Price Discrimination Based on Downstream Regulation: Evidence from the Market for SO2 Scrubbers

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CCP Working Paper 10-9

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JEL Classification: L13, Q52, Q58, L94

Keywords: Price discrimination, emission standards, tradable, permits, technology diffusion.

Acknowledgements: I would like to thank Christian Almer, Frans de Vries, Morten Hviid and participants of seminars at Stirling and UEA for their helpful comments and Catherine Ball and Ali Massadeh for excellent research assistance. All remaining errors are mine. The support of the Economic and Social Research Council is gratefully acknowledged.

ISSN 1745-9648

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July 9, 2010

Abstract

Evidence from the market for flue-gas desulfurization devices [scrubbers] in the U.S. is used to show that the choice and stringency of environmental regulation have substantial effects on the mark-up of an abatement technology. The imperfectly competitive upstream eco-industry charges higher prices for scrubbers to power plants participating in Phase I of the tradable permit scheme for sulfur dioxide than to those subject to emission standards. The mark-up also depends on stringency of the emission standard, geographic location and electricity market regulation. Previous empirical studies neglect this source of endogeneity. Market power and price discrimination have repercussions on the rate of diffusion and innovation incentives.

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1 Introduction

Environmental regulation ideally both internalizes externalities and at the same time provides adequate incentives to both develop and adopt advanced abatement technologies. Early theoretical contributions analyzing the effect of instrument choice on diffusion and innovation (Milliman and Prince 1989, Jung et al. 1996, Requate and Unold 2003) treat the costs of abatement technologies as exogenous. More recently a number of papers (Denicolò 1999, Fischer et al. 2003,

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Support from the ESRC Centre for Competition Policy is gratefully acknowledged. I would like to thank Christian Almer, Frans de Vries, Ian Lange, Morten Hviid and participants of seminars at Stirling and UEA for their helpful comments and Catherine Ball and Ali Massadeh for excellent research assistance. All remaining errors are mine.

David and Sinclair-Desgagne 2005, Requate 2005, Perino 2010, David et al. 2010) have emphasized the potential conflict between optimal diffusion of new abatement technologies and the need to reward innovating firms for their (research) investments. If abatement technologies are protected by patents or the upstream industry supplying the abatement technology is not perfectly competitive for some other reason, the price of abatement equipment will not reflect its true social costs.

With an imperfectly competitive upstream eco-industry, the regulatory instrument used to control pollution affects the elasticity of demand for abatement technologies and the mark-up charged on them. Requate (2005) and Perino (2010) predict distorting effects of market power on the rate of diffusion under taxes and tradable permits. David and Sinclair-Desgagne (2005) compare design standards with taxes and voluntary agreements. They find that a design standard makes polluting firms more vulnerable than taxes to exploitation by an imperfectly competitive upstream eco-industry supplying abatement technologies and services. However, none of these theoretical contributions explicitly considers price discrimination which will be central to the following analysis.

The main contribution of the present paper is to provide empirical evidence confirming that boilers participating in Phase I of the U.S. sulfur dioxide tradable permit scheme face higher mark-ups on flue-gas desulfurization devices also called 'scrubbers' than similar boilers subject to emission standards. Permit trading introduced by the 1990 Clean Air Act Amendments (CAAA) hence affected the price of abatement technologies which has repercussions on both the rate of diffusion and - in the medium to long run - on research incentives and thereby on the rate of technological change in abatement technologies.

The size of the mark-up under permits depends on how far away boilers are located from the Powder River Basin, WY where the bulk of low-sulfur coal - which provides an alternative way to reduce sulfur dioxide emissions - is mined. The further away a power station is from the Powder River Basin, the higher the transportation costs and hence the more attractive are scrubbers - and scrubber producing firms take advantage of this. The upstream industry also price-discriminates based on the stringency of the emission standard for boilers not participating in permit trading and on state-level regulation of the electricity market. Market power and price discrimination based on downstream regulation are therefore important factors in the markets for scrubbers.

There is a small empirical literature testing the effects of environmental instrument choice on pricing and adoption of abatement technology. Kerr and Newell (2003) study the U.S. lead phase-out and find evidence that tradable permits result in more cost-effective but less widespread adoption of isomerization technologies among refineries than emission standards.

