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POLLUTION CONTROL INNOVATIONS AND THE CLEAN AIR ACT OF 1990

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ABSTRACT

Although economists cite potential gains from induced innovation as an advantage of using market-based mechanisms to protect the environment, counts of patents related to flue gas desulfurization units ("scrubbers") peaked before trading of sulfur dioxide (SO_2) permits began. This paper uses plant level data to study the effect of these patents on pollution control. I find that requiring plants constructed before 1990 to install scrubbers created incentives for innovation that would lower the costs of operating scrubbers. There is little evidence that the new patents created before 1990 improved the ability of scrubbers to more effectively control pollution. However, patents granted during the 1990s, when market-based mechanisms were in place, do serve to improve the removal efficiency of scrubbers.

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Economists cite potential gains from induced innovation as one of the advantages of using market-based mechanisms over command and control (CAC) policies to protect the environment. Several theoretical papers, such as Milliman and Prince (1989, 1992) and Magat (1978) have demonstrated the advantages of market-based mechanisms for inducing technological innovation. Recent empirical work, such as Popp (2001), Newell *et al*. (1999), Jaffe and Palmer (1997), and Lanjouw and Mody (1996), demonstrates that environmental innovation does indeed respond to incentives such as prices or regulation. However, there is no empirical work containing a direct comparison of innovation between a command and control and market-based policy regime. Using data on coal-fired electric utilities from before and after passage of the 1990 Clean Air Act, this paper attempts to fill that gap.

One of the most prominent examples of a market-based environmental policy is the trading of sulfur dioxide (SO_2) allowances created by the 1990 Clean Air Act (CAA). In this paper, I combine data on steam-electric power plants provided by the Energy Information Administration (EIA) with data on patents granted in the United States to look at innovations in pollution control for power plants before and after the 1990 CAA. Contrary to theoretical predictions, patent counts related to SO_2 pollution control technologies, such as smokestack scrubbers, are higher before the 1990 CAA. In this paper, I argue that this empirical fact is not inconsistent with the theoretical prediction that market-based environmental regulations induce more innovation. Rather, I show that the change to a market-based policy in 1990 did not necessarily lead to *more innovation*, as measured by patent counts, but did lead to *more environmentally-friendly innovation*, as measured by the effect of the new innovations on air quality.

Before the CAA of 1990, plants were required to use the best available technology for pollution control, which was often a scrubber. As a result, there were incentives for innovation that would lower the costs of installing and operating scrubbers. However, there would be little incentive for innovations to improve the efficiency of the scrubbers' ability to actually remove pollutants. Theoretical models of induced innovation and environmental policy typically do not distinguish between these two types of innovation. Matching patent data with data from the EIA on installation costs, operating costs, and removal efficiencies of the scrubbers, this paper looks for changes in the types of innovation that were taking place before and after the Clean Air Act of 1990. I show that patents granted before 1990 had no effect on removal efficiency, but did lower the operating cost of scrubbers. In contrast, patents granted during the 1990s not only lowered operating costs, but also increased the removal efficiency of scrubbers. Thus, although the level of innovation did not change upon the introduction of the market-based permit trading policy, the nature of innovation did.

Previous empirical work on pollution control technologies for coal-fired electric utilities includes Bellas (1998) and Carlson *et al.* (2000). Looking at scrubbers installed by 1992, Bellas finds no significant evidence of technological change in abatement technology. In contrast, Carlson *et al.* find that about 20%, or $50, of the change in marginal abatement costs that have occurred from 1985 to 1995 can be attributed to technological change. Since Bellas sample includes few scrubbers installed after passage of the 1990 CAA, and none installed after trading in SO_2 permits began, the results of these two papers are consistent with economic theory, which predicts that market based policies induce more technological change. However, the results are inconsistent with the observation that pollution control patents and R&D activity is highest during the early 1980s. One possible explanation for this discrepancy is that both papers simply use a time trend to represent technological change. The use of a time trend may not accurately reflect changes in technology, as there are variations in patenting and R&D efforts over time. By using patent data, I can more accurately model the progress of innovation that may have occurred in scrubber technology. In particular, I use the patents to observe changes in the *types* of research done in each policy era. Furthermore, by using data through 1997, I am able to compare changes in technological progress before and after passage of the 1990 Clean Air Act.

I. History of Environmental Regulations Facing Utilities[1]

Before the 1990 Clean Air Act established the sulfur dioxide permit market, electric utilities faced command and control regulations that focused on pollution control technology. Regulation of sulfur dioxide emissions began with the 1970 Clean Air Act, which listed SO_2 as one of six criteria pollutants. The 1970 Clean Air Act required the EPA to establish "national ambient air quality standards" (NAAQS) for such pollutants at levels that would ensure the public health and welfare. Once the NAAQS were set by the EPA, states were to develop a plan, known as a "state implementation plan" (SIP) for attaining the required standards. Although the EPA has the authority to review a state's SIP, each state was given freedom to choose how it would attain the emissions goals required by the NAAQS (Martineau et al, 1997).

The criteria used by the EPA to evaluate SIPs were technology-based. Because Congress was concerned that retrofitting older sources of pollution would be costly, they instead instructed the EPA to require that new sources meet more stringent pollution control standards. The EPA listed 61 sources that contribute significantly to air pollution, and required these sources to satisfy "new source performance standards" (NSPS). Among these sources were fossil fuel fired

[1] Table 1 provides a summary of the key regulations facing coal-fired steam-electric power plants.

steam boilers for which construction began after August 17, 1971, which were covered under NSPS Subpart D (NSPSD). NSPSD required that newly constructed utilities, or existing units undergoing modification or reconstruction, meet minimum emission standards. The standards were to be set based on the best technology that had been "adequately demonstrated." Since NSPSD was set at the national level, it was an exception to the rule that states were given freedom to implement individual SIPs. However, regulations in the SIPs that were more stringent than NSPSD took precedent, so that the national NSPSD standards can be seen as minimum standards to be met (Ellerman *et al*. 1997). The Act required NSPS standards to be reviewed every four years (Brownell & Zeugin 1991).

NSPS Subpart Da (NSPSDa) of the 1977 Clean Air Act, which covers boilers for which construction commenced after September 18, 1978, clarified the national standards for sulfur dioxide and added an additional technology requirement for electric utilities. Most importantly, the 1977 amendments required that most new coal-burning plants use flue gas desulfurization units (FGD units, or "scrubbers") to remove 90% of SO_2 emissions from their exhaust.[2] The intent of the requirement was to protect the jobs of miners in states with high-sulfur coal by making it less likely that utilities would meet the Clean Air Act's emission requirements by switching to low-sulfur coal. (Brownell and Zeugin 1991).

The 1977 amendments also added new technology-based standards. First, major new sources of pollution required "prevention of significant deterioration" (PSD) permits. The list of major new sources includes fossil-fueled fired steam electric plants or boilers totaling more than 250 million BTU/HR heat (Brownell & Zeugin 1991). To receive a PSD permit, the applicant

[2] Specifically, plants needed to either achieve emission rates less than 1.2 lbs SO_2/million Btu heat input *and* reduce 90 percent of their pre-treated emissions (a 90% removal efficiency) or achieve emission rates less than 0.6 lbs SO_2/million Btu heat input *and* achieve 70% removal efficiency.

must show that the "best available control technology" (BACT) will be used for each pollutant emitted. Finally, the EPA set more stringent guidelines for air quality control regions that were not in attainment of the NAAQS. SIPs for nonattainment areas required permits for new or modified pollution sources. At a minimum, the permit program must require that these sources install pollution control equipment designed to achieve the "lowest achievable emission rate" (LAER). Furthermore, existing sources in nonattainment areas could be required to install "reasonably available control technology" (RACT) (Brownell & Zeugin 1991).

Unfortunately, the concept of best available control technology was not well-defined by the EPA. The 1977 CAA stated that BACT limits would be determined on a case-by-case basis. Determination of the BACT should consider energy, environmental, and economic impacts. However, the relative weight assigned to each factor was to be determined by individual states. The burden of the BACT analysis was placed on the permit applicant. To demonstrate that the chosen technology was the BACT, the applicant had to show that alternative technologies with more stringent pollution control would cause "unreasonable adverse energy, environmental, or economic impacts." (U.S. EPA 1978) For example, a slightly more stringent control technology could be ruled out if the economic or energy costs of the technology are significantly greater. Economic impacts considered could include investment costs, operations and maintenance costs, and annualized costs of operations and maintenance plus depreciation. In addition, applicants could consider impacts on the local economy. For example, if a region suffered from high unemployment, a more stringent control technology could be ruled out if it would lead to a loss of jobs (U.S. EPA 1978).

In 1987, EPA guidelines on BACT changed to focus on the most stringent control available. The 1987 guidelines, known as "the Potter memorandum," instituted a top-down approach to BACT analysis. Applicants must begin by determining the most stringent control technology available. That technology could only be ruled out if it can be shown to be technically or economically infeasible. If it was ruled out, the applicant was to proceed to the next most stringent control technology, and so on, until a technology that could not be ruled out is found (Brownell & Zeugin 1991). The top-down approach made the BACT requirement similar to the "lowest achievable emission rate" (LAER) requirements for new sources in non-attainment areas. A LAER technology must be at least as stringent as any technology in use in any state. The costs of such technology could be considered, but only if the costs were so high that they would prohibit the new source from operating at all (Brownell & Zeugin, 19991).

