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Knowledge versus technique in SO2-saving technological change:
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Abstract

Greenhouse gas emission limits are a major source of technical and policy uncertainty for electric power industry professionals. This paper tries to reduce some of this uncertainty by investigating the main forces that were responsible for the productivity gains made by the electric power sector with respect to SO2 emissions under the US SO2 cap and trade program. The SO2 cap and trade experience has important parallels with the GHG pollution problem, in both policy design and technical response. Linear and quantile regression are used to compare the effect of new technical knowledge (R&D) on SO2 productivity, against the effect of pre-existing techniques that did not involve very much new knowledge creation. Compliance techniques that involved little new technical knowledge and which were incremental and pragmatic played the most important role in SO2-saving technological change. Implications of this finding for electric power plants' technical response to GHG pollution limits are elaborated.

Key words

Technological change, knowledge, environmental productivity

Research highlights

- Greenhouse gas compliance is a major source of uncertainty for electric power sector professionals
- Lessons from the technological change experience with SO2 emissions can reduce this uncertainty
- Quantile regression tests for the most important plant-level SO2 compliance methods
- Pragmatic techniques involving little new technical knowledge played a larger role than pure knowledge acquired through R&D

Outline

Tables

Figures

1. Introduction

How to comply with present and future greenhouse gas (GHG) emission limits is a source of considerable uncertainty for electric power industry professionals. It is very difficult to predict from today's vantage point which techniques and technologies will be viable and economical in a GHG-constrained industry. Technological uncertainty is compounded by policy uncertainty since the way that policymakers go about regulating GHG pollution will strongly influence plant-level capital investment and planning decisions.

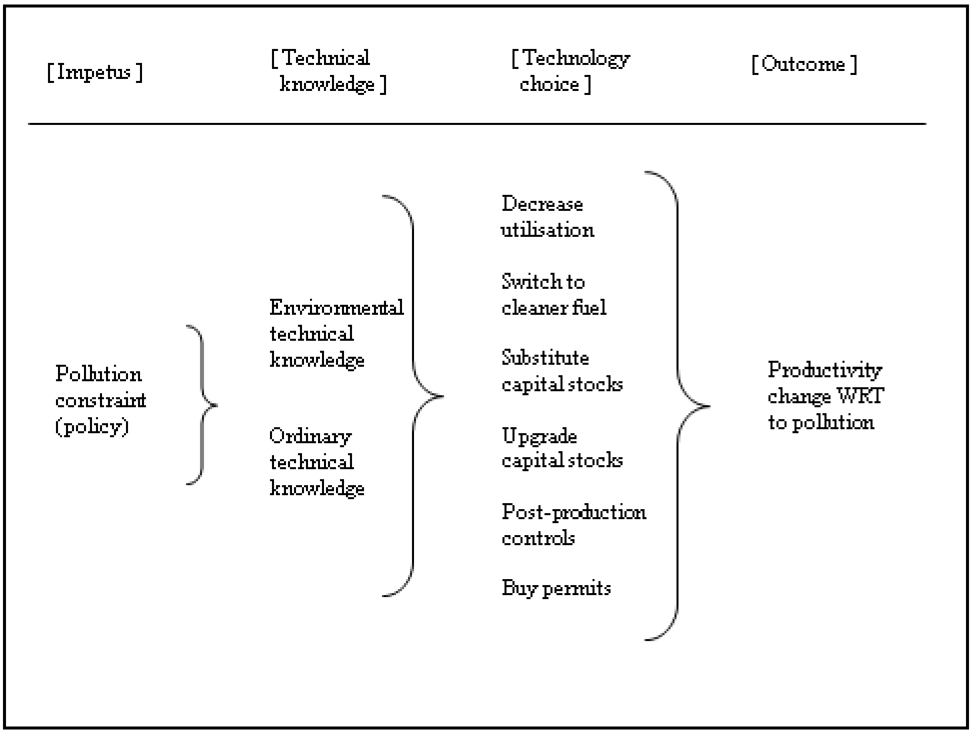
This paper tries to roll back some of this uncertainty by analysing which technological change channels played the most important role in the environmental productivity improvements that occurred under the US SO2 cap and trade program, a policy context that is argued to have important parallels with GHG pollution. The paper uses linear and quantile regression to compare the effect of pure technical knowledge acquired through utility level R&D on this outcome, relative to the effect of range of compliance techniques and technologies involving various amounts of new technical knowledge. Careful examination of this historical case is one of the least-bad historical guides electric power industry professionals, technological change scholars and energy and environmental policymakers have to predicting the technological change pathway the industry might (continue to) follow under binding GHG pollution limits.

The next section reviews the prior literature about the role that new technical knowledge (technology) has played in pollution-saving technological change outcomes in the electric power industry and elsewhere. Section 3 describes the data and the appropriateness of SO2 cap and trade policy context to investigating effect of pure technical knowledge and other compliance techniques comparatively. Section 4 gives the regression results while section 5 draws out implications for the present and future response to GHG pollution control policy.

2. Prior literature

Power plants have historically improved the level of electric power output with respect to NOx, SO2, PM and mercury by a wide range of methods geared to comply with binding pollution limits. Figure 1 illustrates the essential components of a pollution-saving technological change process where the outcome is measured by the change in output relative to the pollutant, in this case SO2 emissions. Productivity change is brought about by the discovery and accumulation of pure new technical knowledge by the plant operators, by the technical alterations plant operators make to existing production methods using existing knowledge, and by the uptake of altogether new production technologies embodying new technical knowledge that was produced elsewhere (Nordhaus 1994; Mazzanti and Zoboli 2007; Perkins and Neumayer 2008).

Figure 1: Pollution-saving technological change



Note: Some of the influences on technological change pollution control policy in the electric power industry, illustrated

Since pollution is an externality that the producer would not otherwise have an incentive to reduce or avoid, a technological change process that is specifically pollution-saving tends to be initiated by a policy event setting out limits in law on emissions of the pollutant. The policy limits make it unviable or uneconomical for the producer to continue to generate electricity by the method it was using prior to the policy.

Policy induces the plant to consider the problem of how to adapt its production method to the changed regulatory-economic environment in which it now operates. An early step is to take inventory of the technical knowledge relevant to controlling emissions of the pollutant that the plant already possesses. The plant may also take inventory of the technical knowledge that it already possesses that could potentially be re-purposed to the problem of controlling the pollutant. Knowledge that can be re-purposed might lie in the producer's prior experience with using alternative fuel types, or with using different generation techniques, or with using available generation types or capital stocks in different ways. The size and relatedness to pollution control of the technical knowledge stock determines the compliance technology choices available to the plant. Once the plant has physically implemented its chosen compliance methods the result is measureable as a change in the productivity with which power is produced relative to the pollutant.

Prior empirical work has shed light on the role that pure knowledge and various other compliance techniques play in this outcome. Technological change that is energy-saving is also pollution-saving to the extent that pollution is reduced incidentally. Some studies investigating the role of technical knowledge in energy-saving technological change have found that knowledge creation and the uptake of new technology play a small role while pre-existing but re-purposed knowledge and techniques play a larger role.

Newell, Jaffe and Stavins (1999) found that government regulation and energy price changes explained up to 62 per cent of the change in the energy intensity of several energy-using household appliances during the period 1958 – 1993. Substitution of energy unintensive models for energy intensive models was also an important factor. Newell, Jaffe and Stavins did not find statistically significant evidence that either the rate or direction of knowledge creation explained the remaining 38 per cent. They did not test the effect of pure knowledge on the productivity outcome directly. They explained the residual in their model as evidence of the effect of knowledge creation and technological progress (969 - 970). This is consistent with the tendency in technological change studies where the outcome variable is a productivity measure to refer to the model residual as evidence of the effect of unobservable knowledge creation and technological progress (Brock and Taylor 2010; Levinson 2009; Solow 1956; Solow 1991).