Lange and Bellas (2005) provide evidence that both installation and operating costs of scrubbers decreased after the introduction of the Phase I of the tradable permit scheme for SO_2 compared to the level before that point in time. They do not distinguish between boilers actually participating in the permit scheme and those still subject to command-and-control regulation. They can therefore not pick up any effect due to price discrimination.

Keohane (2005) compares the price elasticity of installation decisions and finds that adoption of scrubbers by US coal-fired power plants was more sensitive to total scrubbing costs under permit trading than under command-and-control. The main contribution of the present paper to Keohane (2005) is that the price of scrubbers is considered to be endogenous due to imperfect competition in the upstream industry and the focus is on installation costs of scrubbers as opposed to overall scrubbing costs. Treating the price of scrubbers as endogenous allows one to test for price discrimination on the basis of environmental regulation and disentangle such effects from other potential interactions between costs and regulation such as technological change. The focus on installation costs is important in this context since (expected) operating costs are a crucial determinant of the willingness-to-pay to install a scrubber at a particular boiler and hence can potentially affect both the adoption decision and mark-ups.

Busse and Keohane (2007) are the first to provide empirical evidence for the interaction between environmental regulation and mark-ups charged by an imperfectly competitive upstream industry. They show, again for U.S. coal-fired power plants, that railway operators delivering coal to power plants price discriminate on the basis of geographic location (distance to the Powder River Basin) and the regulatory instrument. However, low-sulfur coal is a commodity and hence the issue of research incentives for advanced abatement technologies cannot be addressed in this context.

For the same industry but another pollutant, Fowlie (2010) presents evidence that the type of regulation in the electricity market affects adoption incentives of power plants for nitrogen oxide (NO_x) abatement technologies. Plants in states with restructured electricity markets tend to invest less than those in states using rate-of-return regulation. The present paper confirms this result for sulfur dioxide abatement equipment and adds a price discrimination dimension to it.

Bellas and Lange (2010) investigate the development of installation costs for flue-gas particulate collectors again for U.S. coal-fired power plants. They find evidence that operating costs decrease while capital costs increase over time. This lends support to the idea that the upstream industry supplying the abatement devices captures the rents arising from technological progress.

In contrast to the present paper, they do not consider price discrimination and do not control for the endogeneity of adoption decisions.

The present paper focuses on some 830 boilers that were built before 1979, the year the 1977 CAAA made scrubbing effectively mandatory for newly built boilers. All of these boilers were subject to emission standards at least until 1994. Starting in 1995 this changed for 247 so-called Table A boilers which were required by Title IV of the 1990 CAAA to take part in Phase I of emission trading from 1995 to 1999. Focusing on this set of boilers makes sure that adoption of scrubbers is voluntary and not mandated and all scrubbers installed had to be retro-fitted and not planned and built at the same time as the boiler itself. This at the same time provides a higher degree of technological homogeneity and allows to observe installation decisions occurring during the same period of time but at boilers subject to different regulatory regimes: emission standards and tradable permits.

The remainder of this paper is organized as follows. The next section gives relevant information on the industry under concern and the regulatory framework it is subject to. Section 3 derives theoretical predictions for the effect of environmental regulation on the mark-ups for scrubbers. Section 4 presents the empirical strategy. The data is described in section 5 and results are presented in section 6. The last section concludes.

2 Coal-Fired Power Plants and Regulation of Sulfur Dioxide in the U.S.

In 1999, the year this paper focuses on, over 50% of electricity in the U.S. was produced by some 1,400 coal-fired power stations. Each plant consists of one or more generator-boiler units. Since there is not always a one-to-one relationship between boilers and generators and environmental regulation is usually tied to boilers, the focus is on boilers in what follows.