The 1990 amendments to the Clean Air Act (1990 CAA) changed the regulation of electric utilities' SO_2 emissions from a command and control approach to a market-based approach. It also changed the focus from state-based implementation plans to one aggregate national emissions limit to be met. The 1990 amendments repealed the requirement that 90% of SO_2 emissions at coal-burning plants be scrubbed. Instead, Title IV of the 1990 CAA introduced tradable SO_2 emissions allowances. Starting in 1995, Phase I utilities[3] were required to have permits for each ton of SO_2 emitted. In Phase I, allowances were allocated to allow each affected utility to emit 2.5 lbs/mmBtu per year. Firms that were not able to meet this requirement could emit more if they purchased additional permits from a plant that was able to reduce emissions by more than the required amount. Total allowances equaled 8.7 million tons. For comparison, these plants emitted 9.3 tons of SO_2 in 1985 (Ellerman *et al.*, 1997). Firms could receive additional allowances if they installed "qualifying control technologies" that reduce a plant's SO_2 emissions by at least 90 percent. (Martineau & Novello 1997)

[3] Phase I utilities include the 263 dirtiest utilities, based on 1985 emissions levels.

Because plants were no longer required to install scrubbers, they could choose the most cost effective methods to reduce emissions. Ellerman *et al*. (1997) estimate that 45.1% of reductions in 1995 came from SO_2 scrubbing, with the remaining 54.9% coming from switching to other fuels, such as low sulfur coal.

Phase II of Title IV begins in the year 2000. Phase II expands the permit trading program by including most existing or new plants. Over 2000 plants are now included. Aggregate annual emissions are limited to 8.95 million tons – roughly 50% of 1980 emissions levels (Ellerman *et al.* 1997).

II. Innovation levels before and after the 1990 CAA

A large body of environmental economic literature has demonstrated the benefits that market-based mechanisms have for inducing research and development (R&D) on environmentally friendly technologies. These models universally predict that market based environmental policies will induce more innovation than command and control policies. However, each of these papers focuses only on the overall level of innovation.

In this paper, I use patent data to look for changes in the *nature* of the R&D performed. Even though the best available control technology policy of NSPSD and NSPSDa provides no incentives for firms to develop scrubbers that exceed the removal efficiency requirements, there were incentives to perform research designed to reduce the costs of these scrubbers.[4] Since firms were required to install scrubbers, such research would reduce the costs of compliance with the BACT regulations.

[4] Not only is there no reward for exceeding the standard, if regulators respond to technological advances by increasing the standard (the ratchet effect), there may actually be a disincentive to develop new technologies. The ratchet effect hypothesis is not explored in this paper.

Cost-reducing innovations would still be beneficial in a permit trading market. Permit markets work by taking advantage of differences in marginal abatement costs across firms. Thus, firms that could lower their marginal abatement costs would benefit by being able to sell pollution allowances to firms with higher marginal abatement costs. However, firms could also have additional permits to sell if they used pollution abatement technology that removed more pollution. Thus, there are incentives for innovation to increase the removal efficiency of scrubbers in the market-based policy regime. This additional incentive suggests the following two hypotheses to be tested in the empirical work that follows:

1) Innovation under the command and control regime should have focused on lowering costs, rather than increasing efficiency.
2) Innovation after passage of the 1990 CAA may focus on either lowering operating costs or increasing removal efficiency.

I begin by looking at the level of innovative activity in sulfur dioxide pollution control. To measure the level of innovative activity, I use U.S. patents related to sulfur dioxide pollution control. To identify such patents, I use the classification and subclassification assigned to each patent by the U.S. Patent Office. These classifications describe the type of invention represented by the patent. I began by identifying classifications that were related to SO_2 pollution control. These are shown in Table 2. Then, using data available on Lexis/Nexis, I identified all patents in these classifications from 1900 to 1997. In addition, using data from a set of CD-ROMs produced by MicroPatent, I obtained additional details on pollution control patents granted since 1975, including the application date and country of origin.

The use of patent data to measure innovative activity offers several advantages. The biggest advantage of patent data is that, unlike other data on inventive activity, such as R&D

expenditures, patent data is available in highly disaggregated forms. General data on air pollution expenditures in the U.S. are available since 1972. However, it is not possible to tell how much of this R&D effort went towards SO_2 pollution control. Furthermore, using patent data allows me to construct a longer time series, as historical patent data is available since 1793.

Nonetheless, when working with patent data, it is important to be aware of its limitations. The existing literature on the benefits and drawbacks of using patent data is quite large.[5] An important concern is that the quality of individual patents varies widely. Some inventions are extremely valuable, whereas others are of almost no commercial value. This is partly a result of the random nature of the inventive process. Accordingly, the results of this paper are best interpreted as the effect of an "average" patent, rather than any specific invention.

Another potential pitfall is that the propensity to patent new inventions may have changed over time. If this is the case, using patents rather than R&D to measure innovative activity misstates the returns to R&D. Historically, the ratio of patents to R&D expenditures has fallen in the United States (as well as in other industrialized nations). Some researchers, most notably Evenson (1991), consider the falling ratio to be evidence of diminishing returns to R&D.[6] The intuition is that, as researchers continue to search for new ideas, it gets harder and harder to find something yet to be discovered. Similarly, Kortum and Lerner (1998) argue that a recent upswing in patenting activity in the United States is due to the increasing fertility of new research opportunities. Other researchers, most notably Griliches (1989), claim that research opportunities have not declined. Griliches argues that the fall in the patent-to-R&D ratio is due to changes in the willingness of inventors to patent new inventions. An exogenous fall in the

[5] Griliches (1990) provides a useful survey.

[6] Here, diminishing returns to research refers to the expected return on the *inputs* to the research process, not the returns to the output. The notion that there are increasing returns to the *output* of knowledge, usually attributed to the public good nature of knowledge, is by no means compromised by claiming that the *inputs* to research experience

willingness to patent – caused, for example by changes in patent laws that affect the benefits of holding a patent – would result in a falling patent-to-R&D ratio even if the productivity of research spending remained the same.

Acknowledging these concerns, a first look at the data suggests that the 1990 CAA had little effect on innovative activity. Figure 1 shows an index of the percentage of successful patent applications related to SO_2 control per year, as well as an index of air pollution R&D expenditures, taken from the U.S Department of Commerce (1994). Only patents granted to U.S. applicants are considered, as these would be the inventors most influenced by changes in American environmental regulations. Application data is available for patents granted since 1975. Patents are sorted by their year of application because several researchers have found that patent applications are highly correlated with levels of R&D expenditures. Thus, the year of the patent application is a good proxy for when the R&D occurred (Griliches 1990). Since a patent application is only made public when a patent is granted, the data have been scaled up to account for patents applied for but not yet granted.[7] I use a percentage of successful applications, rather than a raw count, to adjust for changes in patenting activity due to growth in the economy and changes in the propensity of inventors to file for patent protection.[8] Note that both general air pollution R&D expenditures and SO_2 pollution control patents fall over time. In addition, there is no upswing in innovative activity after passage of the Clean Air Act in 1990.[9]

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diminishing returns. Diminishing returns to research simply implies that it becomes more and more difficult to develop new inventions as time progresses.

[7] To scale the data, I first find the distribution of the lag between application and grant for all patents granted in the U.S. Using this distribution, the percentage of patents remaining to be granted after 1997 was calculated for each application year and added to the data.

[8] That is, if the propensity to patent has fallen because of exogenous changes to patent law, both the numerator and the denominator of the percentage will be equally affected.

[9] One additional concern is that, if there are diminishing returns to R&D, patenting activity could be falling even though inventors perceive other incentives to perform R&D, such as environmental policy, to be greater. To check this, I used regression analysis on policy variables and a time trend to account for diminishing returns. The results showed no significant increase to inventive activity after passage of the Clean Air Act, although the fit of the regressions is poor. Results of these regressions are available from the author on request.

III. Did Pollution Control Innovations Control Pollution?

The patent data presents a puzzle. Although economic theory predicts that market-based environmental policies should induce innovation, there is less innovation on scrubbers after the 1990 CAA. It is possible that there are other mitigating factors that discouraged R&D. For example, permit prices were lower than initially predicted. Early predictions were that permits would sell for $250-$350 per ton during Phase I, and over $500 per ton during Phase II. However, actual prices fell quickly, approaching, and sometimes even falling below, $100 per ton (Joskow *et al*. 1998). Since one of the benefits of developing a more efficient pollution control technology is that it enables plants to sell permits to other plants with less effective technology, decreases in the price of pollution permits would lower the incentive to do R&D.

More importantly, the 1990 CAA allowed utilities more flexibility to control SO_2 emissions. Other researchers have noted that, as a result of falling prices, many utilities shifted to low sulfur coal during the early 1990's.[10] Prices for low-sulfur coal fell dramatically during the late 1980s and early 1990s due to deregulation of railroads, which lowered the shipping costs of low-sulfur coal.[11] Thus, these utilities would be able to meet their emissions reduction targets without needing to invest in new technologies. In contrast, before the 1990 CAA, new utilities were required to install a scrubber with a minimum 90% removal efficiency. Although there was no reward for improving the removal efficiency of the scrubber (that is, the percentage of sulfur dioxide that the scrubber removes from smokestack emissions), there was incentive for innovations that lowered costs of scrubbers, as such innovations lowered the cost of complying with the regulation.

