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Abstract

This paper relies on interviews and documentary evidence to describe federal RD&D policy for SO_2 and NOx emissions controls for coal-fired power plants from 1970 to 2000 and to assess its impact on technology development. The narrative begins by describing the RD&D program of the EPA in the 1970s, which many observers deem to have been successful, but which was largely dismantled after the election of Ronald Reagan to the presidency in 1980. We then turn to the contributions of the U.S. Department of Energy (DOE), which has been the main federal agency operating in this area since 1980, and particularly to DOE's Clean Coal Technology Demonstration Program (CCTDP), which began in 1985. The narrative as a whole suggests a mixed verdict on the effectiveness of past federal emissions control RD&D.

In the paper's conclusion, we mine this narrative history for insights that may be useful to current policy-makers. We argue first that regulatory pull is a necessary component for an effective greenhouse gas reduction policy, while technology push is not. However, a well-designed technology push may enhance the impact of regulation and lower the cost of compliance. Second, we should not expect that these two components will be well-aligned, due to the differences in the institutional frameworks for making the two types of policy. Third, RD&D policy should not be judged a failure if the technological options it supports are not widely commercialized or adopted. Instead, the standard should be whether RD&D led to options that might have been widely adopted if circumstances (regulatory, market, and technical) had been somewhat different. Determining what constitutes a plausible range of circumstances for application of this standard is a job that should be delegated to program managers, who must be able to exercise independent judgment, advised by technical experts who are drawn from diverse backgrounds.

Alignment and Misalignment of Technology Push and Regulatory Pull: Federal RD&D Support for SO_2 and NOx Emissions Control Technology for Coal-Fired Power Plants, 1970-2000[1]

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1. Introduction

Over the past forty years, the U.S. federal government has sought to control airborne emission of pollutants from coal-fired power plants that pose risks to human health and the environment. The scope of federal regulation in this domain has expanded from an early focus on the precursors of local smog to less visible toxic chemicals (like mercury) and regional pollutants (such as those responsible for acid rain). As the country considers whether and how to expand its air pollution control policy once again, in order to reduce carbon dioxide emissions that cause global climate change, its past experience may be plumbed for lessons. We focus in this paper on possible lessons about federal research, development, and demonstration (RD&D) policy that may be learned from past efforts to improve technology for reducing emissions of sulfur dioxide (SO_2) and nitrous oxides (NOx) from coal plants.

SO_2 and NOx contribute to smog at the local level as well as acid rain at the regional level. Not surprisingly, they were among the earliest air pollutants to be regulated by the federal government, with the imposition of standards for new coal plants starting in 1971. The most outstanding fact of the national experience since that date is that concentrations of both gases have declined significantly. The U.S. Environmental Protection Agency (EPA 2009b, 2009a) reports that SO_2 concentrations declined by 71% from 1980 to 2008, while NO_2 concentrations declined by 46% in that period.

A substantial fraction of these reductions is attributable to emissions controls at coal-fired power plants. Although substitution of other fuels for coal has occurred at the margin in recent decades, coal remains the dominant fuel for electric power generation in the U.S., with a market share of about 50%. In absolute terms, electricity production from coal plants grew by 26% between 1980 and 2007 (EIA 2008, Table 1.2), even as SO_2 and NOx pollution declined.

At the plant level, reductions in SO_2 and NOx emissions have been even more impressive. Coal plants constructed today typically emit 98% less SO_2 and 90% less NOx than those built forty years ago (Rubin et al. 2004, NESCAUM 2001). The retrofitting of older plants, although much delayed by legislative deals and legal wrangling, had by 2001 yielded

[1] We would like to thank the Doris Duke Charitable Foundation and the Industrial Performance Center for their support of this research. Margaret Taylor's pioneering work on this subject over the past decade deserves special recognition as well as ample acknowledgement in this paper's citations.

plant level reductions in the neighborhood of 40% on average for the two pollutants (DOE 2001b).

Federal regulation[2] has been the most important immediate cause of these declines. Table 1 summarizes the evolution of SO_2 and NOx emissions standards over time. The 1971 and 1979 New Source Performance Standards (NSPS) implementing the Clean Air Act of 1970 mandated that up to 90% of SO_2 be removed from emissions from new coal-fired power plants on a plant-by-plant basis. The 1990 Clean Air Act Amendments required a group of 265 existing units to reduce their combined SO_2 emissions to the level of 2.5 pounds per million BTU generated under a "cap and trade" policy. Phase II of this legislation extended the cap and trade policy to the entire coal fleet in 2000. (Taylor, Rubin, and Hounshell 2005 provide a detailed history of these standards.)

NOx emissions were reduced at new coal-fired power plants on a plant-by-plant basis by about 65% under the 1971 and 1979 NSPS. These standards were extended to older plants and tightened modestly for new plants under Phase I of the 1990 CAAA under a cap and trade system. In phase II of this act's implementation, EPA imposed a much tougher standard, requiring 80% or more reduction in NOx emissions on a state-by-state or regional basis for all plants in the eastern U.S. under the 1997 "SIP Call,"[3] and for all new units under the 1998 NSPS. (Taylor 2006 provides a more detailed history of these standards.)

Clearly, federal regulation of SO_2 and NOx from coal-fired power plants has "worked" from the perspective of protecting human health and the environment. Whether SO_2 and NOx emissions reductions were achieved in the most economical fashion has been the subject of much debate. The shift in regulatory design for SO_2 control from plant-by-plant mandates (so-called "command and control" regulation) to regional or national aggregate targets mediated by marketable emissions allowances ("cap and trade" regulation) reflects this debate. As the prospect of regulations to limit greenhouse gas emissions draws closer to realization, researchers are making an even more intensive effort to extract lessons about regulatory design from the recent history of U.S. air pollution policy (Burtraw and Palmer 2004; Ellerman, Joskow and Harrison 2003; Jaffe, Newell, and Stavins 2005; Stavins 1998).

Researchers have paid much less attention to the federal government's role in emissions control RD&D. In principle, public support for RD&D can accelerate the pace of emissions reduction by overcoming market failures in the generation of new ideas and inventions and in the translation of these ideas and inventions into commercial practice. Although regulatory policy is the dominant force driving emissions control technology forward, RD&D policy may play a valuable complementary role (Jaffe, Newell, and Popp 2009). Such considerations encouraged federal appropriators to invest hundreds of millions of dollars in RD&D programs related to SO_2 and NOx controls between 1970 and 2000.

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[2] States are partners in U.S. air pollution regulation, and some states (notably, California) have imposed emissions standards that are more stringent than the federal government's. But the federal government is the dominant partner, and it seems highly unlikely that stringent state-level standards could be sustained in the absence of the national baseline provided by federal regulation.

[3] Section 110 of the 1990 CAAA authorizes EPA to impose restrictions on sources of NOx emissions, if it deems necessary, to help downwind states comply with nation-wide ozone standards. EPA invoked this authority in 1998 by asking 22 states and the District of Columbia to complement their State Implementation Plans with measures to establish state-level NOx emission caps during the summer. This rule became known as the SIP Call. The federal and state governments have devised regional trading schemes to facilitate compliance (Burtraw and Evans 2004).

Table 1: Federal SO_2 and NOx emissions limits from 1971 to 1998

Source and subjects of application	**SO_2**	**NOx**
1971 NSPS Units built after August 17, 1971	1.2 lbs/MMBtu (0%-85% removal rate)	0.7 lbs/MMBtu
1979 NSPS Units built after September 18, 1978	1.2 lbs/MMBtu (90% removal rate) 0.6 lbs/MMBtu (70% removal rate)	0.5-0.6 lbs/MMBtu (65% removal rate)
1990 CAAA, Title IV Phase I: 265 old coal-fired units Effective as of 1996	2.5 lbs/MMBtu	0.45 lbs/MMBtu (T-fired units) 0.50 lbs/MMBtu (dry bottom wall-fired units)
Phase II: 2,500 existing coal-fired units Effective as of 2000	1.2 lbs/MMBtu	0.40 – 0.86 lbs/MMBtu (depending on boiler type)
1997 EPA SIP Call Units in 19 states and the District of Columbia		0.15 lbs/MMBtu (85% removal rate)
1998 NSPS Units built after July 9, 1997		0.15 lbs/MMBtu (modified sources) 1.6 lbs/MWh (new sources)

Sources: Burtraw and Evans (2004), p. 135 and p. 141; DOE (2005), p. 6; 40 Code of Federal Regulations, Title 40, Part 60.