There were several 'waves' of federal regulation on SO_2 emissions from coal-fired power stations complemented by additional regulation at state and local level. The 1970 Clean Air Act (CAA) introduced uniform emissions standards of 1.2 pounds (lbs) per mm Btu (million British Thermal Units) for boilers built from 1972 onwards. The 1977 Clean Air Act Amendments (CAAA) added the requirement that all boilers built after 1978 remove at least 90% of the sulfur dioxide from their emission stream. This effectively made the use of scrubbers mandatory since for virtually all coal-fired power plants they represent the only economical way to achieve this target.[1] Finally Title IV of the 1990 CAAA (often called the Acid Rain Program) introduced

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[1] In principle the sulfur can be removed from the coal before it is burned. However, with the exception of plants

tradable permits in two phases. Phase I lasted from 1995-1999 and included some 263 so-called Table A units, named after the table which listed them in the legislation.[2] Phase II started in 2000 and included all coal-fired power stations with a generating capacity of more than 25 MW.

All Table A boilers were built before 1979 and hence are not required to operate scrubbers. Essentially all power plants (and certainly all in the sample studied in this paper) were subject to some form of emission standard on sulfur dioxide either at the federal, state or local level in 1999 or in the case of Table A boilers until 1994. Most of these come in the form of pounds of sulfur dioxide emitted per unit of heat content (lbs/mm Btu).[3] There is substantial heterogeneity in the stringency of the emission standards imposed on individual boilers reaching from 0.1 lbs/mm Btu up to well above 10 lbs/mm Btu.[4]

For all boilers installation of a scrubber was voluntary[5]. A handful of boilers that installed a scrubber within 24 months of entering service are excluded as those cannot reasonable be assumed to be retro-fitted.

During the thirty-one years between 1969 and 1999 on average less than six firms were active in the market for scrubbers per year.[6] The upstream industry was considered to be moderately concentrated according to the merger guidelines of the U.S. Department of Justice in most years and concentrated in some using a five year flowing average Herfindahl-Hirschman Index (HHI).

One other regulatory issue has to be considered in the context of power plants. Most - but not all - plants are investor-owned utilities and in many states they are heavily constrained by regulation in the output market (i.e. electricity). In the U.S. this mainly comes in the form of rate-of-return regulation which has been associated with distorted incentives to invest in the capital base (Averch and Johnson 1962, Fabrizio et al. 2007, Fowlie 2010). Since scrubbers are a significant capital investment, the decision to adopt them might be influenced by the type

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using a technique called coal gasification (of which there were two in the U.S.) this option is more expensive than installing a scrubber.

[2] The 263 units refer to generators. The sample used includes 247 boilers. The difference stems from the following: not all units have a 1:1 relation between boilers and generators and five Table A boilers were excluded due to missing data.

[3] Those specified using a different measure can be transformed into the lbs/mm Btu scale.

[4] In the analysis the relevant variable measuring the stringency of emission standards is truncated at 9 lbs/mm Btu since none of the boilers in the sample used coal with a sulfur concentration that would result in a higher emissions per unit of heat generated regardless of their emission standard and whether they operated a scrubber or not.

[5] There are a dozen boilers that were required by the state or local authority to install a scrubber although built before 1979. They are excluded from the sample.

[6] This includes all 205 scrubbers installed in this period, including those at plants were scrubbing was mandatory which are excluded from the dataset used in this paper.

of regulation a power plant is subject to. The empirical analysis therefore controls both for ownership and the type of electricity market regulation.

3 The Model

3.1 Adoption Decision

The following simple model of the adoption of abatement technology by coal-fired power plants provides the motivation for the structure of the empirical model presented in the next section. A coal-fired power plant can drastically reduce its emissions (by more than 90%) by installing a scrubber (S) or by input substitution i.e. by switching to low-sulfur coal (C).