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[10] See, for example, Ellerman *et al.*(1997) or Carlson *et al*. (2000).

In this section, I test the hypothesis that incentives for the *type* of innovation changed after passage of the 1990 CAA. I ask whether the innovations that occurred in scrubber technology had an effect on the removal efficiency of the scrubbers – that is, did the innovations actually help to improve pollution control. I also check to see whether this effect is constant over time, or whether effect of new innovations changed after passage of the 1990 CAA.

Data on the plants included in this section comes from the Steam-Electric Plant Operation and Design Report (FORM EIA-767). This report contains data from an annual survey of all U.S. power plants with a total existing or planned steam-electric generator nameplate rating of at least 10 megawatts (MW). Results of these surveys are available from the Energy Information Administration for the years 1985 to l997. The survey includes comprehensive data on electric power plants, including the fuels burned, their operating and capital expenditures, environmental regulations that they are under, and their pollution control activities. Of particular interest for this paper is data on the flue gas desulfurization unit (FGD unit, or scrubber) used by coal-burning plants.

The data set includes 193 plants that use coal as their primary fuel and have an FGD unit. For each of these units, the data set contains, among other things, the year the scrubber went on line, the removal efficiency of the scrubber, the operating and maintenance costs of the scrubber, and the costs of installing the scrubber. Of these, scrubbers with efficiency ratings less than or equal to 50 percent were removed from the data set, as such scrubbers, which were still being installed as late as 1994, do not represent the latest in technological advances. Also, to insure that the data on pollution control regulations from Form 767 is consistent with the regulations faced by the plants *when the scrubber was installed*, I delete observations for which the current

[11] Most low-sulfur coal comes from the remote areas of the western U.S., and is thus not located near many power plants.

regulations took affect more than three years after the scrubber went online.[12] This leaves 180 FGD units for analysis.

Table 3 lists the variables used in this section and their descriptive statistics.[13] The variables in the last section of the table represent regulations faced by the plants when the scrubber went on-line. Note that each type of regulation is faced by only a subset of the plants, as the regulations may be imposed by federal, state, or local authorities.[14] NSPSD and NSPSDa are dummy variables equal to one if the plant is covered by each of these federal regulatory regimes. CAA90 is a dummy variable equal to one for plants that went on-line in the 1990s. The no policy dummy covers those plants for which construction commenced before August 17, 1971, and are thus not affected by any of these three federal clean air policy regimes.

In addition, Figure 2 plots the average removal efficiency of new scrubbers per year, as well as a three-year moving average. The figure is divided into three policy regimes, corresponding with the 1970 CAA, the 1977 CAA, and the 1990 CAA. Note that the average removal efficiency rises during the NSPSD period before leveling off during NSPSDa. This is the period in which newly constructed coal-fired plants were required to install FGD units with 90% removal efficiency ratings.[15] During the NSPSDa period, there was little incentive to install a scrubber with a removal efficiency rating exceeding 90%. However, the average once again increases after passage of the 1990 CAA. Particularly striking is that the moving average in the NSPSDa era is nearly flat. One the desired removal efficiency is met, there is little incentive for

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[12] I assume that plants that brought scrubbers online within three years of when the regulations took affect could have been anticipating the regulatory changes that took place.
[13] Data on the price of low-sulfur coal is an average of the delivered price of low-sulfur coal per year, taken from the Federal Energy Regulatory Commission's Form 423, *Monthly Cost and Quality of Fuels for Electric Plants*. Prices are in 1982 dollars, and are deflated using the producer price index for electric power.
[14] In the data sample, states imposed 63% of regulations, the federal government imposed 32%, and local governments imposed 5%.

plants to exceed the standard. In contrast, the moving average steadily increases after passage of the 1990 CAA, suggesting that technological innovation plays an important role in this era.

Table 4 provides additional data on the scrubbers installed in each policy regime. The top table shows the number of scrubbers of varying removal efficiencies installed under each policy regime, and the second shows the percentage of scrubbers of varying removal efficiencies installed under each regime. No policy represents scrubbers for which construction commenced before August 17, 1971, and CAA90 represents plants that went online in 1990 or later, and were not subject to either NSPSD or NSPSDa regulations. Note that 44% of FGD units installed under NSPSDa exactly met the 90% removal efficiency standard. Only 17% exceeded the standard. Of the 16 plants that installed scrubbers with removal efficiency ratings below 90%, 14 had SO_2 emission rates less than 0.6 lbs per million Btu heat input, and thus only required to install scrubbers with 70% removal efficiency ratings. Only 2 plants appear to be in violation of the NSPSDa requirements. Converesely, during the CAA90 era, 73% of scrubbers installed achieved removal efficiencies of at least 95%.

My goal is to see how the knowledge embodied in SO_2 pollution control patents affected the removal efficiency of scrubbers. For this, I first construct a stock of pollution control knowledge. I begin with a count of all patents related to SO_2 pollution control from 1900 to 1997. To construct the stock of knowledge, I use a rate of decay, represented by β_1, to capture the obsolescence of older patents. Over time, the knowledge embodied in a patent becomes obsolete, as new and better inventions take its place. In addition, it takes time for the knowledge embodied in a new patent to spread throughout the economy. A new patent represents invention, the first step in technological change. Before it can have an effect on the economy, the new

[15] Because some plants received exceptions for having SO_2 emissions rates below 0.6 lbs/million Btus of heat input, and because construction on some plants going online during this period commenced before the NSPSDa starting

invention represented by a patent must be developed for commercial use. This stage of development is known as innovation. By measuring the effect of knowledge on removal efficiency, I am measuring the results of this commercialization, rather than simply the benefits of discovery of the new invention. Thus, the stock of knowledge also includes a rate of diffusion, β_2, to capture delays in the flow of knowledge. Defining *s* as the number of years before the current year, the stock of knowledge at time *t* is written as:

(1) $$K_t = \sum_{s=0}^{\infty} e^{-\beta_1(s)}(1-e^{-\beta_2(s+1)})PAT_{t-s} \, .$$

The rate of diffusion is multiplied by *s*+1 so that diffusion is not constrained to be zero in the current period. To test whether there is a change in the type of research done after passage of the 1990 CAA, I also create a second knowledge stock that includes only patents granted in or after 1990:

(2) $$K_t^{90} = \sum_{s=0}^{\infty} e^{-\beta_1(s)}(1-e^{-\beta_2(s+1)})PAT_{t-s} * dum90_{t-s} \, ,$$

where *dum90* is a dummy variable equal to one if year t-$s \geq 1990$. Thus, K_t^{90} picks up any *additional* effect that patents granted since 1990 have compared to patents granted prior to 1990.

To illustrate the effect of various rates of decay and diffusion, Figure 3 shows the weight placed on each patent *x* years after its grant date. The decay rate is constant across each row, and the rate of diffusion is constant down each column. Note that patents have a more immediate impact when the rates of decay and diffusion are high. Figure 4 shows the actual stocks over time for various rates of decay and diffusion. Panel A varies the rate of decay, and panel B varies the rate of diffusion.

date, the average is slightly below 90%.

Because in any given year, units going online are affected by different policy regimes, I use regression analysis to control for other factors influencing the decision to install a scrubber with a given removal efficiency rating. I include the stock of knowledge as an explanatory variable in a regression of the removal efficiency of FGD units. In addition, I include dummy variables for the federal SO_2 policy regime affecting the unit,[16] and variables representing any emissions limits in place at the time the unit went on line, such as the maximum rate of SO_2 emissions allowed, and on the price of low sulfur coal.[17] Because the knowledge stock is likely correlated with policies in place at the time the scrubber went online, I use a two-stage estimation strategy. First, for any year *t* in which a scrubber was installed, I regress the knowledge stock on policy and price variables that influence the evolution of technology.[18] These results give me predicted values for the knowledge stocks, K_i^P and K_i^{P90}, for each year from 1972-1997.

I use the predicted values of the knowledge stock in the following regression. Defining *REMEFF* as the removal efficiency of the FGD unit, **POLICY** as a vector of policy variables, **D** is a vector of dummy variable equal to one when a specific policy affects plant *i*, P_{LSC} as the price of low sulfur coal in the year the scrubber went on line, and *d* as a dummy variable equal to one for years greater than or equal to 1990, I estimate the following equation:

(3) $$REMEFF_i = \alpha + \beta K_i^P + \gamma K_i^{P90} + \chi P_{LSC} + \boldsymbol{\eta}\mathbf{POLICY_i}\ \boldsymbol{\varphi}\mathbf{D^{\cdot}POLICYi} + \varepsilon_{i,t}$$

For each observation, I use the predicted value of knowledge for the year in which the scrubber was installed.

[16] The dummy variables represent the four regimes in Table 3, plus an additional dummy for plants covered by NSPSDa that only need to install a scrubber with 70% removal efficiency. The excluded dummy variable in the regressions is CAA90.

[17] Because each type of limit is only in force for a subset of the plants, for each regulation type I also include for dummy variables equal to one when a plant is affected by the regulation.