There is no guarantee, however, that public RD&D spending will achieve its goals. It may be wasted on projects that would have been carried out by the private sector in any case, captured and diverted to private ends by narrow interests, or spent carelessly on the pipe dreams of technological enthusiasts (Cohen and Noll 1991, Greenberg 1967). In the case at hand, shifts in regulatory policy design from "command and control" to "cap and trade" also created challenges for RD&D policy-makers. In the next section of the paper, we review key issues in the design and implementation of RD&D policy.

Our historical narrative follows this review. It relies on interviews with participants with decades of experience in SO_2 and NOx emissions control RD&D and related policy-making as well as on documentary evidence. The narrative begins by describing the RD&D program of the EPA in the 1970s, which many observers deem to have been successful, but which was largely dismantled after the election of Ronald Reagan to the presidency in 1980. We then turn to the contributions of the U.S. Department of Energy (DOE), which has been the main federal agency operating in this area since 1980, and particularly to DOE's Clean Coal Technology Demonstration Program (CCTDP), which began in 1985. The narrative as a whole suggests a mixed verdict on the effectiveness of past federal emissions control RD&D.

In the paper's conclusion, we mine this narrative history for insights that may be useful to current policy-makers. Federal RD&D expenditures to support the development of carbon dioxide emissions control technology have begun to be made and will likely grow quite substantially in the near future. Indeed, the high probability that this spending will exceed by an order of magnitude or more that of previous emissions control RD&D programs makes it all the more imperative that we distill whatever guidance may be available from the historical experience.

2. Market and Government Failures and the Design and Implementation of Public RD&D Programs for Emissions Control Technology

The development of emissions control technology is subject to what Margaret Taylor (2008) calls a "dual" market failure. The environmental costs of harmful emissions are not included in the market prices of goods that create emissions. This "environmental" market failure provides the rationale for environmental regulation to reduce emissions. One way to reduce emissions is to develop new technology. But investments in technological innovation, and the scientific research that may underpin such innovation, typically fall victim to "innovation" market failures. Innovation market failures may lead firms to reduce emissions by switching fuels or shutting down plants, rather than by improving their technology.

In the case of coal-fired power plants, we must add a third form of market failure to our analysis. Exceptionally high barriers to entry, such as the capital costs of building transmission and distribution systems, are assumed to preclude competition, creating an "economic" market failure in electric power. Electric utilities in the U.S. have historically been subject to price and entry regulation with the aim of remediating this failure. This rationale has been challenged in recent decades, but neither the rationale nor the regulatory edifice built upon it has been entirely dismantled (Hogan 2009).

The "triple" market failure framework – environmental, innovation, and economic market failure – leads to several insights into the design and implementation of RD&D policy that help us to interpret the history of SO_2 and NOx control technology. The first is that neither environmental nor economic regulation (that is, emissions limits and price controls), even if they effectively address environmental and economic market failures, will necessarily solve innovation market failures. Markets provide weak incentives to invest in any ideas, such as many of those underlying new technologies, that are difficult to protect from imitation (Nelson 1959, Arrow 1962). Regulated firms, like unregulated firms, would usually rather free ride on others' production of these public goods than be the first mover, which may leave no first mover at all unless government steps in.

The second set of insights concerns the role of technological knowledge in the establishment of environmental regulations. Environmental policy-makers, tacitly or explicitly, weigh the expected costs of compliance – including the cost of emissions control technology – against the expected benefits of regulation. Both costs and benefits are subject to uncertainty, which might be reduced through RD&D. However, the utilities that might be subject to environmental regulation are unlikely to invest in uncertainty-reducing RD&D, because it might strengthen the case for regulation, which they would generally prefer not to see imposed. The vendors of emissions control technologies have a stronger incentive to carry out such RD&D, but they must take care not to alienate the utilities, because the utilities are their existing customers as well as the future customers for any new control systems that they might develop. A government role in RD&D might address this form of innovation market failure, but to do so the government would need to extend its support for RD&D beyond the creation of the public goods described in the previous paragraph to include more specific and potentially proprietary knowledge about the capital, operations, and maintenance costs of emissions technology (Sarewitz and Cohen 2009).

Even if such knowledge is generated by a government emissions control RD&D program, it will not necessarily be used. Innovation market failures may impede its transmission from the recipients of government RD&D support, such as vendors or government laboratories, to utilities (Taylor 2001). Lack of trust between utilities and RD&D performers, for instance, might limit knowledge use, because utilities perceive a pro-regulatory bias among the performers or doubt their operational expertise. In addition, some of this knowledge may be intrinsically difficult to transmit, because it is tacit knowledge about a complex industrial system. RD&D policy might be designed to take into account these kinds of barriers to effective knowledge use.

The third set of insights incorporates the impact of economic regulation on utilities' technological decision-making. In general, economic regulation is likely to make utilities cautious about adopting new technology (Flamm 1989, Winston 1998). There is, by definition, no market incentive to adopt new technology. More important in the domain of emissions control technology, there is no certainty that economic regulators will authorize rates that adequately cover the utilities' costs of adoption, especially when these costs are uncertain.

Utilities must also consider the risk that environmental regulation will be inconsistent. If the environmental rules do not conform to the original expectations once investments in new emissions control technology have been made, the costs of those investments may well be stranded. The rules may change for a variety of reasons, including litigation, changes in the political mood, fiscal constraints on enforcement, and discoveries by environmental scientists. Utilities' technological conservatism may therefore be quite well-founded, justifying a more extensive government RD&D policy than would make sense in the absence of the economic and environmental market failures.

The triple market failure provides several justifications for a government-funded emissions control RD&D program, but does not ensure that such a program will be effective (Cohen and Noll 1991). Program managers must have sufficient technical insight and flexibility to support a portfolio of RD&D projects that stands a reasonable chance of success, when judged on both environmental and economic grounds. They must also understand the incentives of vendors and utilities, so that they do not subsidize work that would have been done even in the absence of the government program. The political context – notably, imperatives from the legislative branch – may make it difficult for program managers to avoid these forms of "government failure," even when the managers are well-informed and well-intentioned.

These insights drawn from the literature on market and government failure inform our interpretation of the historical materials that we have gathered. At times, especially in the early part of our three decade period of study, federal RD&D programs effectively solved market failures and encouraged the development and deployment of technology for controlling the emissions of SO_2 and NOx from coal-fired power plants. At other times, these programs did not accomplish this objective, failing to fully address market failures, falling prey to government failures, or simply suffering from bad luck.

3. The 1970s: EPA in the Lead

In the early 1970s, the federal government established the first nationwide standards for SO_2 and NOx emissions from coal-fired power plants. Congress assigned the newly-formed EPA the leading role not only in writing and enforcing these standards, but also in supporting RD&D for emissions control technologies. The federal program in these years addressed many of the market failures described above, while avoiding most of the government failures. In some respects, however, its technological aspirations ran ahead of regulatory realities, leading to some investments that did not pay off for many years.