The plant's decision of whether and when to install a scrubber depends on the change in instantaneous profits $\pi^C(t) - \pi^S(t)$ brought about by adoption, the time of switching T and the costs to install the scrubber $I(T)$. The power plant will solve the following optimization problem to determine the optimal time to adopt

$$\max_T \quad \int_{t=0}^{T} \pi^C(t) \cdot e^{-rt} dt - I(T) \cdot e^{-rT} + \int_{t=T}^{\infty} \pi^S(t) \cdot e^{-rt} dt. \tag{1}$$

Defining the present value of the change in the profit stream as the willingness-to-pay for a scrubber $WTP(T) = \int_{t=T}^{\infty} \left[\pi^S(t) - \pi^C(t)\right] e^{-rt} dt$, (1) can be simplified to

$$\max_T \quad WTP(T) - I(T) \cdot e^{-rT}. \tag{2}$$

The first-order condition yields

$$WTP'(T) = \left[I'(T) - rI(T)\right] \cdot e^{-rT} \tag{3}$$

which determines the optimal point in time to invest T^* by equalizing the marginal costs of postponing adoption on the left-hand side and the gains from doing so on the right-hand side. While most technical specifications that determine the WTP to install a scrubber at a given boiler are constant over time, both the market and regulatory environment might change. For example, the transition from emission standards to tradable permits can significantly change the profitability of scrubbing (see next subsection). While none of the Table A boilers had installed a scrubber previous to the passage of the 1990 CAAA, twenty-two scrubbers were operating at such units by 1999, i.e. at a point in time when all boilers under concern were already in service for two decades or more.

In order for T^* to be finite, i.e. for adoption to occur eventually, the willingness-to-pay has to exceed the installation costs at least at one point in time.

$$\exists t : WTP(t) > I(t) \tag{4}$$

Condition (4) determines whether adoption occurs and (3) specifies at which point in time it is most profitable to adopt.

3.2 Willingness-to-Pay

The willingness-to-pay for a scrubber is determined by the reduction in variable abatement costs realized compared to alternative means of meeting regulatory requirements. Assuming constant marginal costs for both scrubbing and buying low sulfur coal[7] a power plant subject to an emission standard has a positive willingness-to-pay for a scrubber if the marginal costs of scrubbing, mc^S, are smaller than those of low-sulfur coal, mc^C,

$$mc^S < mc^C. \tag{5}$$

A power plant will only abate so much as to meet the emission standard regardless of the abatement option used. The instantaneous savings from scrubbing for such a plant are given by area A in panel (a) and areas $E + F$ in panel (b) of figure 1.

Under tradable permits the plant has a positive willingness-to-pay for a scrubber if both condition (5) holds and the marginal costs of scrubbing are lower than the price of permits, λ, times the removal efficiency of the scrubber, γ,

$$mc^S < \gamma\lambda. \tag{6}$$

Buying permits effectively provides an additional means to abate emissions (externally).

A tradable permit system has an important effect on the way in which traditional abatement options are used, if they are used. Permits impose a marginal cost on emissions which makes it profitable to scrub a hundred percent of the emission stream or use low-sulfur coal exclusively. Plants gain the difference between the permit price or the cost of low-sulfur coal - whichever is lower - and the marginal costs of scrubbing for each unit scrubbed.

This change in the utilization rate induced by tradable permits, ceteris paribus, increases the willingness-to-pay for a scrubber (areas B and G in figure 1) given it was positive in the first place. Plants that satisfy conditions (5) and (6) and for which the marginal costs of low-sulfur coal is smaller than the permit price,

$$mc^S < mc^C \leq \gamma\lambda, \tag{7}$$

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[7] Keohane (2005) finds evidence that average operating costs are decreasing in utilization. This would further reinforce the following argument that firms' willingness to pay for a scrubber increases with higher rates of utilization.

have an unambiguously higher willingness-to-pay for a scrubber under permits than under emission standards (see figure 1(a)).