To estimate the model, I first create a predicted knowledge stock for a given value of β_1 and β_2. Once the knowledge stock has been created, equation (3) is linear in parameters.[19] The results are corrected for autocorrelation.[20]

Table 5 presents results of the regression for a decay rate of 0.1 and a rate of diffusion of 0.25.[21] As expected, variables affecting low sulfur coal, which can serve as a substitute for scrubbing, have positive effects. More efficient scrubbers are installed when the price of low sulfur coal is high, or when the design specifications of the scrubber call for greater sulfur content in the coal. Plants facing regulations on the sulfur content of coal also install more efficient scrubbers.[22] In addition, the presence of additional SO_2 emissions limits leads to the installation of more efficient scrubbers, but efficiency does not increase as the magnitude of the regulation increases. Similarly, minimum efficiency standards for scrubbers also lead to less efficient removal efficiencies, suggesting that these regulations do not keep up with changing technology – even though more efficient scrubbers are available, utilities choose not to install

[18] I regress the knowledge stock on a constant, two dummy variables stating whether NSPSD or NSPSDa are in effect, the real price of low sulfur coal, current and lagged prices of SO_2 permits, and a time trend. For the post-90 knowledge stock, the NSPSD and NSPSDa dummy variables are omitted.

[19] It is possible to estimate the rates of decay and diffusion by performing this estimation for a range of β_1 and β_2 and minimizing a generalized method of moments (GMM) criterion. For this example, the optimal decay rate is 0.49, and the optimal rate of diffusion is 0.32. Unfortunately, this estimation strategy suffers from two drawbacks. First, the minimization assumes that the effect of knowledge is accurately captured by changes in removal efficiency, rather than by other variables. As the following results show, this is not the case. Second, the resulting standard errors are unreliable. Computing the standard errors from the GMM estimation requires a derivative of the error term with respect to each of the parameters of the model. If β_1 and β_2 are treated as endogenous parameters to be estimated, the matrix needed to compute the covariance matrix is highly collinear and cannot be inverted. As a result, the standard errors presented in the paper do not account for the randomness of the rates of decay and diffusion, and thus should be treated as upper bounds.

[20] Correcting for autocorrelation should help to address changes that occur in the propensity to patent over time. For example, if the falling patent-R&D ratio is due to a decrease in the propensity to patent, newer patents should be more valuable, as they represent more R&D effort. Thus, the error associated with knowledge should increase over time. In fact, the results suggest that this is not a concern, as the Durbin-Watson statistic for the regression is 1.90.

[21] These rates are consistent with others used in the R&D literature. For example, discussing the literature on an appropriate lag structure for R&D capital, Griliches (1995) notes that previous studies suggest a structure peaking between three and five years. The rates of decay and diffusion used in this paper provide a lag peaking after four years.

[22] To evaluate the effects of the policy variables, it is necessary to look at both the dummy variables and slope coefficients. I evaluate the slope coefficients at the mean levels for the variables.

more efficient scrubbers because such scrubbers are not necessary to comply with the regulations they face. Also, note that each of the pre-CAA90 policy regimes led to the installation of less efficient scrubbers. For example, controlling for other factors, scrubbers installed by plants under NSPSDa were 2.8% less efficient than scrubbers installed in the CAA90 era, and plants that only faced the 70% removal efficiency requirement installed scrubbers that were an additional 1.8% less efficient. In each case, the effect is statistically significant.

My particular interest is to observe the effect of the knowledge stock on removal efficiency. As expected, before the CAA90 policy era, knowledge had no effect on removal efficiency. The coefficient is just 0.001, and is statistically insignificant. However, patents granted in or after 1990 do have a significant effect on removal efficiency. Also, as Table 6 shows, this result does not change much as the rates of decay and diffusion are allowed to vary. For any given decay rate, higher rates of diffusion lower the magnitudes of the coefficients. For any given rate of diffusion, the coefficients, as well as the impact of each patent, increase as the decay rate increases. However, as we will see below, the magnitude of the effect depends not just on the coefficients on knowledge, but also on the rates of decay and diffusion assumed.

To more clearly illustrate the magnitude of the effect of new knowledge, Table 7 shows the effect of a new patent on removal efficiency, using the ten percent decay rate and 25 percent rate of diffusion. The marginal effect of a new patent is simply the knowledge coefficient from equation (3), multiplied by the appropriate rate of decay and diffusion. The table shows the impact of a patent four years after it is granted, since, for the rates of decay and diffusion used, that is the year in which a patent has its maximum impact. The table is divided into three periods, representing the three Clean Air Acts.[23] As noted before, a new patent granted from the two command and control eras has almost no effect on removal efficiency, increasing it by just 0.0003% after four years. However, the effect of patents granted in the 1990s is significant. A new patent from the SO_2 permit trading era increases removal efficiency by 0.024% after four years. To understand the full magnitude of the knowledge created in each era, the last column of Table 7 multiplies the gain per patent by the average number of patents granted per year in each era. During the CCAA90 regime, the knowledge created each year increased removal efficiency by 1.58%.

Although choosing rates of decay and diffusion so that the value of a patent peaks after four years is consistent with other findings in the R&D literature, a potential concern is that such rates are inappropriate here. Since there were little policy incentives to install higher efficiency scrubbers during the NSPSD and NSPSDa eras, it is possible that the inventions completed during that time would have increased removal efficiency, but simply weren't installed because they weren't needed – that is, these new innovations simply hadn't diffused yet. To check this, Table 8 repeats the results of Table 7 for a decay rate of 0.05 and a rate of diffusion of 0.01. By using slower rates of decay and diffusion, a new patent would have its greatest impact 17 years after its initial grant. Thus, patents from the late 1970s, when scrubber patenting activity peaked, would have a maximum effect in the mid 1990s, when permit trading began. Even when the knowledge stock weights are changed so that patents from the 1970s have their greatest impact in the 1990s, these patents have almost no effect on removal efficiency. In addition, the patents from the 1990s still do have a significant effect, even though, using the lower rates of decay and diffusion, they have not yet had the chance to diffuse completely.

[23] Because the patent data is sorted by year of grant, and it takes, on average, two years for a patent application to be granted, the starting date for patents from each era is two years after passage of the respective Clean Air Act, so that

Finally, Table 9 shows how the value of a post-1990 patent varies as the rates of decay and diffusion vary. To allow for variations in the diffusion of knowledge, panel A presents efficiency gains one year after a patent is granted, and panel B presents efficiency gains that occur four years after the patent is granted.[24] Although the estimated coefficients fall as diffusion rates increase, the increases in removal efficiency, while still small, are higher with larger rates of diffusion, as the knowledge embodied in each patent is transmitted more quickly.

IV. Did Pollution Control Innovations Lower Costs?

Although regulations requiring the installation of scrubbers do not provide incentives to increase the *removal efficiency* of scrubbers, they do provide incentives for innovation that lowers costs. By lowering the cost of utilizing the best available control technology, such innovation would lower the cost of compliance with BACT regulations without adversely affecting future regulatory burdens placed on the firm.

To test the hypothesis that scrubber innovations before 1990 lowered the costs of operating scrubbers, I once again use data from the Steam-Electric Plant Operation and Design Report (FORM EIA-767). In addition to the variables used in the previous section, this report contains detailed information on the operating costs of FGD units, as well as characteristics of the units that may affect the costs of operation.[25] Table 10 presents the variables chosen for analysis in this section, along with descriptive statistics.[26]

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it includes patents induced by changes in the relevant regulations.

[24] This table only presents results for the pre-1990 era. Changing the assumed rates affects the *level* of the effect, but does not change the relative results between eras.

[25] Operating and maintenance costs are in 1982 dollars, and deflated using the producer price index for electric utilities.

[26] The choice of variables concerning scrubber characteristics follows Bellas (1998).

Constructing the stocks of knowledge in the same way as in section IV, I regress the real operating and maintenance (O&M) costs of scrubber units on characteristics of the scrubbers.[27] Because knowledge will be correlated with the various characteristics of the scrubbers, I once again use an instrumental variables approach, regressing the knowledge stock on policy and price variables that influence the evolution of technology.[28] These results give me predicted values for the knowledge stock for each year from 1972-1997, which I use as an independent variable in the O&M cost regressions. Proceeding as before, I first present results using a decay rate (β_1) of 0.1, and a rate of diffusion (β_2) equal to 0.25.[29]

Define $OM_{i,t}$ as the operating and maintenance cost of scrubber i in year t, K_i^P as the predicted knowledge in the year that the scrubber was installed, d as a dummy variable equal to one if the scrubber was installed since 1990, $\mathbf{Z_i}$ as a vector of scrubber characteristics that do not vary across time, such as plant location, and $X_{i,t}$ as a vector of scrubber characteristics that do vary over time. The model estimated is:

(4) $$OM_{i.t} = \alpha + \beta K_i^P + \gamma K_i^{P90} + \boldsymbol{\chi}\mathbf{Z_i} + \boldsymbol{\eta}\mathbf{X_{i,t}} + w_{i,t}$$

Because the key variables of interest do not vary over time, I use a random effects specification of the error term, so that $w_{i,t} = \varepsilon_{i,t} + u_i$.

Table 11 presents the regression results. Note that the knowledge stock has a significant negative effect on operating costs in all eras, and the effect is somewhat larger during the 1990s.

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27 Similar results are obtained using the capital cost of scrubbers, except that the magnitude of the savings before CAA90 is smaller, suggesting that plants were willing to accept larger upfront capital costs in exchange for lower O&M costs. However, the capital expenditure data is not available for every unit, and is less reliable due to reporting differences across plants. Thus, I only report the results for O&M costs in the paper.