Outside the electric power sector, Linn (2008) investigated the effect of energy-saving technology adoption on energy demand by a group of US manufacturing plants during the period 1963 – 1997. Linn found that new technology adoption accounted for less of the variation in energy demand than expected. A ten per cent increase in the price of energy associated with plants adopting energy-saving technologies sufficient to reduce their plant-level energy demand by one per cent. Linn concluded that the effect of technology adoption on energy demand is smaller than expected.

Popp (2001) investigated the effect of energy technology knowledge stocks on industry-level energy demand. Popp found that the effect of knowledge (technology) on energy-saving technological change was not as large as expected. Knowledge stocks were constructed from patent data for 13 industries. The stocks were regressed on energy demand in a range of energy-using industries. While new knowledge (technology) accounted for one-third of the total elasticity in energy demand across industries on average, the remaining two-thirds was due to simple factor substitution.

Sue Wing (2008) decomposed the change in the energy intensity of output in the US economy for the period 1958-2000. The energy intensity of aggregate output declined steadily during this period. New technical knowledge created in response to higher energy prices and leading to new technological possibilities with respect to energy use accounted for the smallest portion of this change (-8.8 per cent). Inter-sectoral structural change accounted for the largest portion (-32.6 per cent). Changing capital stock structures accounted for -16.1 per cent while input substitution accounted for a four per cent increase. In Sue Wing's study, inter-sectoral structural change accounted for over five times as much of the decline in the energy intensity of output as the production of new knowledge (technology) in response to higher energy prices.

Studies that have decomposed the sources of productivity gains from technological change processes that were pollution-saving have also found a limited role for knowledge and technology that is distinctly new. They have tended to find a larger role for existing knowledge and techniques that may already be in widespread use or which only needed to be adapted to the new pollution control problem rather than invented anew. Levinson (2009) decomposed the change in the pollution (NOx, SOx, CO and VOC) intensity of 450 four-digit US manufacturing sectors for the period 1987 – 2001. He decomposed the change into effects from the scale of output, sector composition effects including international trade, and 'technique' effects. Scale and composition effects together accounted for a 30 per cent increase in emission intensity but the 'technique' effect accounted for a 60 per cent fall. As in Newell, Jaffe and Stavins (1999) the technique effect is measured indirectly as the unexplained residual after accounting for scale and composition.

Germane to the empirical focus of the present study, Popp (2010) investigated the causes of adoption of two NOx control technologies, post-combustion and combustion modification, among US coal-fired power plants. Popp tested the effect of technological progress, which was measured by US and foreign patent data, regulatory stringency, and a set of adopter characteristics. Regulatory stringency was by far the most important predictor of technology adoption. The knowledge stock effect was more mixed. One specification showed that the anti-adoption effect of foreign knowledge effectively offset the pro-adoption effect of domestic knowledge, for a net effect of technological progress of near zero (2010: 24). Knowledge played a more important role in the adoption of post-combustion technology by increasing the expected adoption rate by over 20 per cent. Knowledge increased the adoption rate for combustion modification technology by less than one per cent.

The present paper tests role that various compliance methods played in a technological change process with respect to sulphur dioxide emissions. Stern (2002) decomposed the change in sulphur emissions for 64 countries for the period 1973 – 1990 into scale effects, inter-industry composition effects, input effects, and ‘technical change’ effects. Technical change effects are decomposed into emission-specific technical change effects and general technical change effects (217). Both types of technical change exerted a strong negative effect on sulphur emission intensity, especially through the agriculture, manufacturing and energy sectors. The effect of new knowledge and technological progress on sulphur intensity change is not directly tested.

In the context of SO2 control by power plants in the US, Carlson et al. (2000) investigated the extent to which the unexpectedly low cost of abating SO2 under the

1990 CAA Amendments could be explained by the flexibility brought about by the allowance trading provision. Carlson et al. concluded that the combination of 'technological change' (used interchangeably with 'technological improvements' and 'technological progress') and the fall in the cost of low-sulphur coal lowered the marginal abatement cost curves faced by emitters by over 50 per cent compared to the inflexible regime that was in place in 1985. Fuel switching accounted for 80 per cent of the cost reduction while technological change accounted for 20 percent.

Ellerman et al. (1997) similarly estimated that 45.1 per cent of total emission reductions after 1990 came from installing flue gas desulphurisation (FGD) units, and 54.9 per cent came from switching to lower sulphur fuels. They also observe that a smaller part of the unexpectedly low cost of abatement was due to 'unanticipated improvements in instrumentation and controls that reduce personnel requirements, innovative sludge removal techniques, and higher than expected utilization of scrubbed units . . . Moreover, new ways were found to adapt Midwestern boilers to blends of local and Powder River Basin [low sulphur] coals' (1998: 65).

These prior studies tend to find that new technical knowledge and technology like that created through R&D and the patenting process play a smaller role in the pollution-saving technological change process than might be expected. Pre-existing knowledge and techniques modified to deal with the pollution problem tend to play a bigger role, as do 'technique' changes within sectors. Technological 'change' seems to have accounted for more of the change in productivity with respect to conventional pollutants historically than technological 'progress'. This motivates the hypothesis tested in the remainder of the paper.

New technical knowledge and technology plays a smaller role in the pollution-saving technological change process than pre-existing technical knowledge and *techniques that are expanded, re-deployed or re-purposed to be effective in a pollution-constrained production environment.*

1. Data and methods

The hypothesis is tested in the context of the SO2 cap and trade program implemented in the United States by Title IV of the 1990 CAA Amendments. Title IV established the Sulfur Dioxide Allowance Trading Program[1] (the Program). Cap and trade established an initial national cap on SO2 emissions of 8.95 million tons per year. It targeted coal-fired electric power plants to achieve approximately 85 per cent of the reduction to meet this cap (Reitze 2001: 264). It proceeded in two phases: Phase 1 ran from 1st January 1995 to 31st December 1999 and mandated the participation of only the plants with the highest-emitting generation units in the country. Operators of the dirtiest plants were required to reduce emissions from the affected units by approximately four million tons per year. Phase 2 of the Program began on 1st January 2000. In Phase 2, Program coverage was extended to 2,300 additional generation units and to all generation units that had yet to be built. Under Phase 2, a further four to five million tons of SO2 per year were to be eliminated. The Program was the regulatory impetus behind the fall in the SO2 emission intensity of electricity production from affected plants during the period 1996 - 2001.

The hypothesis is tested in this context because the design of the policy instrument for controlling pollution was largely neutral with respect to technical choices polluters could make to comply with the Program. Cap and trade did not force plant operators to install any specific control technology, as the regulatory regime that in

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[1] For a detailed discussion of Title IV (Acid Deposition Control) and the Programme itself, see Reitze (2001). For evaluations of the Programme's effectiveness see Schmalensee et al. (1998). For an exposition of the role of tradable permits in the Programme, see Tietenberg (1999). For an estimate of the financial gains of the Programme attributable solely to permit trade, see Carlson et al. (2000).

was in place prior to 1990 tended to (Reitze 2001; Popp 2002). Cap and trade left power plants largely free to choose among all feasible techniques, technologies, adaptive approaches and compliance methods that were available to them for conforming to the new constraint in their operating environment. Methodologically this makes it possible to observe the most important influences on plant-level productivity change in a process that was not unduly influenced by regulators' technology preferences (Davis et al. 1977; Seskin, Anderson and Reid 1983).

