formation of a more collaborative community of researchers, developing shortly after the implementation of the more stringent 1979 NSPS. This implies that regulatory stringency—as well as the increasing political saliency of acid rain in the 1980s, which contributed to wide anticipation of new SO_2 control requirements (especially for existing sources)—strengthened the innovative community that revolved around SO_2 control technology. This community remained relatively strong in the immediate aftermath of the 1990 CAA, as indicated by continued stability in cross-organizational ties at the SO_2 Symposium as well as continued growth in the number of ties in the network overall.

D. OUTCOMES OF INNOVATION

Figure 9 demonstrates the maturation of FGD technology as operating experience with the technology grew around the world. The *x* axis in this figure is the cumulative capacity (GWe) of wet FGD systems around the world, according to information adapted from IEA Coal Data. The series at the top of Figure 9 shows the improvement in the average SO_2 removal efficiency of

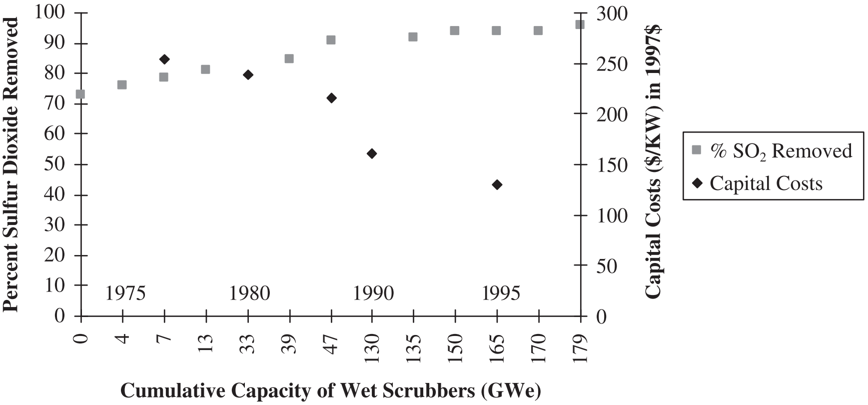


Notes: Figure shows percentages of total ties in each period. "NP R&D" = non-profit research and development organizations; "Firm" includes FGD vendors and architect-engineering firms.

Figure 8. Evolving Co-authorship Ties Between Organization Types for Three Time Periods.

FGD systems coming online, to the point where new FGD systems today are routinely designed for efficiencies in the range of 95–98 percent+ and the entire curve is clearly asymptotically approaching 100 percent.[18] The bottom series shows substantial reductions in the capital cost of new wet limestone systems doing the "same job" (i.e., 90 percent SO_2 removal at a standardized 500 MW plant burning high-sulfur coal) as the technology diffused over time.[19] Over the twenty-year period represented in this figure, capital costs decreased by a factor of two, although costs also appear to be leveling out (see Taylor, Rubin & Hounshell 2003 for curve fitting to these series).

Figure 9 also shows that the majority of the performance and capital cost improvements in the dominant technology to achieve SO_2 control occurred *before* the 1990 CAA. As of 1989, state-of-the-art wet FGD removal efficiencies had reached 95 percent.[20] These systems were also dramatically more reliable than earlier wet FGD systems; this was a major contributor



Note: Costs—based on historic projections—were standardized as if they applied to a new 500 MWe wet limestone FGD system burning 3.5% sulfur coal, with 90% SO_2 removal.

Figure 9. Experience Curves: U.S. Wet FGD SO_2 Removal Efficiency and Capital Cost as a Function of World Wet FGD Installed Capacity.

to both the capital cost reduction documented in Figure 9 as well as the operating cost decline documented in the learning-curve progress ratio. Thus, by the time the 1990 CAA was implemented, the maturation of wet FGD systems meant that there was no need for public efforts in SO_2 control RD&D: EPA concluded its program after 1992; TVA discontinued its FGD program in 1994 (including its influential Shawnee test facility); and DOE did the same by the end of 1997. On the industry side, EPRI, which represented most of the FGD RD&D being conducted by the utilities, reduced its efforts significantly, as did scrubber vendors hurt by the unexpectedly low scrubber demand caused by the dominant technology strategy for meeting the emissions trading program.