28 I regress the knowledge stock on a constant, two dummy variables stating whether NSPSD or NSPSDa are in effect, the real price of low sulfur coal, current and lagged prices of SO_2 permits, and a time trend.

29 Autocorrelation does not appear to be a problem, as the Durbin-Watson statistic is 1.9.

The signs of other variables are as expected.[30] Table 12 presents sensitivity analysis of the knowledge coefficients to the rates of decay and diffusion. For any given decay rate, the coefficients fall as diffusion increases, and for any given rate of diffusion, the coefficients rise as the decay rate rises. Also, for low decay rates, knowledge has less impact on operating costs after passage of the 1990 Clean Air Act.

Table 13 presents the average operating cost savings resulting from a new pre-1990 patent. As before, panel A presents savings after one year, and panel B presents savings after four years. For the ten percent decay rate and 25 percent diffusion rate, the average patent saves a firm $4,077 after four years. This figure rises to $6,445 for patents granted in the 1990s. For comparison, average O&M costs throughout the sample period are $3.05 million per year. In general, the savings occurring after one year increase as the rate of diffusion increases. However, for the highest rates of diffusion, the impact of knowledge is almost immediate, so the highest savings after four years are for patents with mid-range rates of decay and diffusion.

To put these numbers into perspective, it is interesting to consider the social value of a new patent, in terms of O&M cost savings. If we assume a 30 year lifespan for a new FGD unit and a 7% discount rate, the present value of cost savings from a new pre-1990 patent over the life of the unit is $34,883. There are 174 firms included in the regression sample. If each firm, on average, experiences these savings, the present value of total savings for the industry are $6.07 million. For comparison, about $1.5 million of R&D are spent for each patent granted in

[30] I interact the age of the unit and the percent of time the FGD is in service because I assume these two variables are related, as older units are more likely to break down. Without this interaction, the effect of age on operating costs is positive, which would imply that individual units become cheaper to run as they age.

the United States.[31] Thus, as would be expected, given the positive externalities that result from research and development, the social returns to these patents are quite high.

V. Conclusions

This paper began with a puzzle: despite theoretical evidence that market-based environmental policies should increase innovation, the number of patents related to sulfur dioxide pollution control fell after passage of the 1990 Clean Air Act, which instituted a market for tradable SO_2 permits. By combining data on flue gas desulfurization units with this patent data, I find that, although the level of innovative activity fell after passage of the 1990 Clean Air Act, the nature of innovative activity changed. Prior to 1990, most new plants were required to install a scrubber with a 90% removal efficiency rating. As a result, there were no incentives for R&D that would increase the ability of scrubbers to control pollution. However, there were incentives to perform R&D to lower the costs of operating these scrubbers, and thus lower the costs of complying with the regulation. In contrast, the SO_2 permit market established by the 1990 Clean Air Act provided incentives to install scrubbers with higher removal efficiencies, and thus led to more R&D designed to improve the removal efficiency of scrubbers.

Analysis of the results suggests a couple of key points. First, it is important to note that command and control regulations do provide incentives for R&D. However, the nature of the R&D changes. In particular, the research preformed under the command and control regime did not result in a cleaner environment, but just in lower compliance costs for utilities. Although these lower costs are clearly valuable, unless the cost savings are passed on to consumers in the

[31] This figure represents $121,015 million of R&D spending from non-government sources in 1996, divided by 79,276 patents granted to U.S. non-government entities in 1998. The two-year lag allows time for the patents from the R&D to go through the patenting process.

form of lower rates for electricity, these are rents captured by the firms.[32] In comparison, the benefits of cleaner air resulting from more efficient scrubbers affect society as a whole. Second, the results raise the question of whether the resources devoted to such R&D could have been put to more productive uses. That is, do command and control policies not only not encourage productive R&D, but also lead to wasteful R&D spending to avoid the costs of regulation? Finally, the results show that trends in patent or R&D data are not sufficient to monitor micro-level trends in innovative activity. Information on the uses of new innovations is also important. In particular, although the level of innovative activity related to scrubbers did not increase after passage of the 1990 Clean Air Act, the types of innovative activity did change, so that innovation after institution of market-based policies was more beneficial to the environment.

[32] Whether the rents are captured by the utilities themselves or the firms that produce the scrubbers depends on how much market power the producers of new scrubbers have.

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Figure 1 – Air Pollution R&D Expenditures and SO_2 patents