Despite the many differences between SO2 and GHG emissions[2] SO2 is also one of the least-bad proxies for GHG pollution because it is an air pollutant that is heavily concentrated in the electric power sector. In the United States the actual physical electric power plants that participated in cap and trade are often the exact same power plants that will eventually have to comply with GHG pollution limits. These plants will face GHG pollution limits with similar knowledge and skill levels, similar geographic features, similar ownership structures, similar electricity supply obligations and similar relationship with regulators. Moreover it is difficult to imagine the US Congress *not* exploiting the efficiency, popularity and effectiveness of a flexible policy instrument like cap and trade or an emission tax that gives polluters the latitude to choose the compliance techniques that are the most economical for their plant-specific circumstances (Tietenberg 1999; Hahn and Hester 1989; Barakat and Chamberline Consultants 1991: 18).

[2] Perkins and Neumayer (2008) summarise these: the great majority of SO2 emissions originate from stationary, point-source, coal-burning facilities mainly in the electric power sector while GHG emissions come from a much wider range of point and non-point sources spanning many industrial sectors. Scientific understanding of the acidifying effect of sulphur deposition on ecosystems is relatively certain and mature yet scientific understanding of the extent of anthropogenic involvement in the warming process and the secondary effects of warming on ecosystems is comparatively less mature and more uncertain. The time lag to damage from SO2 emissions is a few months or years while the time lag to damage from GHG can be decades or longer.

The data for the estimations in the next section come mostly from Energy Information Administration (EIA) form 767.[3] The unit of analysis is the electric power plant rather than the utility or the generation unit (Popp 2006; Taylor 2001; Yaisawarng and Klein 1994). All power plants in the US with a total organic or nuclear-fuelled steam electric generator rating of 10mW or greater must complete form EIA-767. Plant-level SO2 emissions data come from the Environmental Protection Agency's (EPA) Clean Air Markets Database. A plant was included in the dataset if it had at least one generation unit affected by the Program in any year during the period 1997-2001. This includes plants that voluntarily 'opted in' units to the Program (Reitze 2001; Schmalensee et al. 1998). There are 540 unique plants in the final dataset.

2. Estimations

a. Model

The dependent variable is the extent of productivity change undergone by the plant with respect to SO2 over the period 1997 – 2001. It is measured as the change over this period in the SO2 intensity of electric power output. Note that the *change* in SO2 intensity is calculated for each plant. This means that the dataset has a cross-sectional structure. The estimation method is OLS. The dependent variable is estimated by the reduced-form equation:

$$D_i = \alpha + \beta \boldsymbol{K'}_i + \beta \boldsymbol{A'}_i + \beta \boldsymbol{C'}_i + \varepsilon_i$$

[3] The form EIA-767 'Steam-electric plant operation and design' gathers information on plant characteristics, plant configuration, boiler operations and fuel use, FGD unit design characteristics and FGD unit operation.

where *i* denotes the plant, α is the intercept interpreted as the value of the dependent variable *D* when all independent variables are zero, and ε is a classical error term. The variables in vectors ***K'*** and ***A'*** are the variables of main interest. The variables in vector ***K'*** relate to the quantity and varieties of technical knowledge available to each plant. The variables in vector ***A'*** relate to the compliance techniques and technologies implemented by the plant, such as switching to cleaner fuels, scrubbing and buying allowances. The variables in vector ***C'*** control for characteristics of the plant itself.

In the regressions, the knowledge variables and the compliance technique variables are included additively on the right hand side of the model. Figure 1 depicted the technical knowledge stock in one column and the various compliance methods in a second, separate column. The regressions treat all the independent variables conceptually as if they existed in a single column. This is consistent with the aim of the hypothesis which is to test the strength of the effect of pure technical knowledge creation relative to other compliance methods that already existed or which involved re-purposing previously known techniques. It also makes it possible to compare the effect of different varieties of knowledge relative to one another. Additivity follows other studies that have aimed to estimate the effect of pure knowledge relative to the effect of other non-pure-knowledge variables (Peri 2005; Popp 2001; Popp 2002; Sue Wing 2006).

b. Dependent variable

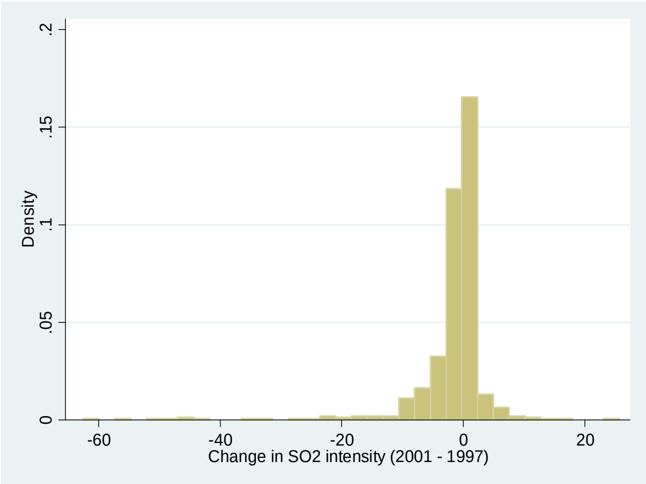
The dependent variable is the extent of change undergone by each plant in the SO2 intensity of electricity output. It is measured as the *change in the SO2 intensity of electricity output between 1997 and 2001* for each plant. Values for the SO2 intensity of output are first calculated for each plant-year as pounds of SO2 emitted divided by megawatt hours (mWh) of electricity generated. Intensity in 1997 is then subtracted from intensity in 2001 to give a change-in-intensity value for each plant *i*:

$$\text{Change}_i = \left(\frac{\text{Pounds SO2}_{2001}}{\text{mWh electricity}_{2001}}\right) - \left(\frac{\text{Pounds SO2}_{1997}}{\text{mWh electricity}_{1997}}\right)$$

This gives change-in-intensity values ranging from -62.5 to 25.7 pounds of SO2 per mWh. The range of values from negative to positive shows that change with respect to SO2 emissions was not unidirectional. Technological change which *saved* SO2 occurred at many plants but technological change which *augmented* SO2 occurred at others. About 63 per cent of plants in the sample underwent SO2-saving technological change. Negative values denote SO2-saving technological change. Any independent variable that associates with a decrease in the dependent variable means that that variable contributes to more SO2-saving technological change (over the range of negative values) or less SO2-augmenting technological change (over the range of positive values). Independent variables with negative coefficients are exerting an effect that is 'good' for the environment.

Figure 2 gives the distribution for the dependent variable. The distribution of the values illustrates how productivity change across plants relative to the initial state of production was not unidirectional. Plants underwent both SO2-saving and SO2-augmenting change. Again, negative values are 'good' for the environment. Change-in-intensity is skewed to the left by the relatively small number of plants whose SO2 intensity changed by more than -10 pounds SO2 per mWh of electricity produced. The plants in the left tail are important to the quality of the model predictions because they could bias the estimates away from the relationship that is representative of the experience of the majority of plants. The plants in the left tail are also substantively interesting because they are the plants that underwent the very most SO2-saving technological change.

Figure 2: Distribution of plants by change in SO2 intensity



Note: The dependent variable, the extent of change in SO2 intensity undergone, is skewed to the left by plants that underwent a change greater than -10 pounds of SO2 per mWh of electricity produced, between 1997 and 2001.

a. *Independent variables*

The two variables in the first group of independent variables ***K'*** are the *environmental knowledge stock* and the *ordinary knowledge stock* available to the plant over the study period. The knowledge stock available to each plant *i* is calculated from environmental R&D expenditure and all other ordinary R&D expenditure performed at the level of the utility during the period 1990 - 2001. R&D expenditure is a proxy for new technical knowledge creation. The data come from Federal Energy Regulatory Commission (FERC) Form 1, which US electric utilities are required to file annually. FERC Form 1 defines R&D spending as:

> '…costs incurred and accounts charged during the year for technological research, development, and demonstration (R, D &D) projects initiated, continued or concluded during the year… [as well as] support given to others during the year for jointly-sponsored projects…' (FERC 2010: 352)

One of the subcategories on the reporting form for reporting R&D expenditure is 'Environment'. The stock of 'environmental' knowledge is calculated from all R&D expenditure falling into this category. The stock of 'ordinary' knowledge is calculated from all remaining R&D expenditure falling into all the other categories combined, which include 'Generation', 'Transmission', 'Distribution', 'Regional Transmission & Market Operation', and 'Other'. The original R&D expenditure figures are adjusted for inflation using the US Bureau of Labor Statistics' Producer Price Index for Utilities.