Consequently, the weight of evidence of the history of innovation in SO_2 control technology does not support the superiority of the 1990 CAA—the world's biggest national experiment with emissions trading—as an inducement for environmental technological innovation, as compared with the effects of traditional environmental policy approaches. Repeated demand-pull instruments, in the form of national performance-based standards, along with technology-push efforts, via public RD&D funding and support for technology transfer, had already clearly facilitated the rapid maturation of wet FGD system technology that diffused from no market to about 110 GWe capacity in twenty-five years. In addition, traditional environmental policy instruments had supported innovation in alternative technologies, such as dry FGD and sorbent injection systems, which the 1990 CAA provided a *disincentive* for, as they were not as cost-effective in meeting its provisions as low sulfur coal use combined with limited wet FGD application.[21]

VI. POLICY IMPLICATIONS

Although this case is only the first in what will be a series of cases that will provide an empirical basis for generalized insights about the influence of government actions on environmental technological innovation, there are a number of policy implications that can be drawn from its findings alone. This section explores some of these implications and uses them to frame the study's overall findings.

First, it is important to recall that the first commercial scrubbers were built in 1926 in the United Kingdom, yet they were not implemented commercially in the U.S. until the late 1960s (the first major plant work was done in 1965) and early 1970s (in 1971, there were three commercial scrubber units operating on U.S. power plants). This was despite U.S. public RD&D expenditures on the technology dating back to 1955, as well as despite the existence of the 1955 Air Pollution Control Act (APCA) and the 1963 CAA, both of which were instruments more of technology-push than demand-pull. Although experts point to the importance of technology-push instruments such as federal support of the SO_2 Symposium in driving the technology, it is clear that in SO_2 control, technology-push, as measured by RD&D expenditures, was not as important as demand-pull as an inducement of invention on its way to commercial application, as measured by patents. Without the market stimulated by government regulation, patenting activity levels are extremely low. This means that until the late 1960s, the private sector, which owns most patents in SO_2 control technologies, was not fully engaged in commercially relevant invention worthy of filing patent applications. It also means that the overall research community had one less public source of knowledge to draw on about novel, useful, and non-obvious inventions in this technology area. In addition, without the market stimulated by government regulation, operating experience could not contribute useful insights into how to improve the technology.

The implication of this is that an "RD&D and wait" environmental policy —one that invests in RD&D and otherwise does not require environmental performance until environmental technologies have matured—is likely to find environmental improvements either a long time in coming or dependent on the innovative activities of other nations. The second of these outcomes, while more timely and low cost to U.S. polluters, is unlikely to be the best economic solution for the country, as it means that other nations will capture the spillovers of whatever innovations are induced in this arena.

We saw, too, that industry's anticipation of environmental regulation, not just the existence of regulation itself, also drives innovation. Does this suggest that an environmental policy of "deliberate uncertainty" would allow the U.S. to capture some of these spillovers without polluters having to make as high investments in environmental technology as in cases of true environmental regulation? For example, the government could deliberately foster a situation such as existed in the 1980s, when the repeated introduction of bills in Congress raised expectations for a growing market for pollution control technology. One difficulty with this strategy is how to implement deliberate uncertainty without having the government's bluff called. When that day comes, if the government chooses to regulate, it might provide the kind of downside to innovators seen when the 1990 CAA effectively stopped the growth of a market in dry FGD and sorbent injection systems because of the incentives it provided for a combination of a large amount of least-cost low-level SO_2 removal (through the use of low sulfur coals) and a small amount of highest-level SO_2 removal wet FGD systems.

A better alternative is an "informed traditional" environmental policy, in which true demand-pull is coupled with technology-push to induce innovation; this approach would result in faster innovation in a technology that would mature to its lowest cost more quickly, while still allowing the U.S. to capture the spillovers of innovation in an environmental technology.