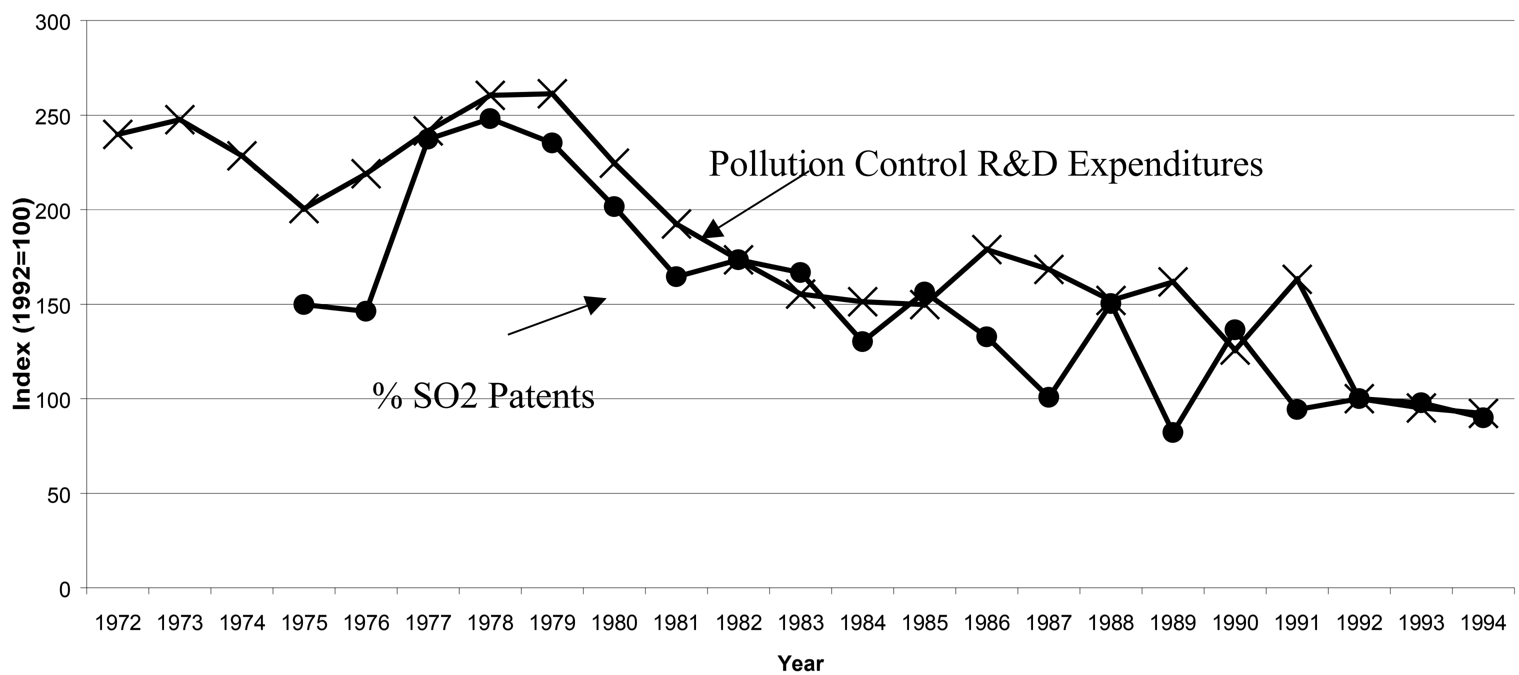
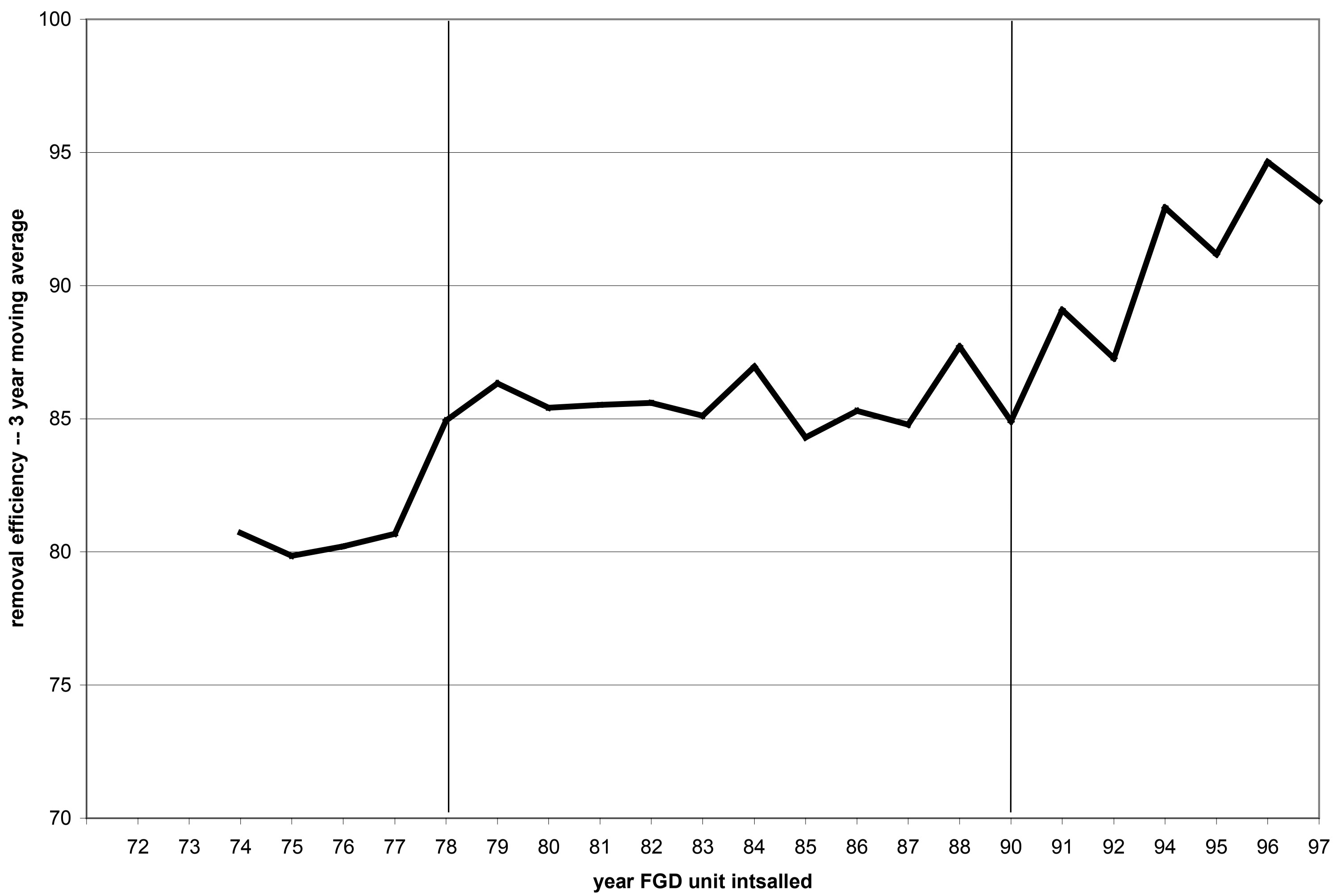
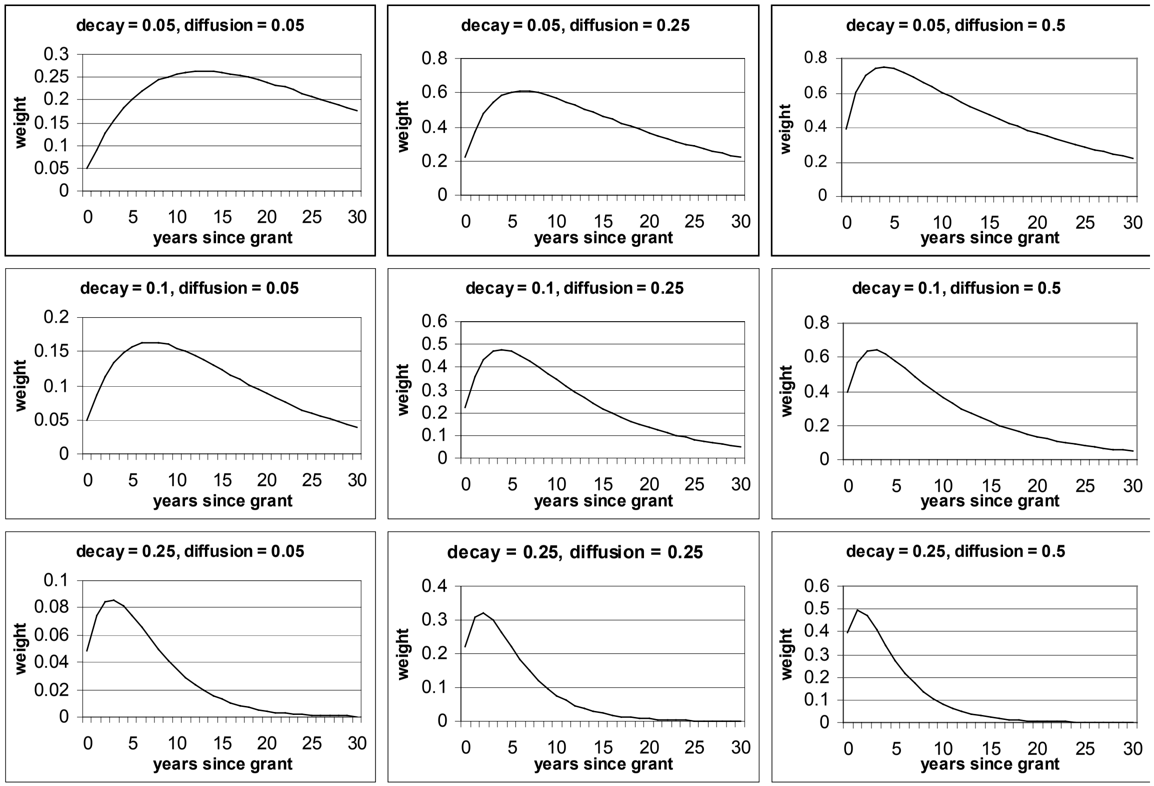


Figure 2 – FGD Removal Efficiencies by Year



The figure shows the average removal efficiency for newly installed FGD units, presented as a three year moving average. The vertical lines delimitate the three policy eras – NSPSD, NSPSDa, and the 1990 CAA.

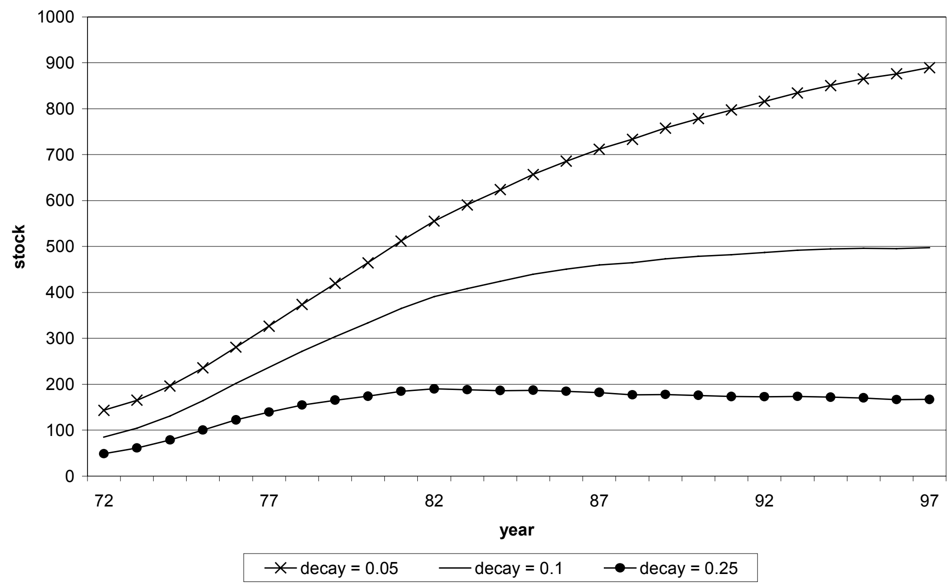
Figure 3 – Patent Weights x Years After Grant



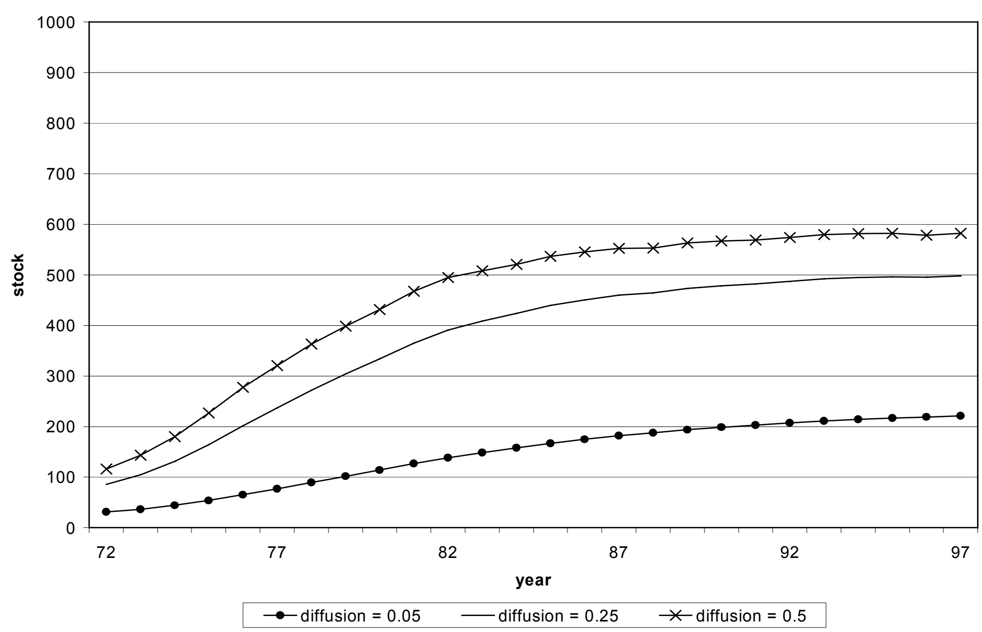
The Figure shows how the weights assigned to a patent vary as time passes. The x axis measures years since the patent was granted. The weights are calculated as $e^{-\beta_1 s}(1-e^{-\beta_2(s+1)})$, where s is the number of years since the patent was granted.