The knowledge variables are calculated as stocks rather than flows because it is not realistic to think about the amount of technical knowledge available to a plant as disappearing at the end of each year. It is more realistic to think of knowledge gained from R&D carried out in past years as being available to the plant or utility in the current year. Stocks are calculated by the perpetual inventory method where most of the knowledge created through R&D in one year carries over to the next year, so that most knowledge accumulates over time (Nadiri and Prucha 1993). Since knowledge also tends to lose its relevance over time, the stock of knowledge retained from a previous year depreciates in each subsequent year at a fixed rate of ten per cent, following Popp (2010). This means that only 90 per cent of the stock in year *t* carries over to year *t+1.*

Stocks are calculated not just from the R&D performed in the years 1997 - 2001 but also from the R&D performed in all years back to 1990. From 1990 is when plants and utilities could reasonably have been expected to begin to invest in R&D to respond to the new SO2 control requirements under the entirely new form of regulation ushered in by cap and trade under Title IV (Reitz 2001; Popp 2002). Constructing stocks from the starting point of 1990 does not assume that plants were devoid of initial knowledge stocks gained through R&D performed prior to 1990. Rather, constructing stocks from 1990 assumes that the R&D performed prior to 1990 yielded a kind of knowledge that was characteristically more relevant to helping the plant comply with a different set of regulatory requirements under an entirely different regulatory regime (Reitze 2001; Taylor 2001; Kemp 1997). It assumes that it was the R&D performed in the post-1990 years that was most relevant and useful to the task of reducing SO2 emissions under cap and trade.

The environmental and ordinary knowledge stock variables are expected to facilitate productivity improvement in electricity production with respect to SO2 at plant level, taking a negative sign.

The second group of independent variables ***A'*** captures the compliance techniques and technologies plants implemented in response to the SO2 pollution constraint.

Total scrubber operating hours captures the extent to which a plant dealt with its SO2 emissions under the Programme by scrubbing. The variable is measured as the total number of operating hours over all years in the study period of all scrubber units at the plant combined, in thousands of hours. More scrubbing should reduce SO2 emissions, giving a negative coefficient.

Change in coal sulphur content captures the extent to which plants chose to burn lower sulphur coal. It measures the difference between the per cent sulphur content of coal burned in 1997 and the per cent sulphur content of coal burned in 2001. If sulphur content was lower in 2001 then the difference is positive. It is expected that the larger the difference, the less SO2 emitted. The variable should take a negative coefficient.

Change in coal consumption measures the extent to which a plant chose to burn less coal altogether. The variable is measured as the difference between total coal consumption in 1997 and 2001. If coal consumption was lower in 2001 then the difference is positive. The larger the difference, the less SO2 emitted. This variable should take a negative coefficient.

Expand clean capital stock captures the extent to which plants built new gas-fired generation units to produce electricity in place of coal-fired generation units. It is measured as the proportion of all new boiler units built at the plant whose primary fuel was gas. A larger proportion of clean capital stock should reduce SO2 intensity of electricity production. The expected sign is negative.

Two variables are measured using 'compliance strategy' data reported by plant operators on EIA form 767. These data are interesting in their own right and described briefly here. Plant operators were free to choose whichever compliance strategy they wished but they had to report their strategy to the EIA. EIA collected data on the frequency of use of the 14 most common compliance strategies. The questionnaire instructed respondents to 'Select the existing and/or planned strategies to meet the sulphur dioxide requirements of the Title IV of the Clean Air Act Amendments of 1990'.

Table 1 summarises these data. The frequency column gives the total number of 'declarations' during the period 1996-2005. This is a longer period than the period estimated in the regressions, but missing data for the years 1998, 1999 and 2000 limit the extent to which these data can be used in the estimations. One declaration is equivalent to a plant operator reporting that this compliance strategy was being used for one generation unit in one year. Operators however had the option to state up to three compliance strategies for each generation unit in each year. Table 1 includes all strategy declarations regardless of primacy, e.g. whether the strategy was stated as the first, second or third strategy. The last column 'KR' is the author's own assessment of the amount of new knowledge the plant would have needed acquire to implement the strategy. Zero denotes little or no new knowledge, three denotes a considerable amount. A hyphen means inestimable. Values are assigned on the basis of the author's understanding of what each compliance strategy involved technically, some of which is conveyed in the footnotes.

Table 1: Compliance strategy declarations, 1996 – 2005 [4]

	Label	Freq	Perc	KR
Allocated allowances and/or purchase allowances	WA	6,527	42.17	0-1
No change in historic operation of unit	NC	3,579	23.12	0
Switch to lower sulphur fuel	SS	3,100	20.03	1-2
Not determined at this time	ND	440	2.84	0
Designate Phase II unit(s) as substitution unit(s)[5]	SU	434	2.80	1
Other	OT	309	2.00	-
Decrease utilisation – designate sulphur-free generator(s) to compensate	US	240	1.55	1
Transfer unit under Phase I extension plan[6]	TU	276	1.78	0-1
Install FGD unit (other than under Phase I extension plan)	IF	294	1.90	3
Control unit under Phase I extension plan[7]	CU	119	0.77	2
Decrease utilisation – rely on energy conservation and/or improved unit efficiency[8]	UE	56	0.36	2
Decrease utilisation – purchase power	UP	43	0.28	0
Repower unit[9]	RP	34	0.22	3
Decrease utilisation – designate Phase II units as compensating units	UC	28	0.18	1

4 Data come from form EIA-767, schedule III, section B, question 3(g). Data do not appear for 1998, 1999 and 2000. The response rate for the compliance strategy question in the survey was 91.9 per cent for all other years.

5 This involved shifting the unit's emission reduction obligation to a different unit under the operator's control. The emission reduction requirement could be reassigned to a unit with a lower compliance cost for example (US Congress 1990: 2593 – 2594).

6 Same as 'designate Phase II unit(s) as substitution unit(s)', except instead of controlling unit emissions directly using a 'qualifying' technology the operator transferred the emission reduction obligation to a unit employing a qualifying technology.

7 Under a Phase 1 extension plan a plant operator was allowed to extend the compliance deadline for a unit by up to two years provided that the operator held valid allowances for all emissions from the unit during the two years and that the operator either employed a 'qualifying Phase 1 technology' or transferred the emission reduction obligation for the unit to a unit employing a qualifying Phase 1 technology. A qualifying Phase 1 technology is 'a technological system of continuous emission reduction which achieves a 90 per cent reduction in emissions of sulphur dioxide from the emissions that would have resulted from the use of fuels which were not subject to treatment prior to combustion' (US Congress 1990: 2588).

8 For each ton of SO2 emissions an operator avoided through energy conservation measures, the EPA awarded an equivalent number of emission allowances.