British utilities pioneered “wet scrubbing” of flue gas from coal-fired power plants to remove sulfur before World War II. (Rochelle interview) These early efforts proved far too modest to protect public health adequately, a state of affairs demonstrated tragically by the death of thousands of Londoners as a result of the “Great Smog” of December 1952. (Sarofim interview) With the Air Pollution Control Act of 1955, Congress took note of public concern in the U.S. about smog. This act provided the first federal RD&D funding for emissions control technologies. (Taylor 2001) As Congress inched toward extending federal authority over air pollution policy over the next decade and a half, the Tennessee Valley Authority (TVA), the Bureau of Mines in the Department of Interior, and the National Air Pollution Control Administration in the Department of Health, Education, and Welfare all conducted research on wet scrubbers. (Taylor, Rubin, and Hounshell 2005)

These programs became the foundation of an expanded RD&D effort to be managed by EPA, which was authorized by the Clean Air Act of 1970 (CAA). The EPA had been set up by President Richard M. Nixon just a few months before the CAA’s passage. Over the next decade, EPA built an air pollution RD&D program that typically spent over \$30 million annually and over \$100 million in some years (Taylor, Rubin, and Hounshell 2005, figure 5; Taylor 2006, figure 2.3). (These amounts are measured in 2003 dollars.)

The EPA program emphasized flue gas desulfurization (FGD), particularly debugging and improving the wet scrubbing method that had been invented in pre-World War II Britain. (See Box 1 for a brief explanation of SO_2 control technologies.) Projects at the 10 megawatt scale at the TVA’s Shawnee plant in Tennessee, where Bechtel Corporation was the technology vendor, showed that wet scrubbing could work well in a practical setting (Taylor, Rubin, and Hounshell 2005). EPA-funded work over the course of a decade led to the development of a wet scrubbing process that was commercialized in the U.S. and ultimately worldwide. The process generated gypsum as the main byproduct. Gypsum could be used in wallboard, a construction material; sludge, the previous byproduct, had to be disposed of. EPA-funded RD&D also improved the efficiency of SO_2 removal by wet scrubbers to above 90% by using organic additives with limestone. (Princiotta interview, Rochelle interview) Wet scrubbers accounted for roughly 86% of the world market for SO_2 controls through 2000 (Rubin et al. 2004).

Box 1: SO2 Control Technologies

Wet scrubbing or flue gas desulfurization (FGD) – in a wet scrubber process, a liquid sorbent is sprayed into the flue gas in an absorber vessel. The pollutant comes into contact with a sorbent liquid and is dissolved or diffused into the liquid. A wet slurry waste or by-product is produced, which may require additional treatment, or when oxidized, [it] results in a gypsum by-product that can be sold. New wet scrubbers achieve regular SO2 removal efficiencies from 95% to 99%.

Dry scrubbers - in a dry scrubber or FGD process, particles of an alkaline sorbent are injected into a flue gas, producing a dry solid by-product. In dry FGD scrubbing, the flue gas leaving the absorber is not saturated (the major distinction between wet and dry scrubbers). Dry scrubbers systems can be grouped into three categories: spray dryers, circulating spray dryers, and dry injection systems.

In a ***spray dryer***, a slurry of alkaline reagent is atomized into the hot flue gas to absorb the pollutants. The resulting dry material, including fly ash, is collected in a downstream particulate control device, typically an electrostatic precipitator or fabric filter. Spray dryers achieve SO2 removal efficiencies of 70%-95%.

Circulating spray dryers use an entrained fluidized bed reactor for contacting the reagent with sulfur dioxide and particulate laden flue gas. The mixture of reaction products and fly ash is carried to a downstream particulate collector. Part of the dry waste product is removed for disposal, but most of the waste product is mixed with fresh calcium hydroxide and reused in the reactor.

In ***dry injection systems*** a dry sorbent is injected into the flue gas in the upper reaches of the boiler, or in the ductwork following the boiler. Sulfur oxides react directly with the dry sorbent, which are collected in a downstream particulate control device. Because a separate scrubber vessel is not needed, capital costs are minimized. Dry injection systems have removal efficiencies from 50% to 70%.

Sources: Institute of Clean Air Companies (2009), "Technologies" <http://www.icac.com/i4a/pages/index.cfm?pageid=3401>, accessed on 05-04-09.

"Dry scrubbing" using atomized lime particles was a second successful outcome of the federally-funded SO_2 emissions control RD&D program. This technology works well with low-sulfur coals. It was discovered serendipitously by researchers studying the possibility of using molten carbonate as a scrubbing agent. (Rochelle interview) EPA-funded researchers explored a variety of other technological pathways, particularly emphasizing "regenerable" systems in which the sorbent was released from the SO_2 and recycled. (Rochelle interview, Licata/Lisauskas interview, Hilton interview) However, as one interviewee summarized it, "nothing in this area went very far. Utilities were reluctant to use such technology, due to their higher capital cost and complexity." (Princiotta interview) By about 1975, wet scrubbing was firmly established as the

SO_2 emissions control technology of choice, with dry scrubbing also filling an important niche (Rochelle interview). EPA's other lines of work were wound down after that date.

An interviewee from a major emissions control technology vendor stated flatly that government-supported RD&D was "instrumental" in getting SO_2 emissions control technology to a basic level of functionality. (Hilton interview) Taylor, Rubin, and Hounshell (2005, 706) also conclude that federally-funded RD&D was "key" to the development of wet scrubbing.

Similar claims appear warranted with respect to NOx control technology, which advanced substantially in the 1970s with EPA RD&D support (Pershing interview, Licata/Lisauskas interview, Sarofim interview). Staged combustion and overfire air technology, for instance, were devised to prevent the nitrogen in the fuel from forming NOx in the burner.[4] Natural gas reburning was developed to destroy NOx that has been created earlier in the combustion process, so that it is no longer emitted. (Box 2 describes NOx control technologies.) In its assessment of federal investments in energy research, a 2000 National Research Council panel concluded that "EPA…played a strong leadership role" in emissions control technology through 1980. (NRC 2001, 179)

Several interviewees emphasized that the EPA emissions control RD&D program was "balanced." By this term, they mean that the program operated on multiple scales, from bench-scale fundamental research to pilot plant scale to full-scale demonstration (Martin interview, Pershing interview). Researchers working at each of these scales communicated regularly with one another. This approach addressed both the innovation market failure around basic research and the potential government failure that basic research might become detached from the practical needs of the eventual downstream users of technology. One might argue that EPA wasted money by supporting exotic technologies, such as molten carbonate scrubbing. The incumbent SO_2 emissions control technology, wet scrubbing, proved to be very resilient. On the other hand, EPA support for most of these alternatives never reached beyond small scale tests, and they were generally dropped once it was clear that users were not interested in them.

Another important feature of the EPA program was its cooperative relationship with vendors. Vendors, such as Combustion Engineering and Babcock & Wilcox, provided valuable input into the program's technical agenda, and they were often engaged in carrying it out (Beer interview). Cooperation at this level allowed knowledge to be diffused quickly and adopted confidently by the vendors. Knowledge generated with EPA support was generally in the public domain, but vendors were often able to improve upon it and then patent the resulting new designs, which in turn created an incentive for further follow-in investment (Martin interview, Sarofim interview, Licata and Lisauskas interview). The EPA also built a technical community in the emissions control field by supporting symposia with participants from its RD&D program, other domestic programs, and comparable efforts abroad. A vendor interviewee stressed that the participants viewed these symposia as opportunities for learning, rather than selling: "Everybody went and everybody learned" (Licata and Lisauskas interview).

[4] The fact that nitrogen in the fuel as well as nitrogen in the air leads to NOx emissions was discovered by scientists at the U.S. Atomic Energy Commission's Argonne National Laboratory in the late 1960s. This discovery was met by vendors and utilities with some disbelief according to MIT combustion experts Janos Beer (interview) and Adel Sarofim (interview).