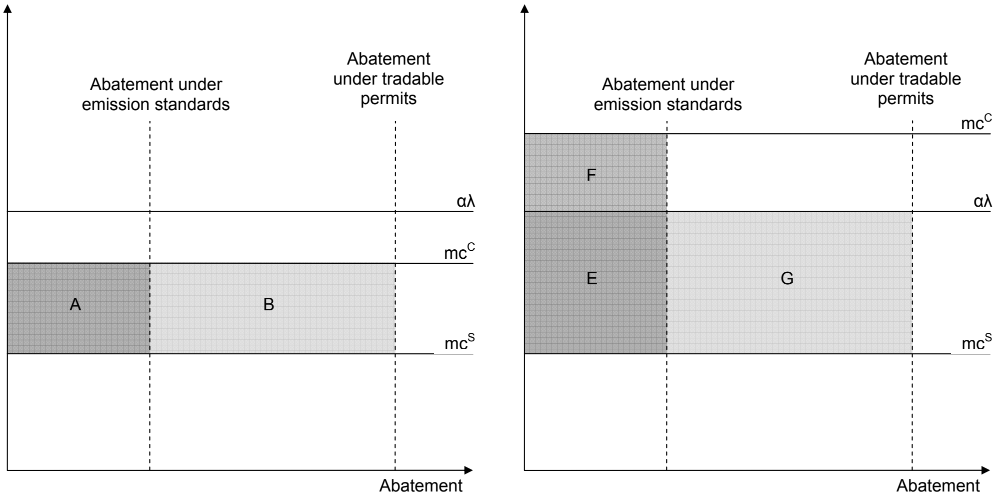
For firms that do not satisfy condition (7) but still meet both (5) and (6) the change in the willingness-to-pay induced by a change in the regulatory regime is ambiguous (see figure 1(b)). Since

$$mc^S < \gamma\lambda < mc^C, \tag{8}$$

there are two countervailing effects. The increase in the utilization rate makes scrubbers more attractive (gain of area G) while the reduction in the per unit gain has the opposite effect (loss of area F). Which one dominates depends on the difference between the permit price and the costs of scrubbing and the stringency of the emission standard. The stricter the emission standard and the greater the difference between permit price and marginal costs of low-sulfur coal the less likely is an increase in the willingness-to-pay when permits are introduced. Hence, at any given level of installation costs at or above the one before the passing of the 1990 CAAA, willingness-to-pay for a scrubber has increased and demand for scrubbers became less elastic. For installation costs below that level, the effect on demand is in principle ambiguous. Hence, the change in the regulatory instrument makes (residual) demand for scrubbers less elastic at least for some range of installation costs and potentially for all levels.

None of the Table A boilers installed a scrubber before the passing of the 1990 CAAA but two dozen did so during Phase I of permit trading which indicates an increase in demand of Table A boilers. This is in line with results by Requate and Unold (2003) who predict that for sufficiently high installation costs firms would not adopt an abatement technology under emission standards but that there is partial diffusion under permits.

A less elastic demand for scrubbers under a tradable permit scheme seems to contrast both previous theoretical predictions (David and Sinclair-Desgagne 2005) and empirical findings (Keohane 2005). However, in the model by David and Sinclair-Desgagne (2005), which does not claim to be tailored to the case of scrubbers, there is only one abatement option - which makes firms vulnerable to expropriation by the eco-industry under command-and-control - and the utilization effect is not present. Keohane (2005) finds adoption decisions under tradable permits more sensitive to changes in the costs of scrubbing than under emission standards. However, he considers total costs of scrubbing (installation plus the present value of running costs). Using total instead of installation costs is not appropriate for our purposes because the higher utilization rate of scrubbers under permits would induce higher running costs but at the same time increase the willingness-to-pay for scrubbers.



(a) Willingness to pay (WTP) for a scrubber of a plant with medium marginal costs of low-sulfur coal (mc^C). Under emission standards the annual saving due to scrubbing is given by area A. Under tradable permits the annual saving of using a scrubber is the sum of areas A and B.

(b) WTP for a scrubber of a plant with high marginal costs of low-sulfur coal (mc^C). Under emission standards the annual saving due to scrubbing is given by area E + F. Under tradable permits the annual saving of using a scrubber is the sum of areas E and G. If G > F, then the WTP is higher under tradable permits than under emission standards.

Figure 1: Stylized Willingness-to-Pay for Scrubbers under Emission Standards and Tradable Permits

The following hypothesis summarizes the factors predicted to, ceteris paribus, increase the willingness-to-pay for a scrubber.