9 See definition in-text.

In Table 1 the compliance strategies that involved the most new knowledge received the least uptake and the compliance strategies that involved the least new knowledge received the greatest uptake. It would seem that plant operators avoided those compliance strategies that would have involved a large amount of technical learning. For example, 'repowering' a unit is arguably the strategy that would have stretched the plant the furthest given the meaning of 'repowering' in the 1990 CAA Amendments. 'Repowering' meant:

> '…replacement of an existing coal-fired boiler with one of the following clean coal technologies: atmospheric or pressurised fluidized bed combustion, integrated gasification combined cycle, magnetohydrodynamics, direct and indirect coal-fired turbines, integrated gasification fuel cells… or a derivative of one or more of these technologies and any other technology capable of controlling multiple combustion emissions simultaneously with improved boiler or generation efficiency and with significantly greater waste reduction relative to the performance of technology in widespread commercial use as of the date of enactment of the Clean Air Act Amendments of 1990…' (US Congress 1990: 2587)

Repowering was a new knowledge-intensive compliance strategy because it involved production methods ('atmospheric or pressurised fluidized bed combustion… magnetohydrodynamics, integrated gasification fuel cells... ') that were not in widespread use among affected plants at the time. A plant operator that chose to repower an affected unit would likely have had to: undertake considerable research into how to integrate the new unit into the existing electricity generation system; investigate the suitability of manufacturers to source the technology from; oversee the installation of the unit; learn how to operate the new unit; and maintain considerable practical on-site expertise to maintain and operate the new unit. Plant operators chose repowering as a compliance strategy in 34 out of 15,479 total declarations. This amounts to less than one-quarter of one per cent of all declarations. Repowering ranked the 13th most frequently used strategy out of 14 possible strategies.

The compliance strategies that received the most widespread uptake involved preserving, extending and repurposing existing physical capital stocks, and also by extension preserving, extending and repurposing existing technical knowledge stocks to the extent that plant operators depend on 'knowledge capital' to run the physical capital. Switching to lower-sulphur fuels for example was a very common compliance strategy that accounted for 19.27 per cent of all declarations. The next most frequent strategy was 'no change in historic operation of unit' and the most frequently stated strategy of all was using 'allocated and/or purchased allowances'. Neither of these on its own involved any physical change to the operation of the generation unit at all. Allowance using/buying accounted for 6,527 compliance strategy declarations, 42.17 per cent of the total.

Two of the variables used in the regressions are derived from these compliance strategy data. *Use or buy allowances (WA)* captures the extent to which a plant used or bought emission permits to comply with its obligations under the Program. Greater use of permits should substitute for physical production method changes. Using permits equates roughly to the right to emit SO2 and should associate positively with the dependent variable.

Repower with clean coal (RP) is the extent to which a plant installed clean coal technology to deal with its obligations under the Program. A negative coefficient is expected since repowering with a low-emissions coal combustion technology should reduce SO2 emissions, all else equal.

These two variables are measured from the compliance strategy data as the proportion of generation units in a plant for which a specific compliance strategy was declared. For example, if a plant comprised of ten generation units then it had ten opportunities to declare 'WA' (use or buy allowances) in each year. Over the two years in the study period for which compliance strategy data are available (1997 and

2001) the plant had the chance to make 20 declarations. If the plant reported 'WA' as the compliance strategy for 10 of these then the value for the variable *use or buy allowances (WA)* for that plant was 0.5. These variables are measured as proportions.

The variables in the third group ***C'*** control for plant-level characteristics. One of the most important among these is *initial starting SO2 intensity in 1997*. Controlling for starting SO2 intensity means that the other independent variables in the model are more likely to pick up the extent of the change in SO2 intensity actually undergone in subsequent years, rather than the variation in the initial starting point SO2 intensity of the plant in 1997.

Plant vintage is the average year that all generation units at the plant came into service. It controls for the possibility that older plants contributed less to the change in SO2 intensity because of the way they were constructed or because they were less adaptable, than newer plants.

Initial capital mix captures the extent to which the initial capital stock at the plant was already clean and therefore may not have needed to undergo a change in SO2 intensity, or was not able to undergo this change. This is measured as the proportion of generation units at the plant in the initial year fired primarily by gas.

Plant scale is the maximum plant generation capacity measured in megawatts. This controls for the scale of electricity production capacity at the plant on the idea that larger plants may have been able to undergo greater SO2-reducing change.

Table 2 gives descriptive statistics for the dependent variable and the three groups of independent variables.

Table 2: Descriptive statistics

Variable	N	Mean	Min	Max	p50	p25	p75	S.D.	Variance	Skewness
Change in SO2 intensity, 2001 - 1997	589	-1.730	-62.500	25.700	-0.396	-2.110	0.065	6.480	42.000	-4.530
Ordinary knowledge stock	540	0.821	0.000	119.826	0.000	0.000	0.000	6.876	47.285	12.813
Environmental knowledge stock	540	0.017	0.000	4.940	0.000	0.000	0.000	0.269	0.072	16.218
Scrub: total FGD operating hours	540	2.552	0.000	38.450	0.000	0.000	0.000	6.351	40.332	2.793
Burn cleaner fuels: change in coal sulphur content	540	0.043	-0.985	2.544	0.000	-0.007	0.044	0.252	0.063	4.557
Burn less coal: change in coal consumption	540	0.099	-1.562	2.060	0.000	0.000	0.160	0.345	0.119	0.943
Expand clean capital stock: proportion new boilers gas	540	0.001	0.000	0.200	0.000	0.000	0.000	0.014	0.000	13.538
Use or buy allowances (WA)	540	0.415	0.000	1.000	0.438	0.000	0.714	0.374	0.140	0.312
Repower with clean coal (RP)	540	0.137	0.000	1.000	0.000	0.000	0.250	0.257	0.066	6.726
Initial plant SO2 intensity, 1997	540	10.214	0.003	74.494	7.710	0.610	15.138	11.163	124.619	2.015
Plant vintage: mean boiler in-service year	540	1966	1940	1996	1965	1958	1974	10.330	106.710	0.284
Initial capital mix: proportion boilers gas	540	0.303	0.000	1.000	0.000	0.000	1.000	0.443	0.196	0.855
Plant scale: total generation capacity	540	8.226	0.659	39.534	5.977	2.868	11.959	6.878	47.313	1.348

b. Linear regressions

The functional form of the estimation model is linear throughout because there is no strong theoretical reason to expect that the extent of the change in SO2 intensity undergone by the plants was influenced non-linearly by pure knowledge or by any other explanatory factor. Table 3 gives the regression results for this functional form. Specification (1) estimates the model by OLS with errors clustered on the utility company owners of the plants. Errors are clustered on utility companies because a single utility company frequently operated more than one plant in the sample. Specification (2) gives standardized coefficients. Standardized coefficients make is possible to interpret the magnitude of the effect of the independent variables on the change in intensity undergone relative to one another. This is important for comparing the magnitude of the effect of ordinary knowledge to the effect of environmental knowledge, and the magnitude of the effect of pure knowledge generally to the effect of the other compliance techniques and technologies.

Table 3: Regressions with change-in-intensity measure

VARIABLES	(1) Change	(2) Change
Ordinary knowledge stock	-0.0111*	-0.0117
	(0.00575)	
Environmental knowledge stock	0.386	0.0161
	(0.536)	
Scrub: FGD operating hours	-0.107***	-0.1053***
	(0.0326)	
Burn cleaner fuels: change in coal sulphur content	-11.011***	-0.4298***
	(1.774)	
Burn less coal: change in coal consumption	-0.453	-0.0243
	(0.388)	
Expand clean capital stock: proportion new boilers gas	-3.877	-0.0067
	(8.327)	
Use or buy allowances (WA)	1.436**	0.0828***

	(0.595)	
Repower with clean coal (RP)	0.391***	0.0813**
	(0.130)	
Initial plant SO2 intensity, 1997	-0.366***	-0.6264***
	(0.0839)	
Plant vintage: mean boiler in-service year	-0.0583**	-0.0924***
	(0.0241)	
Initial capital mix: proportion boilers gas	-3.393***	-0.2313***
	(1.161)	
Plant scale: total generation capacity	0.00652	0.0069
	(0.0277)	
Constant	117.7**	
	(48.06)	
Observations	540	540
Adjusted R-Square	0.621	0.621

Note: Dependent variable is change in SO2 intensity (2001 – 1997). Specification (1) gives OLS estimates with standard errors clustered on utilities, (2) gives standardized coefficients. Shading delineates the three blocks of variables: pure knowledge stocks, compliance techniques and technologies, and initial plant characteristics. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

In specification (2), the standardized coefficients on the knowledge stock variables are small relative to the coefficients on the variables capturing the effect of the compliance techniques and technologies. A one standard deviation increase in the ordinary knowledge stock associates with a .011 pound decrease in SO2 emitted per mWh of electricity generated on average. A one standard deviation increase in the change in the sulphur content of coal burned associates with a .429 pound decrease per mWh on average. The linear model estimates the effect of the change in the sulphur content of coal variable to be 39 times stronger than the effect of the ordinary knowledge stock variable.