Box 2: NOx Control Technologies

A. Combustion Modification technologies

Tuning or optimizing of boiler combustion – does not involve a dedicated technology, 5-15% emissions reductions are achievable. [1]

Operational modifications – does not involve a dedicated technology. Instead, certain boiler operational parameters are changed to create conditions in the furnace that will lower NOx production. These include burners-out-of-service (removing of selected burners from service by stopping fuel flow while maintaining air flow to create staged combustion); low excess air (operating at the lowest possible excess air level without interfering with good combustion), and biased firing (injecting more fuel to some burners while reducing fuel to other burners to create staged combustion conditions in the furnace). [2]

Low-nitrogen burner (LNB) – utilizes the principle of staged combustion where the introduction and mixing of coal and air is controlled to create an oxygen-deficient environment with lower combustion temperatures which leads to a lower thermal and fuel NOx production in the first place. LNB are capable of emissions reduction of about 40%. [1]

Over-fire air (OFA) – like LNB, utilizes the principle of staged combustion and prevention of the formation of NOx, but differently from LNB, the air is injected into the furnace above the main combustion zone. OFA is frequently used in combination with LNBs, and can achieve 40% emissions reductions. [1]

Reburning – utilizes the principle of using combustion process to chemically destroy NOx shortly after it is formed. To do so, a second fuel, usually gas, is introduced to the boiler in the reburn zone which is located above the regular combustion zone. The process is finished with introduction of OFA. Emission reductions achievable are from 35% to 60%. [1]

Flue Gas recirculation (FGR) – part of the flue gas is recirculated to the furnace where it can be used to modify the conditions in the combustion zone (lower the temperature and oxygen-concentration), or it can be used as a carrier of fuel into a reburn zone to increase penetration and mixing. [2]

B. Post-Combustion Modification Technologies

Selective noncatalytic reduction (SNCR) – uses an ammonia-containing reagent to convert the NOx produced in the boiler to nitrogen and water. The reagent is injected into the upper furnace at high temperatures (1700ºF-2000ºF). Reduction rates of 30%-40% are achievable, sometimes higher. [1]

Selective catalytic reduction (SCR) – like SNCR, uses an ammonia-containing reagent to convert NOx to nitrogen and water. However, SNR operates at lower temperatures (600ºF) and utilizes a catalyst to produce the desired chemical reaction. Catalyst vessel is installed downstream of the furnace. Ammonia is injected into the flue gas before it passes over the series of catalyst beds. Up to 90% of NOx removal is achievable. [1,3]

Sources:

[1] NESCAUM (2001), "Environmental Regulation and Technology Innovation. Controlling Mercury-Emissions from Coal-Fired Boilers," Boston, MA.

[2] DOE (2001), "Environmental Benefits of Clean Coal Technologies," Clean Coal Technology, Topical Report Number 18, April 2001.

[3] DOE (2002), "Demonstration Of Selective Catalytic Reduction For The Control Of Nox Emissions From High-Sulfur, Coal-Fired Boilers," Project Performance Summary, CCTDP, DOE/FE-0450.

Utilities were initially less cooperative than vendors. A senior EPA manager recalled in an interview a utility-funded advertising campaign during the early 1970s showing Washington DC covered with sludge in order to sow doubt about SO_2 emissions control technology (Princiotta interview). Utilities feared (in the words of another interviewee) that they were "cutting their own throats" by supporting research on emissions control or by cooperating with EPA (Beer interview). Utility litigation that aimed at stalling implementation of the CAA rested in part on the fact that that the efficiency and reliability of emissions control technology had not been established (Taylor 2001; Taylor, Rubin, and Hounshell 2005). And, indeed, EPA's estimates about such matters were not always accurate; for instance, the agency substantially underestimated the capital cost of the first generation of scrubbers (Princiotta interview).

EPA overcame utility resistance in part simply by exerting its authority and defending itself legally and politically. Utilities came to recognize as a result of litigation that they had no choice but to comply and that they therefore had an incentive to find out how to comply in the most cost-effective fashion. By the mid-1970s, the Electric Power Research Institute, a utility trade organization, was playing a central role in emissions control RD&D (a role that it would play for the next twenty years), working closely with its members, vendors, and government agencies, including EPA (Taylor 2001, Nannen and Yeager 1976, Licata/Lisauskas interview).

EPA's RD&D program also helped to build at least a modicum of trust with utilities and vendors when this became possible by displaying independence from the agency's regulatory arm (Pershing interview, Licata and Lisauskas interview). RD&D results were only one input, and not necessarily a decisive one, into standard-setting (Martin interview). In fact, by virtue of their expertise, which extended to operational issues as well as basic research, EPA RD&D managers may have been perceived by utilities as a force for realism in the regulatory process.

If we take widespread technology adoption to be the ultimate measure of the success of a government-funded emissions control RD&D program, then the EPA program of the 1970s and early 1980s was mainly but not entirely successful. The 1979 NSPS effectively mandated the use of SO_2 scrubbers for new and modified boilers by introducing percentage emissions removal requirements by sulfur content of the coal (Taylor 2001). Although coal plants that used high-sulfur coal generally adopted wet scrubbers, those that used low-sulfur coal could take advantage of the lower capital costs offered by dry scrubbers while still meeting the standard (Princiotta interview). This solution satisfied environmental activists as well as East coast coal mining interests and their representatives in the Congress (Ellerman et al., 2000).

The 1971 and 1979 NSPS for NOx, on the other hand, were quite "liberal" and could often be met by making minor modifications to the combustion process, such as lowering the peak temperature. Tangential-fired boilers had a natural advantage over wall-fired and cyclone boilers in this regard because of their distributed heat release (Sarofim interview). The diffusion of NOx control technologies that provided greater removal efficiencies than these kinds of modifications was thus a relatively slow process, driven to a great extent by anticipation of regulations that did not actually materialize until well after the passage of the Clean Air Act Amendments of 1990 (Burtraw and Evans, 2004, p. 134).

The misalignment of technology push and regulatory pull in the case of NOx emissions control in the 1970s and 1980s highlights the possibility that widespread adoption may be too challenging a standard for every regulation-supporting public RD&D program to meet. RD&D program managers are unlikely to be able to anticipate both how technical uncertainties will be resolved in practice and how regulatory decisions will shake out. A more reasonable standard against which to judge the program is its ability to create plausible options for future application at a reasonable cost. By this standard, the EPA NOx RD&D program succeeded.

4. The 1980s and 1990s: DOE Takes Charge

The misalignment between technology push and regulatory pull in the development of SO_2 and NOx emissions control technology became more pronounced in the 1980s and 1990s. The reasons lay on both sides of the equation. On the push side, the federal emissions control RD&D program was radically restructured in the early 1980s. Congress and the new Administration cut the EPA program to the bone, assigned some of its former functions to the recently-founded Department of Energy, and created a new Clean Coal Technology Demonstration Program (CCTDP) within DOE in 1985. This program was less successful in addressing market failures and avoiding government failures than its predecessor. On the pull side, a shift in regulatory policy design from "command and control" to "cap and trade" limited the commercial adoption of new emissions control technologies emerging from federally funded RD&D.

DOE was formed in 1977. Like EPA seven years earlier, it was largely assembled from components that had been scattered across other federal agencies. These components included offices within the Department of Interior that had a long-standing interest in coal-related RD&D, including emissions control RD&D (DOE, "Our History"). In fiscal 1979, the second year of DOE's existence, much of EPA's work on scrubbers was transferred to DOE as well (Taylor 2001). This transfer was consistent with one of the key premises of DOE's construction, which was to separate technology development from regulation because of the possibility of conflict of interest between the two functions.[5]

The EPA emissions control RD&D program was further diminished as a result of the hostility of the Reagan Administration to the agency as a whole. Annual budgets for the program that had been in the tens of millions of dollars in the late 1970s were virtually wiped out in the early 1980s (Taylor, Rubin, and Hounshell 2005, figure 5; Taylor 2006, figure 2.3). Experts interviewed for this paper disagreed about whether the coal or utility industries sought these cuts. It is clear in any case that the cooperative relationship that had been established between EPA, vendors, and utilities at the technical level did not protect the program from the anti-regulatory mood of the period.