Figure 4 – Knowledge Stocks

Panel A – Decay Rate Varies



Panel B – Rate of Diffusion Varies



The Figure shows how the actual knowledge stocks vary as the rates of decay and diffusion change. For Panel A, the rate of diffusion is constant at 0.25. For Panel B, the rate of decay is constant at 0.1.

Table 1 -- Summary of Key Environmental Regulations

Regulation	Plants Affected	Key Requirements
New Source Performance Standards Subpart D (NSPSD)	Construction began after August 17, 1971	Best Available Control Technology (BACT)
New Source Performance Standards Subpart Da (NSPSDa)	Construction began after September 18, 1978	Scrubber with 90% removal efficiency
1990 Clean Air Act	Phase I (1995): 263 dirtiest plants; Phase II (2000):most existing and new coal-burning plants	SO_2 permit trading; 90% scrub requirement repealed for all plants

Table 2 -- Patent Classifications Related to Sulfur Dioxide Pollution Control

423/242-244	Chemistry of Inorganic Compounds/Modifying or Removing Component of Normally Gaseous Mixture/Sulfur or sulfur containing component
423/569-570	Chemistry of Inorganic Compounds/Sulfur or Compound Thereof/Elemental sulfur/Reducing sulfur dioxide by carbon containing material

Table 3 – Descriptive Statistics for Removal Efficiency Regression

Variable	N	Mean	Std Dev	Min	Max	N > 0
Year	180	87.10	3.82	85	97	180
Year FGD unit went online	180	83.77	5.99	73	97	180
Real price of low sulfur coal	180	152.50	26.39	97.98	189.76	180
Removal efficiency of FGD unit	180	86.73	8.47	58.8	99	180
Regulations:						
SO2 emissions limits (lbs. SO_2/mm Btu fuel)*	180	1.33	1.47	0.01	7.41	168
Minimum removal efficiency required*	180	81.68	29.90	70	94	28
% sulfur content of coal allowed*	180	1.9	1.25	1.0	3.5	5
Design specifications for sulfur content of coal	180	2.74	1.94	0	9	179
Federal Clean Air policy:						
no policy	180	0.18	0.39	0	1	33
NSPSD	180	0.44	0.50	0	1	80
NSPSDA	180	0.23	0.42	0	1	41
CAA90	180	0.14	0.35	0	1	26

* -- averages of these variables are for positive observations only

Table 4 – Distribution of Removal Efficiencies by Regulatory Regime

Panel A: Frequency of removal efficiency by policy regime

	regime				
removal efficiency	no policy	NSPSD	NSPSDa	CAA90	Total
< 70	0	7	0	0	7
70	4	1	3	0	8
71-79	2	5	1	0	8
80-89	14	31	12	1	58
90	2	23	18	3	46
91-95	9	7	0	3	19
95+	2	6	7	19	34
Total	33	80	41	26	180

Panel B: Percentage of scrubbers with each removal efficiency by regime

	regime				
removal efficiency	no policy	NSPSD	NSPSDa	CAA90	Total
<70	0.0%	8.8%	0.0%	0.0%	3.9%
70	12.1%	1.3%	7.3%	0.0%	4.4%
71-79	6.1%	6.3%	2.4%	0.0%	4.4%
80-89	42.4%	38.8%	29.3%	3.9%	32.2%
90	6.1%	28.8%	43.9%	11.5%	25.6%
91-95	27.3%	8.8%	0.0%	11.5%	10.6%
95+	6.1%	7.5%	17.1%	73.1%	18.9%
Total	100%	100%	100%	100%	100%

Table 5 –The Effect of Technology on the Removal Efficiency of Scrubbers

Dependent Variable: SO_2 removal efficiency of new FGD units 1972-1997

Variable	**Estimate**	**T-statistics**
Constant	79.342	87.749
Knowledge stock	0.001	0.730
Knowledge stock * $dummy_{CAA90}$	0.049	34.038
Real price of low sulfur coal	0.059	14.084
FGD design specifications for sulfur content of coal	0.448	15.397
SO_2 emissions limit dummy	0.680	3.404
SO_2 emissions limit	-0.107	-4.094
Minimum efficiency requirement dummy	-40.099	-50.452
Minimum efficiency requirement	0.4850	51.618
% sulfur content regulations dummy	10.8458	41.479
% sulfur content regulations	-3.689	-50.770
NOPOLICY dummy	-6.157	-26.646
NSPSD dummy	-6.407	-31.555
NSPSDa dummy	-2.792	-18.989
NSPSDa with 70% requirement dummy	-1.774	-11.414
gamma	0.100	
lambda	0.250	

Table 6 –Sensitivity Analysis of Removal Efficiency Regression Results

Dependent Variable: SO_2 removal efficiency of new FGD units 1972-1997

Rate of decay		Rate of diffusion: 0.01	0.05	0.15	0.25	0.5	0.75	0.9
0.01	K	0.011	0.003	0.001	0.001	0.001	0.001	0.001
		(3.165)	(2.821)	(2.179)	(1.855)	(1.559)	(1.481)	(1.464)
	K^{90}	0.467	0.106	0.046	0.034	0.026	0.024	0.023
		(24.467)	(26.872)	(30.367)	(31.473)	(31.936)	(31.834)	(31.738)
0.05	K	0.015	0.003	0.001	0.001	0.001	0.001	0.001
		(2.364)	(2.026)	(1.516)	(1.265)	(1.040)	(0.988)	(0.978)
	K^{90}	0.582	0.130	0.055	0.041	0.031	0.028	0.027
		(30.098)	(31.818)	(33.332)	(33.640)	(33.568)	(33.309)	(33.157)
0.1	K	0.015	0.003	0.001	0.001	0.001	0.000	0.000
		(1.511)	(1.277)	(0.916)	(0.730)	(0.560)	(0.526)	(0.523)
	K^{90}	0.735	0.163	0.068	0.049	0.037	0.033	0.031
		(33.586)	(33.932)	(34.098)	(34.038)	(33.692)	(33.311)	(33.107)
0.15	K	0.014	0.003	0.001	0.001	0.000	0.000	0.000
		(0.917)	(0.747)	(0.473)	(0.326)	(0.193)	(0.177)	(0.182)
	K^{90}	0.901	0.198	0.082	0.059	0.043	0.038	0.036
		(34.130)	(34.114)	(33.993)	(33.826)	(33.312)	(32.819)	(32.565)
0.2	K	0.011	0.002	0.000	0.000	0.000	0.000	0.000
		(0.479)	(0.347)	(0.130)	(0.012)	(-0.085)	(-0.078)	(-0.059)
	K^{90}	1.086	0.237	0.097	0.069	0.049	0.043	0.041
		(34.017)	(33.942)	(33.731)	(33.477)	(32.781)	(32.166)	(31.860)
0.25	K	0.004	0.000	-0.001	-0.001	-0.001	-0.001	0.000
		(0.138)	(0.034)	(-0.139)	(-0.230)	(-0.282)	(-0.240)	(-0.203)
	K^{90}	1.291	0.281	0.113	0.080	0.056	0.049	0.046
		(33.791)	(33.682)	(33.366)	(33.007)	(32.114)	(31.375)	(31.014)
0.3	K	-0.006	-0.002	-0.002	-0.001	-0.001	-0.001	-0.001
		(-0.131)	(-0.213)	(-0.344)	(-0.405)	(-0.400)	(-0.311)	(-0.248)
	K^{90}	1.517	0.328	0.131	0.092	0.064	0.054	0.051
		(33.467)	(33.307)	(32.861)	(32.390)	(31.304)	(30.444)	(30.030)
0.5	K	-0.081	-0.018	-0.007	-0.004	0.000	0.003	0.004
		(-0.608)	(-0.600)	(-0.532)	(-0.419)	(-0.033)	(0.392)	(0.637)
	K^{90}	2.570	0.547	0.210	0.142	0.092	0.074	0.069
		(30.727)	(30.361)	(29.485)	(28.680)	(26.994)	(25.702)	(25.075)

T-statistics in parenthesis

Table 7 – Effect of New Patents on Removal Efficiency – By Era

Era	Effect of a New Patent*	Ave Pats/Yr	Total Effect
1972-1978	0.0003	74.9	0.03
1979-1991	0.0003	71.0	0.02
1992-1997	0.0240	66.0	1.58

* -- The effect of a new patent is the increase in removal efficiency generated by a new SO2 pollution control patent. To allow for diffusion of the innovation, this effect is calculated four years after the grant of the patent.

Table 8 – Effect of New Patents on Removal Efficiency With Slow Diffusion – By Era

Era	Effect of a New Patent*	Ave Pats/Yr	Total Effect
1972-1978	0.0011	74.9	0.08
1979-1991	0.0011	71.0	0.08
1992-1997	0.0420	66.0	2.77

* -- The effect of a new patent is the increase in removal efficiency generated by a new SO2 pollution control patent. To allow for diffusion of the innovation, this effect is calculated seventeen years after the grant of the patent.