What characteristics should that "informed traditional" demand-pull instrument have? First, like performance-based standards and emissions trading programs, it should be technologically flexible, so that even if the likely "winners" are clear, no technology is barred from competing or developing unless its potential is deemed unworthy of investment by innovative responders to the instrument. Second, it should maximize the number of likely innovators engaged in improving the technology. This argues against emissions trading programs since, as Driesen (2003) points out, such instruments provide equal measure of under-compliance and over-compliance incentives, inducing less innovation than a performance-based standard in which everyone has an incentive to comply.[22]

Third, it should be stringent enough that it can take advantage of the old adage that "Necessity is the mother of invention." Regulatory stringency, as illustrated in the SO_2 case, is tied to increased collaboration within the research community across organizational types. It is also tied to increased patenting emphasis on alternative technologies—dry FGD and sorbent injection versus low-potential pre-combustion technologies—to meet existing and anticipated standards. Lastly, it should use anticipation to its advantage by managing uncertainty, perhaps by designing standards to be revisited periodically (say every five years). The expectation would be that these standards would strengthen in light of technical advances, and the iterative standard-setting process would provide a (more) continuous incentive for innovation.

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NOTES

1. For example, the market that pollution control technologies satisfy is fully defined by government, as the technologies produce no economically valuable good in and of themselves. The market that alternative energy technologies satisfy, on the other hand, is shaped by a more equal combination of the privately valued and publicly valued characteristics of the energy they provide; such privately valued characteristics include cost, availability, and other performance attributes of energy, while their publicly valued characteristic is their impact on the environment.
2. The issue is starting to make inroads in the environmental technology innovation literature, however, through articles like Loiter and Norberg-Bohm (1999).
3. "Performance-based standards" are the norm in traditional environmental regulation, with "many statutory provisions severely restrict[ing] EPA's authority to specify mandatory compliance methods" (Driesen 2003: 50). This fear that EPA will high-handedly restrict a firm's choice of compliance technology is stirred by the politically charged label, "command-and-control," and the seemingly related term "technology-based standards." True "technology-based standards" are rare, however, although the agency's practice of using a "demonstrated" reference technology to set some performance levels seems to help fuel the fear of such standards.
4. Both of these empirical studies can be critiqued based on features Kemp (1997) identifies as distinctive to innovation in environmental technology. Jaffe and Palmer (1997) conduct their analysis as if regulated firms perform all of the inventive activity measured by patents, although the important innovative role of other organizations (especially environmental technology suppliers) has been well established. Meanwhile, Lanjouw and Mody (1996) assume, for measurement purposes, that "all environmentally responsive innovation in a field responds to events in a broadly similar fashion" (ibid.: 557). Yet different technologies focussed on the same environmental problem area often exhibit a variety of control efficiencies, and may well react differently to different standards (such as when standards are strengthened so that a pre-existing technology will no longer meet the new standard).
5. Studies that attempt to capture all environmental technology patents can generally be critiqued as overly ambitious, in light of the diversity of environmental technologies and limitations of the patent classification system. Lanjouw and Mody (1996), for example, attempt to cover nine environmental fields in their patent dataset: industrial and vehicular air pollution, water pollution, hazardous and solid waste disposal, incineration and recycling of waste, oil spill clean-up, and alternative energy. Even though the authors say that they are trying to err on

the side of capturing too many patents rather than too few, the patent classifications they include for industrial air pollution alone are tremendously incomplete, missing almost 94 percent of the SO_2 control technology patents identified using the abstract-based method described below. As this technology is one of the world's most famous and well-understood examples of air-pollution control technology, this puts the results of the Lanjouw and Mody study in great doubt.