Ordinary knowledge stock associates with lower SO2 intensity (good for the environment) and is significant at the ten per cent level. Since the dependent variable encompasses positive and negative values reflecting SO2-augmenting and SO2-saving technological change respectively, this implies that more ordinary knowledge led to either less SO2-augmenting change or more SO2-saving change. Ordinary knowledge was expected to be good for the environment, and in this empirical context this appears to have been the case. The coefficient of -0.011 implies that a one million dollar increase in the stock of ordinary knowledge associates with a change in the SO2 intensity of -0.011 pounds/mWh on average, holding all other variables in the model constant. For comparison the mean change in SO2 intensity for all plants in the sample was -1.730 pounds/mWh as in Table 2. Also in specification (1) the coefficient on the environmental knowledge stock is positive. This is unexpected: more environmental knowledge was predicted to be good for the environment. Environmental knowledge is interpreted to have had an ambiguous effect given that it is not significant at conventional levels. The analysis returns to the environmental knowledge effect below.

As for the compliance technique and technology variables, scrubbing, burning cleaner coal, burning less coal, and expanding the stock of clean production capital all give negative coefficients as expected. They are all good for the environment. The coefficient on the change in sulphur content of coal variable is consistent with the previous finding that switching to lower-sulphur coals was one of the most inexpensive and widespread compliance strategies used by plant operators under the Program (Burtraw and Palmer 2003; Carlson et al 2000; Joskow 1998; Taylor 2001). This finding is consistent with the pattern in compliance strategy declarations in Table 1. The change in sulphur content of coal variable implies that the greater the difference between the mean sulphur content of coal burned in 1997 and the mean sulphur content of coal burned in 2001, the more environmentally favourable intensity change took place. The coefficient of -11.011 implies that a one per cent increase in the change in the sulphur content of coal associates with a change in the SO2 intensity of electricity production of -11.011 pounds/mWh on average, holding everything else constant.

The positive sign on the variable use or buy allowances (WA) implies that plants that purchased and used more SO2 emission permits underwent either less SO2-saving or more SO2-augmenting intensity change on average. This was expected because an allowance is akin to the right to continue to emit SO2.

The repower with clean coal (RP) variable does not perform as expected. This is the only variable in the model with a significant coefficient taking an unexpected sign. Installing clean coal technology would be expected to reduce SO2 intensity in practice but the coefficient of 0.391 implies that a one per cent increase in the proportion of generation units at a plant repowering with clean coal associates with an *increase* in the SO2 intensity of production of .391 pounds/mWh on average. This implies that the greater the proportion of boilers at a plant that repowered with clean coal technology, the more environmentally *un*favourable intensity change the plant underwent.

The explanation probably lies in the wording of the relevant question on the EIA-767 survey questionnaire. This variable measures the proportion of 'declarations' by a plant that it was complying with cap and trade by repowering some or all of its generation units with clean coal technology. The best explanation for the unexpected sign is that very dirty and out-of-compliance plants reported that it was their *intention* to comply with the Program by installing clean coal technology, even though in *actuality* they had not yet installed the technology at the time of reporting. This would lead to the variable associating with the plants' unchanged production method. The wording of the question on the EIA-767 survey questionnaire supports this explanation.[10]

[10] The wording: 'Select the existing *and/or planned strategies* to meet the sulfur dioxide requirements of Title IV of the Clean Air Act Amendment of 1990' [emphasis added] (US DOE 1995).

Table 3 also includes the group of variables controlling for initial plant characteristics, which perform as expected. Higher initial SO2 intensity in 1997 at the plant, newer plant vintage, and a higher initial endowment of clean capital stock all associate with either less SO-augmenting or more SO2-saving intensity change undergone on average, all else being equal. Larger plants associate with slightly more SO2-augmenting or less SO2-saving change meaning that they are slightly worse for the environment, holding everything else constant.

c. Quantile regressions

The outlier plants depicted in Figure 4 could be causing the linear regressions to be giving misleading estimates. The plants in the left hand tail of the distribution underwent a large change in SO2 intensity that was good for the environment relative to the other plants in the sample. These plants could be biasing the effect of the independent variables in such a way that they appear to be exerting a stronger or weaker effect on the change in SO2 intensity than they might exert in a specification that was more accommodating of outlier plants. Table 4 summarises the nature of the outlier plants and the values that the linear model in Table 3 predicts for these observations.

Table 4: Summary statistics for outlier plants

	Cook's D (mean)	Cook's D (max)	Skewness	Variance	Min	Mean	Max	1st decile
Change in SO2 intensity (DV)	-	-	-4.431	50.529	-62.495	-1.957	25.7	-3.013
Change in SO2 intensity (predicted)	0.005	0.826	-4.012	25.746	-42.009	-1.732	7.888	-6.069

Cook's D measures the extent to which outlier plants might unduly bias the model estimates. It combines information on the residual of every observation and the leverage of every observation. The lowest possible value of Cook's D is zero and a value greater than one suggests that the observation is a gross outlier. No observation in the predicted values has a Cook's D that is greater than 1. This does not mean there are no outliers in the estimates, only that there are no gross outliers by this indicator. Table 4 also shows that the model fits the data fairly well in terms of skewness, min and mean, but less well in terms of variance, max and 1st decile.

A crude solution to obtaining independent variable coefficients not unduly influenced by outlying plants would be to drop the observations exhibiting extreme values and re-estimate. This approach would both bias the estimates in other ways and ignore the fact that the outlying plants are interesting from a policy and theoretical point of view. Alternately the model could be estimated by robust regression, which de-weights outlying observations by giving small weight to observations with a high Cook's D and large weight to observations with a low Cook's D. Examination of the residuals under robust regression showed that this approach was still not adequately predicting the extent of change undergone by plants that made the biggest pro-environment productivity improvements.

Quantile regression distinguishes the effect of the independent variables on discrete quantiles of the data (Hao and Naiman 2007; Koenker and Hallock 2000). Quantile regression estimates are more resistant to leverage from outlying observations partly because the effect of outliers is 'contained' to the estimate for the quantile in which the outliers reside. Coefficient estimates are quantile-specific. Engles (1857) used quantile analysis to illustrate the relationship between working class household income and food expenditure. Quantile analysis for Engles overcame the problem that the least-squares regression line fitted to his data failed to predict food expenditure from household income with much accuracy for the households with the lowest incomes. For the poorest households, the mean relationship was misleading. Koenker and Hallock (2000) used quantile regression to analyse the birth weights of a large sample of new born babies in the US. Koenker and Hallock showed that the effect of the mother's age on the weight of the new-born baby was much stronger (positive) at the lowest quintile of the birth weight distribution than at the middle and upper quintiles. Linear regression estimates of the mean conditional relationship between the dependent and independent variables would not have been suitable in either of these examples to capture the relationship of interest at the lower end of the distribution. Quantile regression gives the change in the conditional quantile that associates with a change in an independent variable rather than the change in the conditional mean.

Table 5 gives quantile regression estimates for the first through ninth deciles of the data. The first decile captures the outlying plants that underwent intensity change of more than -3.013 pounds SO2/mWh. Significance levels are based on bootstrapped standard errors. Shading delineates the pure knowledge variables, the compliance technique and technology variables, and the plant-level controls as before.