The establishment of CCTDP a half-decade later did not necessarily reflect a shift in the mood. The program had, by all accounts, a single parent, Senator Robert C. Byrd. Byrd was hardly enthusiastic about air pollution regulation. However, he seems to have recognized that regulation in some form was a reality, no matter what administration was in power, and that technological innovation might therefore be needed to sustain the use of high-sulfur coal from his home state of West Virginia. The Synthetic Fuels Corporation (SFC), which was set up in 1980 under President Jimmy Carter, had promised to pursue such innovation on a multi-billion dollar scale. CCTDP, which drew on funds that had initially been appropriated to the SFC, was

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[5] This issue was raised most sharply in the case of nuclear power. In that case, the primary concern was that the technology development mission had overwhelmed the regulatory mission, regardless of safety and the environment. The Atomic Energy Commission had had responsibility for both missions until 1974. These functions were split between the Nuclear Regulatory Commission and DOE once DOE was formed. In the case of emissions control technology for coal-fired power plants, the argument would have had to run in the opposite direction, that regulators who also had an interest in technology development would impose new technology on industry without regard for cost.

seen as a $750 million "consolation prize" (in the words of one observer) in the wake of the SFC's demise.

The Reagan Administration initially opposed CCTDP, but it soon changed its position as a result of negotiations with Canada about acid rain (Bauer interview, Yamagata interview). Canadian complaints about trans-boundary air pollution leading to acid rain had grown increasingly intense during President Reagan's first term. In March 1985, the U.S. and Canadian governments appointed special envoys to study the problem. The special envoys' report the following year recommended that the U.S. undertake a major demonstration program on SO_2 and NOx emissions control technology (DOE 2006). The Canadian envoy argued that such a program, rather than tougher regulation, was the most that his country could expect the U.S. to agree to (Forster 1993). The president's endorsement of the report ensured that CCTDP would survive and grow.

Table 2: CCTDP Project Costs and Cost-Sharing for Successfully Completed Projects (in thousands of current dollars)

Solicitation Round	Total Project Costs	Program Share (Percent)	Cost Share Dollars		Cost-Share Percent	
			DOE[a]	Participants	DOE	Participants
CCTDP-I	844,363	23	239,640	604,723	28	72
CCTDP-II	318,577	9	139,229	179,348	44	56
CCTDP-III	1,138,741	30	483,665	655,076	42	58
CCTDP-IV	950,429	25	439,063	511,366	46	54
CCTDP-V	0	0	0	0	0	0
Total	3,252,110	100	1,301,597	1,950,513	40	60
Application Category						
Advanced Electric Power Generation	1,978,492	61	814,099	1,164,393	41	59
Environmental Control Devices	620,110	19	252,866	367,244	41	59
Coal Processing for Clean Fuels	431,810	13	192,029	239,781	44	56
Industrial Applications	221,698	7	42,603	179,095	19	81
Total	3,252,110	100	1,301,597			60

[a] DOE share does not include $157,189,000 obligated for withdrawn project and audit expenses.
Source: DOE 2006, B-1.

CCTDP was bigger and broader than the EPA emissions control technology RD&D program of the 1970s. Its appropriations between 1985 and 1989 amounted to $2.75 billion, although in the final accounting only $1.3 billion was actually spent between FY87 and FY03. (See Table 2.) Another $1.95 billion was invested in CCTDP projects by the private partners. Over 60% of this spending was devoted to demonstrating new designs for power plants, rather than to technologies for controlling combustion in conventional boilers or scrubbing flue gases. These new designs, such as integrated gasification combined cycle (IGCC) and fluidized bed combustion (FBC), aimed to eliminate the need for post-combustion controls by producing very little SO_2 and NOx to begin with.[6] Still, CCTDP ultimately expended more than $250 million (about 19% of its total expenditures) on some 21 demonstration projects that sought to improve SO_2 and NOx emissions control technology (DOE 2006).

Most of these projects sought incremental improvements in existing technologies, tested existing technologies on new boiler types, or adapted existing technologies that had been developed abroad. The most ambitious of the six projects that targeted SO_2 reduction was the $150 million Pure Air project carried out by Air Products and Mitsubishi at Northern Indiana Public Service Company's Bailly power plant. DOE's share of the project cost was about $64 million, more than the other five SO_2 emissions control projects combined. The project achieved an average 94% removal rate for SO_2. It also proved to be highly reliable, cut capital costs by about 50%, and reduced the space required by the scrubber (DOE 2003a). The project was completed in 1995.

Seven CCTDP emissions control projects focused on NOx reduction. None of these projects approached the financial scale of the Pure Air project for SO_2 emissions control. Several demonstrated at commercial scale technologies that EPA-funded researchers had developed in the previous decade. For instance, Babcock and Wilcox demonstrated its "dual register" low-NOx burner at Dayton Power & Light's Lorain, Ohio plant with DOE's support. This project contributed directly to the commercialization of B&W's most advanced low NOx burner at that time (EPA 1995, 3). CCTDP also supported the application of selective catalytic reduction (SCR) to high-sulfur U.S. coal at a Southern Company plant in Pensacola, Florida from 1993 to 1995 (DOE 1998). SCR was more expensive than earlier generations of NOx control technology, but it boosted NOx removal efficiencies to levels high enough to meet the Phase II standards under the CAAA of 1990. SCR was invented in the U.S. in 1957, but was developed and adopted widely in Japan and Europe beginning in the 1970s (DOE 2002a, Popp 2006).

The third group of emissions control projects supported by CCTDP sought to demonstrate multi-pollutant controls. These projects were generally larger than those that targeted pollutants individually. For instance, DOE invested about $45 million in the Milliken project in upstate New York, which brought to the U.S. a combined SO_2-NOx control system developed in Europe (DOE 2003b). The felicitously-named SOx-NOx-Rox Box, demonstrated by Babcock & Wilcox at Dilles Bottom, Ohio, with about $6 million in DOE support, combined particulate control with a dry scrubber for SO_2 control and SCR for NOx control (DOE 2003c). Although these projects often achieved their technical targets -- and a couple of them won awards for technical excellence from professional societies -- they did not win widespread commercial acceptance.

Indeed, one interviewee went so far as to say "it's amazing how little [of the technology demonstrated by CCTDP as a whole] was commercialized" (Princiotta interview). Another credited the program with minor contributions in specific market niches (Rochelle interview). The National Research Council's 2001 evaluation was more generous, concluding that the program made available a broader set of choices for the market to consider, even though few

[6] Work on the IGCC, FBC, and other "advanced electric power generation" or "repowering" projects within CCTDP built on prior federally-funded RD&D that had been supported by DOE and its precursor agencies. CCTDP thus combined in a single program efforts that had previously been separated. To the extent that funding for new plant designs that would take many years to demonstrate crowded out funding for control technologies that could reduce emissions from existing plants or new construction in the short term, the CCTDP "missed the target" with respect to controlling acid rain (Martin interview).

customers selected them. A number of interviewees concurred in this view as well, casting CCTDP as a useful portfolio of projects that had generally been worth pursuing and that was in some cases still yielding benefits (Hilton interview, Licata/Lisauskas interview, Beer interview).

The divergence between technical success and limited market penetration manifested in these assessments was in part a consequence of the program's selection process. Although DOE's stated selection criteria emphasized prospects for commercialization in the relatively near term (DOE 1994, 17), DOE managers gave greater weight to technical criteria than to other criteria (GAO 1990b, 17). The Pure Air project that demonstrated a novel SO_2 control system, and in which CCTDP invested more than a quarter of its total budget for environmental control devices, illustrates the point. It received the Outstanding Engineering Achievement award from the National Society of Professional Engineers in 1992 and the Powerplant of the Year award from *Power* magazine the following year (DOE 2003a). Yet, no sales had been reported in the U.S., as of late 1999 (GAO 2000). The project's characteristics (SO_2 removal efficiency and capital costs) appear to be roughly similar to those achieved by typical new scrubbers in the mid-late 1990s, according to the calculations of Taylor, Rubin, and Hounshell (2005, 715).

DOE's heavier reliance on technical criteria than on business, management, and cost criteria did not stem from a lack of cooperation with vendors and utilities. CCTDP's designers felt they had learned from the failure of the Synthetic Fuels Corporation in this regard. They saw the SFC as an example of government failure in which officials tried "pick winners" without regard for the practical advice of industry (Bauer interview). CCTDP solicited industry input through regional meetings in advance of each program solicitation and required that participating firms pay at least 50% of the project cost. The projects were carried out in working power plants on utility premises, facilitating diffusion of tacit knowledge and providing credibility to the results. The GAO (2001, 2), after advancing an array of misgivings about other aspects of CCTDP, stated "Nonetheless, this program serves as an example to other cost-share programs in demonstrating how the government and the private sector can work effectively together to develop and demonstrate new technologies."