6. The mainstream innovation literature provides useful definitions. As stated in Clarke and Riba (1998), "an invention is an idea, sketch, or model for a new device, process or system." "*Adoption*" is the first commercial implementation of a new invention. "*Diffusion*" refers to the widespread use of a commercial innovation, and is often studied as a communication process between current and potential users of a technology (Rogers 1995). Lastly, "*learning by doing*" refers to the post-adoption innovative activity that results from knowledge gained from difficulties or opportunities exposed through operating experience (see Cohen & Levin 1989).
7. Once-through technologies bind the SO_2 permanently to the sorbent for later disposal or by-product use, particularly as gypsum for wallboard, while regenerable technologies release the SO_2 from the sorbent during regeneration for later processing and of byproducts recovery, such as sulfuric acid, elemental sulfur, and liquid SO_2.
8. Surveys by Napolitano and Sirilli (1990), Scherer et al. (1959), and Sirilli (1987) demonstrate that 40–60 percent of the innovations detailed in patent applications are eventually used by firms. Patents are also tightly tied to inventive input, as several studies have shown that "when a firm changes its R&D expenditures, parallel changes occur also in its patent numbers" (Griliches 1990: 1674). This is an important methodological consideration, as RD&D expenditure data are not typically available, especially at a high level of detail, for all inventing entities (see Cohen & Levin 1989; Griliches 1990; Lanjouw, Pakes & Putnam 1998; Schmoch & Schnoring 1994). Pakes (1985) is one of the earlier studies to link patents to outside events.
9. See critique in note 4, above.
10. Similar groupings of patent "art" are given a three-digit class and sub-class. Depending on the breadth of its technical claims, each patent is assigned one or more classes/sub-classes by the patent examiner, who uses them to investigate the legal prior art of a patent application.
11. Personal interview with G. P. Straub, U.S. Patent and Trademark Office, 1999.
12. Not included in this latter trend line are the patents on fluidized-bed combustion and gasification, although they were part of the RD&D picture in the 1970s.
13. Note that the RD&D expenditures in Figure 5 do not include public expenditures on pre-combustion research because of longitudinal data inconsistencies.
14. Interestingly, public RD&D expenditures on pre-combustion coal treatment, including for SO_2 control, continued after 1979.
15. Personal interview, September 1999.
16. In the economics of innovation literature, scientific or technical "tacit knowledge" can be seen as an important element of know-how (see discussion in Senker & Faulkner 1996, which also includes a discussion of the importance of informal networks in the transfer of tacit knowledge from public-sector research institutions).
17. For previous research use of paper co-authorship as a measure of collaboration, see such articles as Cockburn and Henderson (1998); Liebskind et al. (1995); Tijssen and Korevaar (1997); Zucker, Darby, and Armstrong (1994); Zucker & Darby (1995); Zucker and Brewer (1997).
18. SO_2 removal efficiencies were derived from the DOE/EIA Form 767 dataset (U.S. Energy Information Administration 1999).
19. Capital costs were drawn from five historical cost studies (Keeth, Ireland & Moser 1986; Keeth, Ireland & Radcliffe 1990, 1991; Laseke, Melia & Brucke 1982; McGlamery et al. 1980) and adjusted to 1997 dollars.

20. A study of 111 FGD installations in 1986–88 showed that FGD systems contributed 1 percent or less to the total unavailability factor in 70 percent of the installations, regardless of retrofit status or bypass capability; the study declared the reliability problem solved as of 1989 (Rittenhouse 1992: 23).
21. Supporters of emissions trading and its supposed superior effects on innovation can claim that the 1990 CAA came too late in the maturation of FGD to see any substantially greater effects on innovation than the effects of the traditional policy instruments that came before it. Thus, they can argue that emissions trading should be tested on an environmental problem area with a less-mature technology strategy to see if different results might follow. If so, the case of SO_2 control technology innovation—as induced by traditional environmental policy instruments—sets a high bar for future experiments to surpass.
22. It also argues against continued division of sources into "new and substantially modified" and "existing" sources, as all sources would be involved in innovative activities. This appears to be politically infeasible, as it would be too economically disruptive unless it was phased in gradually.

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