Table 9 – Effect of New Patents on Removal Efficiency – Sensitivity Analysis

Panel A: Savings after one year:

decay rate	Rate of diffusion 0.01	0.05	0.15	0.25	0.5	0.75	0.9
0.01	0.0094%	0.0102%	0.0121%	0.0137%	0.0168%	0.0189%	0.0197%
0.05	0.0112%	0.0121%	0.0140%	0.0156%	0.0188%	0.0209%	0.0217%
0.1	0.0134%	0.0143%	0.0162%	0.0179%	0.0211%	0.0232%	0.0241%
0.15	0.0156%	0.0164%	0.0184%	0.0201%	0.0234%	0.0254%	0.0262%
0.2	0.0178%	0.0186%	0.0206%	0.0223%	0.0255%	0.0274%	0.0281%
0.25	0.0200%	0.0208%	0.0228%	0.0244%	0.0274%	0.0291%	0.0297%
0.3	0.0222%	0.0230%	0.0249%	0.0264%	0.0292%	0.0307%	0.0312%
0.5	0.0299%	0.0305%	0.0319%	0.0330%	0.0350%	0.0363%	0.0369%

Panel B: Savings after four years:

decay rate	Rate of diffusion 0.01	0.05	0.15	0.25	0.5	0.75	0.9
0.01	0.0224%	0.0231%	0.0239%	0.0241%	0.0237%	0.0230%	0.0226%
0.05	0.0238%	0.0242%	0.0245%	0.0243%	0.0235%	0.0226%	0.0222%
0.1	0.0245%	0.0246%	0.0244%	0.0240%	0.0227%	0.0216%	0.0211%
0.15	0.0245%	0.0244%	0.0238%	0.0232%	0.0216%	0.0203%	0.0198%
0.2	0.0240%	0.0238%	0.0230%	0.0222%	0.0203%	0.0189%	0.0182%
0.25	0.0232%	0.0229%	0.0219%	0.0209%	0.0188%	0.0173%	0.0166%
0.3	0.0222%	0.0217%	0.0206%	0.0195%	0.0172%	0.0157%	0.0150%
0.5	0.0164%	0.0158%	0.0145%	0.0133%	0.0113%	0.0102%	0.0098%

Table 10 – Descriptive Statistics for O&M Cost Regression

Variable	Mean	Std Dev	Min	Max
Year scrubber went online	81.76	4.52	72	97
Percent of time boiler was online & FGD unit was in service	0.95	0.16	0	1
Age of FGD unit	9.56	5.14	0	25
Dummy = 1 if unit produces saleable by-product	0.20	0.40	0	1
Number of hours the FGD unit in service	6953.12	1621.02	0	8784
Percent of flue gasses that pass through the unit	92.57	15.57	0	100
Flue gas exit rate (cu. Ft./min)	1604356.27	843824.90	13447	4900000
Removal efficiency of the FGD unit	84.91	8.99	50.70	99.9
Total coal burned in the associated boiler(s) (1000 short tons)	14572.99	9782.79	0	49752
Dummy = 1 if unit is in the Northeast	0.08	0.26	0	1
Dummy = 1 if unit is in the West	0.32	0.47	0	1
Real operating and maintenance costs	3049.73	3440.34	0	36371.1

Table 11 –The Effect of Technology on the Costs of Scrubbers

Dependent Variable: operating and maintenance costs of FGD units 1972-1997

Variable	Estimate	T-statistic
Constant	-4,876.363	-4.394
Knowledge stock	-8.523	-7.687
Knowledge stock * $dummy_{CAA90}$	-4.952	-2.118
Percent of time boiler was online & FGD unit was in service	2,975.965	3.597
Age of FGD unit	59.578	0.853
Age * % time online	-135.875	-1.893
Dummy = 1 if unit produces saleable by-product	-533.830	-2.761
Number of hours the FGD unit in service	0.093	1.565
Percent of flue gasses that pass through the unit	4.390	0.904
Flue gas exit rate (cu. Ft./min)	0.001	10.661
Removal efficiency of the FGD unit	65.715	7.453
Total coal burned in the associated boiler(s) (1000 short tons)	0.007	0.604
Dummy = 1 if unit is in the northeast	4,997.768	16.494
Dummy = 1 if unit is in the west	-1,829.680	-10.142
gamma	0.100	
lambda	0.250	

Table 12 –Sensitivity Analysis of Cost of Scrubber Regression Results

Dependent Variable: operating and maintenance costs of FGD units 1972-1997

Rate of diffusion

Rate of decay		0.01	0.05	0.15	0.25	0.5	0.75	0.9
0.01	K	-18.567	-5.473	-3.383	-3.089	-2.988	-2.993	-3.001
		(-5.930)	(-6.128)	(-6.620)	(-6.914)	(-7.206)	(-7.301)	(-7.331)
	K^{90}	56.566	10.676	3.011	1.679	1.005	0.920	0.915
0.05	K	-39.702	-10.517	-5.965	-5.227	-4.816	-4.732	-4.713
		(-6.449)	(-6.737)	(-7.217)	(-7.437)	(-7.579)	(-7.596)	(-7.596)
	K^{90}	38.863	5.371	-0.053	-0.899	-1.182	-1.132	-1.095
		(0.935)	(0.627)	(-0.017)	(-0.410)	(-0.778)	(-0.855)	(-0.865)
0.1	K	-77.268	-19.526	-10.234	-8.524	-7.385	-7.077	-6.991
		(-7.217)	(-7.427)	(-7.659)	(-7.687)	(-7.593)	(-7.511)	(-7.477)
	K^{90}	-7.959	-6.050	-5.393	-4.952	-4.244	-3.876	-3.738
		(-0.188)	(-0.687)	(-1.602)	(-2.118)	(-2.613)	(-2.748)	(-2.780)
0.15	K	-132.510	-32.145	-15.632	-12.433	-10.177	-9.519	-9.324
		(-7.667)	(-7.718)	(-7.668)	(-7.543)	(-7.280)	(-7.126)	(-7.066)
	K^{90}	-76.848	-21.406	-11.625	-9.313	-7.228	-6.434	-6.162
0.2	K	-203.603	-47.656	-21.764	-16.652	-12.965	-11.847	-11.504
		(-7.693)	(-7.622)	(-7.395)	(-7.180)	(-6.808)	(-6.601)	(-6.519)
	K^{90}	-158.101	-38.482	-17.931	-13.481	-9.862	-8.595	-8.176
		(-3.156)	(-3.581)	(-4.219)	(-4.520)	(-4.769)	(-4.821)	(-4.829)
0.25	K	-285.380	-64.930	-28.214	-20.919	-15.597	-13.942	-13.422
		(-7.438)	(-7.302)	(-6.979)	(-6.713)	(-6.275)	(-6.031)	(-5.933)
	K^{90}	-241.613	-55.427	-23.829	-17.229	-12.081	-10.344	-9.776
		(-4.223)	(-4.499)	(-4.882)	(-5.041)	(-5.135)	(-5.128)	(-5.116)
0.3	K	-372.496	-82.941	-34.682	-25.073	-18.009	-15.764	-15.047
		(-7.036)	(-6.868)	(-6.500)	(-6.211)	(-5.739)	(-5.468)	(-5.359)
	K^{90}	-321.002	-71.225	-29.144	-20.522	-13.936	-11.749	-11.037
		(-4.878)	(-5.028)	(-5.212)	(-5.266)	(-5.246)	(-5.191)	(-5.162)
0.5	K	-711.668	-151.244	-57.773	-39.033	-24.904	-20.153	-18.568
		(-5.156)	(-4.992)	(-4.645)	(-4.369)	(-3.885)	(-3.579)	(-3.446)
	K^{90}	-572.203	-120.745	-45.413	-30.318	-19.013	-15.295	-14.082
		(-5.267)	(-5.226)	(-5.118)	(-5.015)	(-4.804)	(-4.655)	(-4.588)

Table 13 – Effect of New Patents on Scrubber Costs – Sensitivity Analysis

Panel A: Savings after one year:

	Rate of diffusion						
	0.01	0.05	0.15	0.25	0.5	0.75	0.9
0.01	364	516	868	1,203	1,870	2,302	2,480
0.05	748	952	1,471	1,956	2,896	3,497	3,742
0.1	1,384	1,681	2,400	3,035	4,224	4,975	5,280
0.15	2,258	2,633	3,487	4,210	5,537	6,365	6,698
0.2	3,301	3,713	4,618	5,365	6,710	7,535	7,862
0.25	4,401	4,812	5,695	6,410	7,678	8,435	8,725
0.3	5,464	5,847	6,659	7,309	8,433	9,073	9,304
0.5	8,547	8,730	9,082	9,315	9,548	9,496	9,401

Panel B: Savings after four years:

decay rate	*Rate of diffusion*						
	0.01	0.05	0.15	0.25	0.5	0.75	0.9
0.01	870	1,163	1,715	2,117	2,635	2,808	2,851
0.05	1,585	1,905	2,577	3,053	3,619	3,783	3,816
0.1	2,526	2,895	3,619	4,077	4,544	4,633	4,634
0.15	3,547	3,902	4,527	4,868	5,127	5,102	5,060
0.2	4,462	4,737	5,160	5,339	5,347	5,198	5,112
0.25	5,120	5,284	5,477	5,491	5,267	5,008	4,883
0.3	5,472	5,526	5,512	5,388	4,979	4,636	4,482
0.5	4,697	4,528	4,125	3,769	3,094	2,663	2,485