Table 5: Quantile regression estimates

VARIABLES	(1) change	(2) change	(3) change	(4) change	(5) change	(6) change	(7) change	(8) change	(9) change
Ordinary knowledge stock	-0.000140	-0.00205	-0.00592	-0.00960	-0.00335	-0.00929	-0.00106	-0.00396	-0.0154
	(0.0168)	(0.0370)	(0.0425)	(0.0250)	(0.0207)	(0.0140)	(0.0145)	(0.00703)	(0.0109)
Environmental knowledge stock	0.108	-0.0952	-0.162	-0.219	-0.333	0.476	0.294	0.0703	-0.0818
	(5.496)	(5.870)	(6.230)	(3.652)	(2.315)	(1.774)	(1.441)	(0.252)	(0.355)
Scrub: FGD operating hours	-0.191***	-0.0957**	-0.0486***	-0.0472**	-0.0263	-0.00904	-0.0134	-0.0112	-0.0119
	(0.0540)	(0.0417)	(0.0147)	(0.0190)	(0.0219)	(0.0151)	(0.0147)	(0.0225)	(0.0464)
Burn cleaner fuels: change in coal sulphur content	-8.941***	-10.43***	-10.04***	-11.27***	-9.774***	-7.554***	-7.019***	-6.439***	-7.148***
	(2.212)	(1.480)	(1.594)	(2.571)	(2.907)	(2.220)	(2.181)	(0.536)	(1.266)
Burn less coal: change in coal consumption	0.282	-0.497	-0.230	-0.347	-0.427	-0.556*	-0.611**	-0.440	-0.457
	(0.496)	(0.659)	(0.294)	(0.389)	(0.339)	(0.313)	(0.274)	(0.356)	(0.725)
Expand clean capital stock: proportion new boilers gas	0.515	0.108	-0.0568	-0.119	-0.303	-0.791	-0.955	-3.287	-13.09***
	(19.78)	(16.23)	(14.68)	(18.78)	(20.24)	(10.58)	(19.77)	(3.265)	(4.955)
Use or buy allowances (WA)	0.343	0.101	0.0408	0.0213	0.0369	0.0744	0.0818	0.246	0.133
	(0.227)	(0.154)	(0.0870)	(0.0728)	(0.0573)	(0.0513)	(0.166)	(0.364)	(0.709)
Repower with clean coal (RP)	0.248	0.176	0.381	0.377	0.302	0.231	0.203	0.188***	0.203***
	(0.530)	(0.266)	(0.232)	(0.238)	(0.311)	(0.292)	(0.316)	(0.0499)	(0.0741)
Initial plant SO2 intensity, 1997	-0.550***	-0.396***	-0.326***	-0.272***	-0.186***	-0.137***	-0.115***	-0.0982***	-0.0274
	(0.0975)	(0.0488)	(0.0401)	(0.0392)	(0.0491)	(0.0284)	(0.0307)	(0.0167)	(0.0394)
Plant vintage: mean boiler in-service year	-0.00789	-0.00409	-0.00217	-0.000809	-0.00169	-0.00593	-0.00414	-0.0165	-0.0304
	(0.00815)	(0.00665)	(0.00529)	(0.00424)	(0.00494)	(0.00361)	(0.00661)	(0.0158)	(0.0310)
Initial capital mix: proportion boilers gas	-2.145***	-1.580***	-1.329***	-1.453***	-1.004*	-0.826**	-1.004**	-1.147***	-0.172
	(0.675)	(0.447)	(0.366)	(0.402)	(0.523)	(0.353)	(0.423)	(0.411)	(0.877)
Plant scale: total generation capacity	0.0197**	0.00873	0.00611	0.00195	-0.000198	-0.00245	-0.00198	-0.00292	-0.0388
	(0.00919)	(0.0117)	(0.0115)	(0.00856)	(0.00494)	(0.00503)	(0.00745)	(0.0224)	(0.0428)
Constant	17.14	9.461	5.536	3.031	4.333	12.52*	9.198	33.79	62.01
	(16.37)	(13.24)	(10.55)	(8.444)	(9.994)	(7.318)	(13.07)	(31.06)	(61.04)

Observations	540	540	540	540	540	540	540	540	540

The coefficients in Table 5 are interpreted similarly to linear regression coefficients. For example the coefficient on the change in sulphur content of coal variable in specification (5) of -9.774 implies that a one unit increase the sulphur content of coal associates with a change in intensity from the fifth decile (median) of -9.774 pounds SO2/mWh. This compares to the estimate of the mean effect of scrubbing over the entire distribution given in the linear regressions above. There, a one unit increase in the same variable associated with a change in intensity of -11.011 pounds SO2/mWh. The median estimate shows that the mean estimate was in fact being influenced by the negative outlier plants. Outlier plants made the fuel switching variable look more influential than perhaps it really was, at least for the fifth decile of the data.

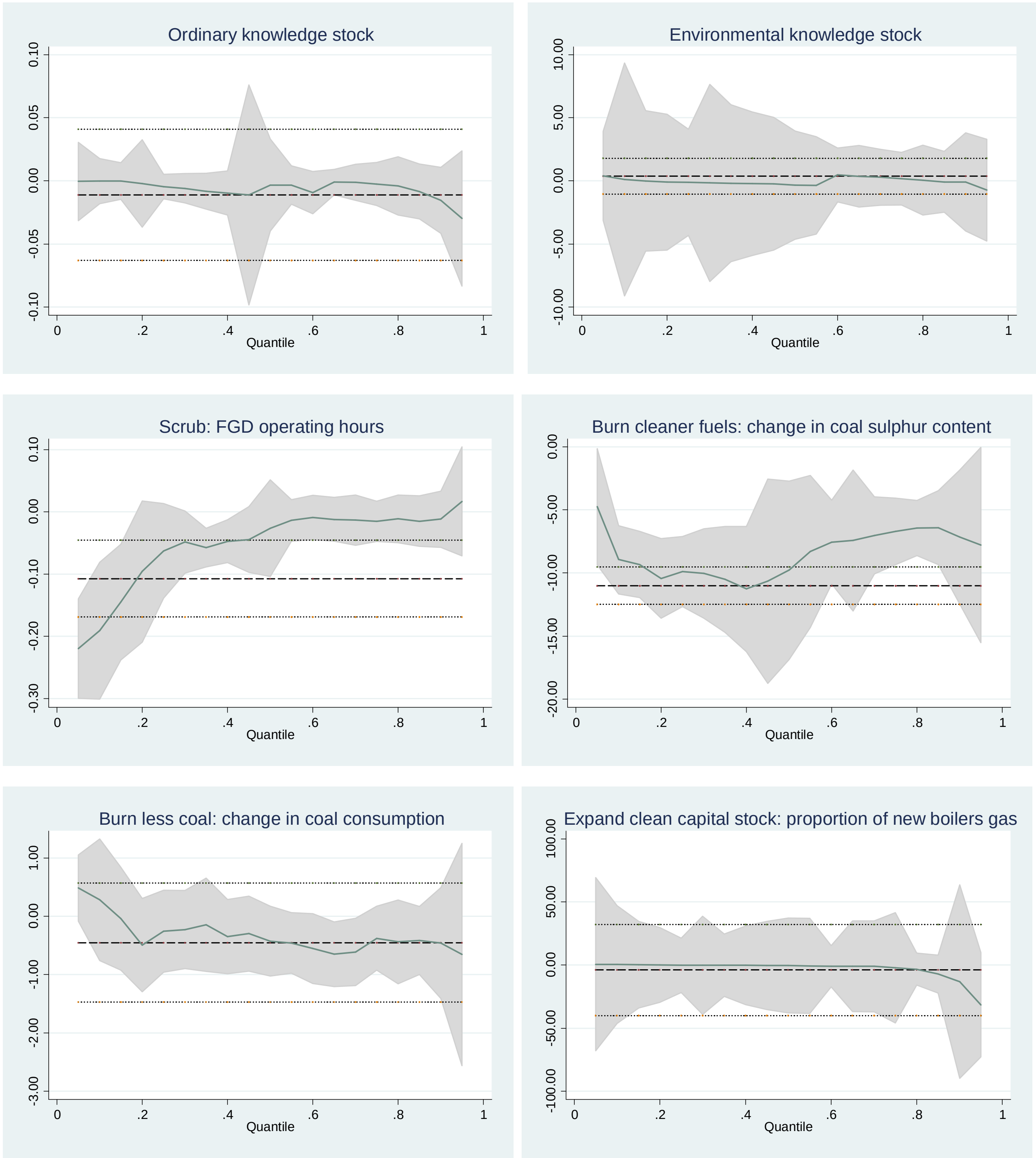
The ordinary knowledge stock variable is negative over all nine deciles of the data and the environmental knowledge stock variable is negative over five of the nine deciles. Neither pure knowledge variable is statistically significant at any decile. This is interpreted as weak evidence that pure knowledge created through new R&D had a generally pro-environment effect on intensity change undergone on the whole, but not an effect that was statistically significant.