In some cases, CCTDP's deference to industry seems to have permitted firms to win government subsidies for projects that they would have carried out in any case. Two vendor interviewees, for instance, stated that that advanced SO_2 control technology demonstrated by Chiyoda and the Southern Company with more than \$20 million in DOE support was "locked up" for the exclusive use of these two firms (Hilton interview, Licata and Lisauskas interview).[7] In some instances, however, technological enthusiasm trumped technological conservatism, the 50% private cost-share requirement notwithstanding. At least three CCTDP emissions control projects were withdrawn before completion. The NOXSO Corporation, which was slated to receive \$41 million in DOE support to demonstrate its multipollutant removal system, for example, entered bankruptcy after about seven years in the design phase.[8] CCTDP's exclusive focus on demonstration meant that relatively little laboratory and pilot scale R&D was performed to provide more fundamental understanding of the processes involved (Beer interview). The

[7] Industry participants in CCTDP were granted ownership of the equipment used and any intellectual property generated.

[8] Even greater technological enthusiasm seems to have characterized other components of the CCTPD, particularly its big-budget advanced power generation projects. 24 projects, comprising 42% of all projects in the program, were withdrawn before completion (DOE, "Clean Coal Technology Demonstrations"). Many others went over budget or ran behind schedule. (GAO 1991, 2000)

community of learning described by participants in the EPA emissions control RD&D program was not sustained as strongly by DOE.

Yet, DOE's design and implementation of CCTDP was probably not the most important reason why the technologies the program demonstrated had limited commercial prospects. Congress's decision to transform the regulatory regime when it passed the CAAA of 1990 was more critical in this regard. Most CCTDP projects were initiated in the late 1980s, when "command and control" regulatory policy essentially mandated use of post-combustion scrubbers for SO_2 control, regardless of boiler design and coal type. By the time the demonstrations had been completed, "cap and trade" made possible alternative compliance approaches for many plants that did not require new scrubbers at all (Lange and Bellas 2005).

Foremost among these alternatives for SO_2 control was fuel switching, which had been precluded by the 1979 NSPS. Low-sulfur western coal had become more affordable for eastern coal plants in the meantime, thanks in part to railroad deregulation (Ellerman et al. 2000). A second alternative for high-emission coal plants was to take advantage of the "trade" element of "cap and trade" by buying emission credits from plants with lower emissions. This strategy was made more attractive by emission credit prices in the 1990s that were lower than had been predicted when the CAAA passed (Ellerman, Joskow, and Harrison 2003). A third compliance approach allowed by the legislation involved averaging emissions across the units and plants of a single utility.

The availability of these alternatives contributed to a significant drop in scrubber installations during the 1990s. (EIA 2005) Learning by doing by firms practicing older scrubber technologies also contributed to the decline in demand for new emissions control technology. Better training and procedures dramatically improved reliability and lowered capital, operations, and maintenance costs (Taylor 2001, Taylor, Rubin, and Hounshell 2005). One interviewee pointed out the irony that some of the biggest recipients of CCTDP support wound up sticking with existing technologies, rather than switching to the newer ones that their projects had demonstrated (Martin interview).

Regulatory regime change came more slowly for NOx than for SO_2. Phase I of the 1990 CAAA tightened NOx controls for about a quarter of all coal-fired power plants. Phase I standards were typically met by applying low-NOx burners, a development for which EPA and DOE both took credit. (NETL, "Knocking"; EPA 1995) Phase II, which took effect in the late 1990s, was much more stringent, effectively requiring an 85% reduction in NOx emissions. It rendered several CCTDP-supported technologies obsolete. For instance, a report on micronized coal reburning technology concludes: "At the time this project was selected in 1991 as part of the CCT program, market opportunities looked attractive, but now almost 10 years later with lower NOx emissions limits, the potential market appears to be smaller" (DOE 2001b).

Although NOx emissions trading at the regional level allowed some operators to take advantage of non-technological compliance options similar to those available under the SO_2 program (Burtraw and Evans 2004), many had no choice but to install SCR. A wave of retrofits ensued (Cichanowicz 2004). Although one of the seven CCTDP NOx emissions control projects demonstrated SCR, extensive implementation abroad was a more important determinant of the relative ease with which the technology was adopted in the U.S. in the early 2000s (Hilton interview, Taylor 2006). Well over 50% of coal plants in Germany and Japan already had such controls in place as of 2000, compared to under 4% in the U.S. (Popp 2006, 55) Not surprisingly, U.S. vendors generally licensed SCR technologies from foreign vendors. (Hilton interview)

The CAAA made multi-pollutant control technologies a particularly hard sell. The stringency of regulation varied among pollutants, compliance options varied as well, and changes in the level of stringency and in the compliance options were not made at the same time. The SOx-NOx-ROx Box and other technologies like it, however appealing in principle from a technical perspective, required utilities in practice to take on technological and regulatory risks that could not be justified.

The regulatory decisions of 1990 could not reasonably have been anticipated by DOE in 1985. The 1979 NSPS laid out, in broad strokes, the path that the emissions control projects of CCTDP generally followed, which was to adapt existing technologies to new coals and new boiler types and to pursue incremental innovation. DOE's implementation of this approach was not flawless.[9] It failed in particular to overcome fully utility conservatism and the industry's fear of knowledge that would support further regulation. But even if DOE had performed flawlessly, it would still have fallen well short of the goal of widespread adoption, because the regulatory factors that influenced adoption so strongly were outside its purview. No matter how much more effective CCTDP might have been in creating a cooperative industry-government-academia learning community, much of its learning would not have been put to use under the regulatory regime enacted in 1990.

5. Looking Back and Looking Ahead: Insights for CO_2 Emissions Control

By 2000, the Department of Energy's emissions control RD&D program had largely turned away from SO_2 and NOx, with the exception of a small program that sought an alternative to SCR for older power plants (Taylor, Rubin, and Hounshell 2005, Lani et al. 2007). Recent solicitations from CCTPD's successor programs have concentrated on other pollutants, on reliability, and, most recently, on carbon dioxide (DOE 2006). DOE's Clean Coal Power Initiative (CCPI), for instance, invested about $1.4 billion in five carbon capture and sequestration (CCS) demonstration projects in 2009 (DOE 4 December 2009). The proposed $2.4 billion FutureGen project, which would seek to integrate coal gasification and CCS in a single facility, is a second initiative in this vein. An expanded CCS demonstration program is likely to be included in any federal climate change legislation.

The history of federally-funded RD&D for SO_2 and NOx control can and should inform the CO2 control effort. There are numerous parallels between past experience and present challenges. Most fundamentally, CO_2 emissions controls from coal-fired power plants face the same triple market failure – environmental, innovation, and economic – that SO_2 and NOx emissions controls did. The variations within the history that we have explored – ranging from EPA's creation of a cross-sectoral learning community in the 1970s to DOE's mixed experience with demonstration in the late 1980s and 1990s, from the rapid development and diffusion of SO_2 scrubbers to the extremely slow pace of adoption for SCR – provide insights into how these challenges might be addressed. That said, we hasten to recall Mark Twain's admonition that history never repeats itself, although it sometimes rhymes. Any future climate change control regime will undoubtedly differ in important respects from the historic air pollution control regime, so one cannot infer lessons too directly from the past.