Scrubbing plays a strong, negative and statistically significant role for the plants that underwent the most SO2-saving intensity change. The scrubbing effect is very strong in the first decile and strong in the second through fourth deciles. The effect of burning lower sulphur coal is uniformly strong, negative and statistically significant across all nine deciles of the data. Switching to lower sulphur coal also played an important role in the change process for the plants that underwent the very most SO2-saving change. Moreover, burning lower sulphur coal played an important pro-environment role for plants that underwent very little change at all and for the plants that underwent SO2-augmenting change. Burning less coal exerted a consistently negative effect throughout the distribution and a statistically significant effect in the sixth and seventh deciles only.

Expanding the stock of clean capital by constructing gas-fired boilers had a very strong, negative and significant effect at the ninth decile but a considerably weaker and statistically insignificant effect at all other deciles. This is consistent with the idea that constructing new gas-fired generation reduced the amount of SO2-augmenting change that would have occurred if newly constructed capacity had been coal fired, but that new gas-fired capacity did little to reduce existing emissions. The effect of using or buy allowances and installing clean coal technology do not change in direction from the linear regressions.

The coefficients in Table 5 can also be plotted graphically as in Figure 3. Figure 3 shows how the size of the coefficient on a given variable changes over the deciles in the distribution, and compares this to the linear estimate which does not change by decile. The straight dashed line is the mean linear regression estimate for the entire distribution. The light dashed lines are confidence intervals for the linear regression estimate. The curving line graphs the quantile coefficient point estimates as they change by decile. The grey shading is the confidence interval for the quantile estimates. The y-axis gives the size of the coefficient.

Figure 3: Coefficients for selected variables by quantile



Note: In each panel the solid curving line gives the estimated coefficient as it changes across quantiles. Grey shading gives confidence intervals. Point estimates by decile are given in Table 5. The heavy dashed line is the linear regression estimate. The light dashed lines are linear regression estimate confidence intervals.

The effect of the pure knowledge stock variables is relatively stable across deciles. The pure knowledge effect remains close to zero and does not deviate appreciably from the mean regression estimates. The strength of the effect of pure knowledge is not greatly different for plants that underwent the most SO2-saving change and for plants that underwent the most SO2-augmenting change, although the direction of the effect tends to be negative throughout. By contrast, the size of the coefficients on the compliance technique and technology variables changes considerably across the distribution. The scrubbing effect is negative and strong in the first four deciles but negative and weak in the last five deciles. The mean regression estimate masks important variation in the scrubbing effect across deciles. The effect of burning lower sulphur coal is negative and strong throughout the entire distribution. The effect of burning less coal is consistently negative but not greatly different from the mean regression estimate. The construction of new gas fired boilers only exerts its effect of mitigating the creation of new pollution for the plants that underwent the most SO2-augmenting change.

3. Conclusions and contributions

This paper tested the idea that pre-existing compliance techniques and technologies played a bigger role in the pollution-saving technological change process that occurred under the US SO2 cap and trade than the creation of pure technical knowledge through R&D. It found that environmental productivity gains associated more strongly with compliance techniques and technologies that involved re-purposing and adapting pre-existing techniques and technologies, rather than with the discovery of technical knowledge and technologies that were altogether new. At least for the 1997 – 2001 period considered here, pre-existing compliance techniques like fuel switching, burning less coal, constructing gas-fired plants and buying SO2 emission permits were the most important channels through which pollution-saving productivity change occurred. Neither new environmental knowledge, nor new ordinary knowledge, nor compliance technologies that would have involved intensive technical learning (repowering with clean coal) exerted a consistently strong and significant pro-environmental effect.

Quantile regression estimates further showed that the strength of the effect of these compliance techniques varied across deciles of the data, and particularly how they influenced productivity change among the plants in the far left hand tail of the distribution that underwent the very most pro-environmental change. Scrubbing, switching to lower sulphur fuels and being a plant that was relatively clean to begin with associated most strongly with the change undergone by these plants.

An important caveat to these findings is the relatively short time frame of the study period, 1997 and 2001. Although it may be reasonable to conclude from these data that pure technical knowledge and learning-intensive compliance techniques played a smaller role than well known, low-learning, incremental techniques, it might not be reasonable to generalise this finding to a cap and trade programme for GHGs for example beyond the short to medium term. These techniques may account for a large portion of productivity change in the short to medium term, but once the economical reductions that can be achieved through these techniques become exhausted, more knowledge-intensive techniques may come to play a bigger role. This could especially be the case if the cuts mandated for existing GHG emissions were deeper and/or were required to be achieved more quickly than the cuts to SO2 emissions under cap and trade.

One contribution of these findings is the idea that the technical learning burden or 'new knowledge richness' of different compliance approaches can itself be an important explanation for the variation across compliance strategies in uptake. Low-cost abatement opportunities were already known to distinguish themselves from high-cost abatement opportunities in part by being more plentiful and more accessible (Hanley, Shrogen and White 2006). These findings imply that low-cost abatement opportunities are more plentiful and accessible in part *because* they entail less technical learning and new knowledge-acquisition than high-cost opportunities. Looking forward to GHG emission reduction techniques this implies that the learning burden embedded in the different opportunities is *itself* a cost and *itself* a reason why these opportunities locate in different places along the abatement cost curve.

These findings also suggest that market-based instruments may not always induce as much environmental innovation as some studies suggest (Jaffe, Newell and Stavins 2002; Vollebergh 2007), or at least that the 'environmental' innovation that they do induce does not always look very 'environmental'. Market-based instruments may be the best policy choice for a range of reasons, but it does not appear from these findings that one of those reasons is that they reward the creation of new technical knowledge, at least in the short term. The key advantage of market-based instruments with respect to GHG emissions may lie in the fact that they give firms the freedom to *dismiss* strategies that would involve a heavy learning burden in favour of well-known, well-tested techniques that plants already possess the knowledge to implement.

These findings also have practical implications for practitioners in the electric power industry trying to deal with the technical and policy uncertainty connected to the GHG pollution regulation question. To the extent that this historical experience can be seen as a guide to the future, this analysis points to a strong role for pragmatic and incremental compliance techniques that are as minimally disruptive to established electric power production methods as possible. It also points to a tendency for some of the most economical abatement possibilities to emerge only once regulation is firmly in place. Where capital planning and investment decisions must be made today these findings imply that innovations from equipment and fuel suppliers, cleaner fuels, and modified combustion techniques are likely to play an important role in reducing GHG emissions in the electric power sector.

4. References

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