We draw three insights from our narrative. The first centers on the limits of technology push as an animating policy principle. Unless accompanied by a strong demand pull, publicly-funded RD&D is not likely to be translated into power plant installations. Solving the innovation

[9] We would remind the reader that we are concentrating here only on assessing the emissions control portion of the CCTDP portfolio and not weighing the predominance of power plant design in that portfolio.

market failure alone is insufficient. Post-combustion NOx controls, for instance, were not applied in the U.S. for a couple of decades after their development, because regulation didn't demand them. Post-combustion SO_2 controls were installed and improved because they were required by regulators. In making this argument, we are reiterating a point well-established in the literature (e.g. Jaffe, Newell, and Popp 2009, Taylor 2006)

Our second insight goes one step further. Stringent regulation does not necessarily mean that demand for federally-funded emissions control technologies will materialize. There may be other means to comply with the regulation or other sources for compliance technology. The most obvious evidence for this point in our narrative is the response to 1990 CAAA. The new regulatory scheme allowed plants to comply by switching fuel or purchasing emissions allowances instead of installing emissions controls.

Other episodes reinforce the point. Old technologies may "fight back," improving enough to enable compliance. Wet scrubbing, for instance, was never displaced as the dominant SO_2 control technology, despite federal RD&D investments in alternative technologies and a regulatory regime that tightened considerably. Improvements in operations and maintenance and incremental innovations based on user feedback led to lower costs and higher removal efficiency. Our narrative also reveals that vendors that are not affiliated with public technology programs may respond to the pull of tighter regulation. Foreign vendors that faced stringent regulation earlier in their home countries were especially important in developing NOx emissions controls. Some domestic vendors as well preferred to keep their distance from public RD&D in order to protect proprietary positions (Hilton interview).

Of course, the purpose of regulation should not be to promote technologies simply because they were federally-funded. That would amount to a costly conflict of interest, a concern that may have contributed to the phasing out of EPA's emissions control RD&D program under the Reagan Administration. Our point is rather that the outputs of federal RD&D comprise only a portion of the portfolio of the available responses to regulation and should be both designed and evaluated in light of the rest of the portfolio.

Our third and final insight builds on the fact that the institutions and interests that produce regulatory policy are different from those that produce emissions control RD&D policy. Sustaining alignment between demand for and supply of emissions control technology is therefore intrinsically difficult. The actual impact of regulation, for instance, often depends on the results of litigation and enforcement, whereas RD&D is more directly the province of the federal appropriations process. The incoming Reagan Administration was thus able to express its hostility toward federal activism in air pollution control more quickly and effectively in the RD&D domain than in the regulatory domain. It was also able to reverse ground more quickly in RD&D during Reagan's second term after it reached a diplomatic understanding with Canada on acid rain.

While RD&D policy can generally be altered more quickly and easily than regulatory policy, it takes longer to yield valuable results. Regulation can produce immediate changes in power plant operations or even shut plants down. Effective RD&D requires the building of technical communities and organizational partnerships as well as the simple passage of time to permit experiments to be run, models to be tested, and demonstrations to yield operational data. In some instances, such as the IGCC and FBC power plant designs supported by CCTDP in the late 1980s, the multi-decade time frame for technology development was far longer than the time horizon of legislators, who acted decisively in 1990 and laid out a firm schedule for the following decade.

Turning from the past to the future, we would put forward several guideposts for carbon dioxide emissions control policy. First and foremost, regulatory pull is a necessary component for an effective greenhouse gas reduction policy, while technology push is not. However, a well-designed technology push may enhance the impact of regulation and lower the cost of compliance.

Second, we should not expect that these two components will be well-aligned. Public RD&D funding should be steady, rather than designed to produce specific results to support a specific regulatory process at a specific time. Regulatory change is episodic and unpredictable, because of the complexity of interests and institutions involved. This complexity is heightened in the case of climate change by the global scope of the problem.

Third, RD&D policy should aim to provide new and otherwise unavailable options in the portfolio of compliance alternatives. But the policy should not be judged a failure if the publicly-funded alternatives are not widely commercialized or adopted. Instead, the standard should be whether RD&D led to options that might have been widely adopted if circumstances (regulatory, market, and technical) had been somewhat different. Determining what constitutes a plausible range of circumstances for application of this standard is a job that should be delegated to program managers, who must be able to exercise independent judgment in this regard.

Finally, in exercising this judgment, program managers should be able to draw on a technical community that balances the interests of vendor and utility experts with the views of government scientists, academics, and consultants who have a less direct stake in the outcome. Cooperation and close communication with industry is essential for findings to move from laboratory, pilot, and demonstration to practice. But industry's views may skew toward excessive conservatism or toward excessive optimism. Program managers must tread a fine line to keep projects in the appropriate zone of risk as best they can.

References

Arrow, Kenneth J., "Economic Welfare and the Allocation of Resources for Invention," in *The Rate and Direction of Inventive Activity* (Princeton: Princeton University Press, 1962), 609-626.

Burtraw, Dallas, and David A. Evans, "NOx Emissions in the United States. A Potpourri of Policies," in Winston Harrington, Richard D. Morgenstern, and Thomas Sterner, eds., *Choosing Environmental Policy. Comparing Instruments and Outcomes in the United States and Europe* (Washington, D.C.: RFF, 2004), 133-157.

Burtraw, Dallas and Karen Palmer, "SO2 Cap-and-Trade Program in the United States: A 'Living Legend' of Market Effectiveness," in Winston Harrington, Richard D. Morgenstern and Thomas Sterner, eds., *Choosing Environmental Policy. Comparing Instruments and Outcomes in the United States and Europe* (Washington, D.C.: RFF, 2004), 41-66.

Cichanowicz, J.E., "Air Quality Control: Why Are SCR Costs Still Rising," *Platt's POWER Newsletter*, April 2004.

Code of Federal Regulations, Title 40, Part 60 "Standards of Performance for New Stationary Sources", accessible at:
<http ://www.tceq.state.tx.us/permitting/air/rules/federal/60/60hmpg.html>, accessed August 27, 2009.

Cohen, Linda, and Roger Noll, *Technology Pork Barrel* (Brookings, 1991).

DOE, “Clean Coal Technology Demonstrations,” undated, available at <http://www.netl.doe.gov/technologies/coalpower/cctc/cctdp/>, accessed December 18, 2009.

DOE, “Knocking the NOx out of Coal,” undated, available at <http://www.netl.doe.gov/technologies/coalpower/cctc/coal101/coal101-3.html>, accessed May 4, 2009

DOE, Office of Fossil Energy, “Our History,” undated, available at <http://fossil.energy.gov/aboutus/history/>, accessed December 18, 2009.

DOE, “Secretary Chu Announces $3 Billion Investment,” press release, December 4, 2009, available at < http://www.netl.doe.gov/publications/press/2009/09081-Secretary_Chu_Announces_CCS_Invest.html>, accessed January 20, 2010.

DOE, “Clean Coal Technology Programs: Program Update 2006,” June 2006, available at <http://www.netl.doe.gov/technologies/coalpower/cctc/ccpi/pubs/2006_program_update.pdf>, accessed November 10, 2008.

DOE (2003a), “Advanced Flue Gas Desulfurization Demonstration Project,” 2003 Project Fact Sheet, available at: <http://www.netl.doe.gov/technologies/coalpower/cctc/cctdp/project_briefs/puair/documents/puair.pdf>, accessed December 10, 2009.

DOE (2003b), “Milliken Clean Coal Technology Demonstration Project,” 2003 Project Fact Sheet, available at: <http://www.netl.doe.gov/technologies/coalpower/cctc/cctdp/project_briefs/milkn/documents/milkn.pdf>, accessed December 10, 2009.

DOE (2003c), “SOx-NOx-Rox Box Flue Gas Cleanup Demonstration Project,” 2003 Project Fact Sheet, available at: <http://www.netl.doe.gov/technologies/coalpower/cctc/cctdp/project_briefs/snrb/documents/snrb.pdf>, accessed December 10, 2009.

DOE, “Demonstration of Selective Catalytic Reduction For The Control of NOx Emissions From High-Sulfur, Coal-Fired Boilers,” Project Performance Summary, November 2002, available at <http ://www.netl.doe.gov/technologies/coalpower/cctc/cctdp/bibliography/demonstration/pdfs/scr/SCRsummary.pdf> accessed March 10, 2009.

DOE, “Environmental Benefits of Clean Coal Technologies,” Clean Coal Technology Topical Report Number 18, 2001a, available at <http ://www.netl.doe.gov/technologies/coalpower/cctc/topicalreports/pdfs/topical18.pdf> accessed October 5, 2008.

DOE, “Micronized Coal Reburning Demonstration Assessment for NOx Control: A DOE Assessment,” 2001b, available at <http ://www.netl.doe.gov/technologies/coalpower/cctc/cctdp/bibliography/demonstration/pdfs/micro/MCRTest2.pdf> accessed February 24, 2009.

DOE, “Demonstration of Selective Catalytic Reduction Technology to Control Nitrogen Oxide Emissions From High-Sulfur, Coal-Fired Boilers: A DOE Assessment,” DOE/FETC-2000/1111, 1998, available at <http://www.netl.doe.gov/technologies/coalpower/cctc/cctdp/bibliography/demonstration/pdfs/scr/scrfinl.pdf> accessed February 15, 2009.

DOE, "The Clean Coal Technology Program. Lessons Learned," 1994, available at <http://www.netl.doe.gov/technologies/coalpower/cctc/resources/pdfsprog/lessons/9400010a.pdf> accessed June 10, 2009.

Ellerman, A. Denny et al., *Markets for Clean Air. The U.S. Acid Rain Program* (Cambridge University Press, 2000).

Ellerman, A. Denny, Paul J. Joskow and David Harrison, "Emissions Trading in the U.S. Experience, Lessons, and Considerations for Greenhouse Gases," prepared for the Pew Center on Global Climate Change (2003), available at <http://www.www.pewclimate.org/docUploads/emissions_trading.pdf >, accessed September 15, 2009.

EIA, *Annual Energy Review 2008*, Report No. DOE/EIA-0384 (2008), available at <http://www.eia.doe.gov/emeu/aer/overview.html> accessed September 4, 2009.

EIA, form 767 database for 2005, available at <http ://www.eia.doe.gov/cneaf/electricity/page/eia767.html>, accessed on January 20, 2009.

EPA, Office of Research and Development, "Combustion Modification Control of Nitrogen Oxides," EPA Report EPA/600/F-95-012, 1995, available at <http://www.epa.gov/nrmrl/pubs/600f95012/600f95012.pdf>, accessed July 10, 2009.

EPA (2009a), "Air Trends: Nitrogen Dioxide," available at <http://www.epa.gov/air/airtrends/nitrogen.html>, accessed December 9, 2009.

EPA (2009b), "Air Trends: Sulfur Dioxide," available at <http://www.epa.gov/air/airtrends/sulfur.html>, accessed December 9, 2009.

Flamm, Kenneth, "Technological Advance and Costs: Computers versus Communications," in Robert W. Crandall and Kenneth Flamm, eds., *Changing the Rules: Technological Change, International Competition, and Regulation in Communications*, (Brookings Institution, 1989), 13-61.

Forster, Bruce A., *The Acid Rain Debate: Science and Special Interests in Policy Formation* (Iowa State University Press, 1993).

GAO, "Clean Coal Technology: Status of Projects and Sales of Demonstrated Technology." RCED-00-86R, 2000, available at <http://archive.gao.gov/f0902b/163510.pdf>, accessed December 18, 2009.

GAO, "Fossil Fuels**:** Improvements Needed in DOE's Clean Coal Technology Program," RCED-92-17, 1991, available at < http://archive.gao.gov/d24t8/140907.pdf >, accessed December 18, 2009.

GAO, "Fossil Fuels. Pace and Focus of the Clean Coal Program Need to be Assessed," GAO/RCED-90-67, 1990, available at <http://archive.gao.gov/d24t8/140907.pdf>, accessed October 20, 2008.

Greenberg, Daniel S., *The Politics of Pure Science* (New York: New American Library, 1967).

Hogan, William W., "Electricity Market Structure and Infrastructure Policy," in Kelly Sims Gallagher, ed., *Acting in Time on Energy Policy* (Washington: Brookings, 2009).

Institute of Clean Air Companies, "Acid Gas/SO2 Control Technologies," available at <http://www.icac.com/i4a/pages/index.cfm?pageid=3401>, accessed on May 4, 2009.

Jaffe, Adam B., Richard G. Newell, and David Popp, "Energy, the Environment, and Technological Change," National Bureau of Economic Research Working Paper No. 14832, April 2009.

Jaffe, Adam B., Richard G. Newell, and Robert N. Stavins, "A Tale of Two Market Failures: Technology and Environmental Policy," *Ecological Economics*, 54: 164-74 (2005).

Lange, Ian, and Allen Bellas, "Technological Change for Sulfur Dioxide Scrubbers Under Market-Based Regulation," *Land Economics* 81:546-556.

Lani, Bruce W. *et al.* "Bringing Advanced Technology to the Marketplace," *DOE/NETL NOx R&D Overview*, April 2008.

Nannen, L. W. and K.E. Yeager, "Status of the EPRI Flue Gas Desulfurization Development Program," in *Proceedings: Symposium on Flue Gas Desulfurization*, *New Orleans, March 1976* (Washington, D.C.: EPA, 1976), 101-114.

Nelson, R.R., "The Simple Economics of Basic Scientific Research," *Journal of Political Economy* 67:297-312 (1959).

NESCAUM , "Environmental Regulation and Technology Innovation. Controlling Mercury-Emissions from Coal-Fired Boilers," 2001, available at <www.nescaum .org/.../rpt000906mercury_innovative-technology.pdf>, accessed August 21, 2009.

National Research Council, *Energy Research at DOE: Was It Worth It? Energy Efficiency and Fossil Energy Research 1978 to 2000* (Washington, D.C.: National Academy Press, 2001).

Popp, David, "International Innovation and Diffusion of Air Pollution Control Technologies: the Effects of NOx and SO2 Regulation in the US, Japan, and Germany," *Journal of Environmental Economics and Management* 51:46-71 (2006).

Rubin, Edward S, Margaret R. Taylor, Sonia Yeh and David A. Hounshell, "Learning Curves for Environmental Technology and Their Importance for Climate Policy Analysis," *Energy* 29: 1551-1559 (2004).

Sarewitz, Dan, and Armond Cohen, *Innovation Policy for Climate Change: A Report to the Nation* (Clean Air Task Force and Center for Science, Policy, and Outcomes, 2009).

Stavins, Robert N., "Significant Issues for Environmental Policy and Air Regulation for the Next Decade," *Environmental Science and Policy*, 1:143-147 (1998).

Taylor, Margaret R, "The Influence of Government Actions on Innovative Activities in the Development of Environmental Technologies to Control Sulfur Dioxide Emissions from Stationary Sources," Ph.D. dissertation, Engineering and Policy Program, Carnegie-Mellon University, 2001.

Taylor, Margaret R, Edward S. Rubin and David A. Hounshell, "Control of SO2 Emissions from Power Plants: A Case of Induced Technological Innovation in the U.S.," *Technological Forecasting and Social Change* 72:697-718 (2005).

Taylor, Margaret R., *Government Actions and Innovation in Environmental Technology for Power Production: The Cases of Selective Catalytic Reduction and Wind Power in California*, Report CEC-500-2006-053 (Sacramento: California Energy Commission, 2006).

Taylor, Margaret R., "Beyond Technology-Push and Demand-Pull: Lessons from California's Solar," Goldman School of Public Policy Working Paper GSPP08-002, University of California, Berkeley, 2008.

Winston, Clifford, "U.S. Industry Adjustment to Economic Regulation," *Journal of Economic Perspectives* 12(3):89-110 (1998).

Interviews

Bauer, Donald L., June 3, 2009.
Beer, Janos, July 13, 2009.
Hilton, Robert G., July 14, 2009.
Licata, Tony, and Bob Lisauskas, June 29, 2009.
Martin, Blair, June 1, 2009.
Pershing, David W., July 17, 2009.
Princiotta, Frank, April 14, 2009.
Rochelle, Gary, April 10, 2009.
Sarofim, Adel, June 9, 2009.
Strakey, Joseph, April 16, 2009.
Yamagata, Ben, May 19, 2009.

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