Hypothesis 3.1 *The willingness-to-pay of a power plant to install a scrubber at a particular boiler increases if the boiler*

- *participates in permit trading as opposed to being subject to an emission standard or*
- *faces a stricter emission standard (for boilers not participating in the permit scheme) or*
- *faces higher costs of low-sulfur coal (e.g. because the unit is located further away from extraction sites of low-sulfur coal).*

Given these predicted effects of regulation and location on willingness-to-pay for a scrubber, previous papers studying the link between tradable permits on sulfur emissions and scrubbing decisions by power plants (Lange and Bellas 2005, Keohane 2005, Frey 2008) neglect a potentially important feature of this market: the market power resulting from the oligopolistic structure of the eco-industry producing scrubbing devices. Observable differences in the willingness-to-pay for a scrubber combined with an imperfectly competitive industry could make price discrimination by eco-firms both feasible and attractive.

4 Empirical Strategy

The price of a scrubber and hence the total costs of installation $I(T)$ are driven by technical characteristics of both the scrubber and the boiler. If the upstream industry price discriminates, the price should also be correlated to at least some observable characteristics that determine the willingness-to-pay for a scrubber but not its real installation costs. However, a hedonic price model of the type

$$I_k(T) \quad = \quad F(R_k(T), M_k(T)) + \epsilon_k, \tag{9}$$

where R_k indicates observable variables that drive the real costs of producing and installing a scrubber, M_k indicates variables that affect the mark-up and k indexes a scrubber, potentially faces a selection problem. Even in a world without any price discrimination and market power, a regression of this type can be expected to pick up a positive relationship between M and I. This is because installation costs can only be observed at boilers that adopt the technology. Hence, according to condition (4) boilers with a higher willingness-to-pay are more likely to install a scrubber. If there are important but unobservable drivers of real costs, this results in higher average installation costs for boilers with a higher willingness-to-pay.

In order to control for this selection bias we use a Heckman model that simultaneously or sequentially estimates the adoption decision (4) and the cost equation (9). The resulting system of equations looks as follows (the time index is dropped for brevity):

$$\ln I_j \quad = \quad \begin{cases} \alpha_0 + \alpha_1 \ln R_j + \alpha_2 \ln M_j + \epsilon_j & if \quad A_j^* > 0 \\ - & if \quad A_j^* \leq 0 \end{cases} \tag{10}$$

$$A_j \quad = \quad \begin{cases} 1 \quad if \quad A_j^* > 0, \\ 0 \quad if \quad A_j^* \leq 0, \end{cases} \tag{11}$$

where $A_j^* = \beta_0 + \beta_1 \ln R_j + \beta_2 \ln M_j + \beta_3 \ln E_j + \mu_j$ is the latent variable indicating the adoption propensity of a boiler. A_j is the adoption dummy that takes the value 1 if a scrubber is installed at boiler j and is zero otherwise. E_j represents the exclusion restriction and includes variables that affect the willingness-to-pay for a scrubber but not installation costs.

While Keohane (2005) also uses a Heckman-type model to analyze the costs of scrubbing he does so for entirely different reasons. Keohane (2005) sets out to predict scrubbing costs for all boilers - including those that did not install a scrubber - and uses the Heckman model to correct for the problem that installation costs tend to be lower at units that do adopt compared to those that do not. He has no variables capturing drivers of willingness-to-pay in his cost equation which are at the heart of the selection problem in this paper.

5 Data

Summary statistics of technological as well as regulatory variables are given in the appendix in tables 4 - 7 and are discussed in sections 5.1 and 5.2 respectively. The sample includes 838 boilers 65 of which operated a scrubber in 1999. Note that some boilers share a scrubber. The necessary adjustments are described below. All scrubbers included are retro-fitted and installation was not mandatory. Boilers linked to a scrubber that does not meet all of the criteria above are excluded.

The bulk of the data comes from the U.S. Energy Information Administration (EIA) form EIA-767. This form contains annual survey data on the design and operations of steam-electric power plants with a net generating capacity of 10 megawatts or greater. The data is available from 1985-2005 and provides specific details on the plant and boiler characteristics. The analysis focuses on the year 1999 which was the last year of Phase I of permit trading and hence covers two distinct regulatory regimes: permit trading for Table A boilers and emission standards for all other boilers.[8]

5.1 Technological variables

The following variables contain information about the technical specifications of both boilers and scrubbers.

MaxFlow refers to the maximum continuous steam flow of the boiler at 100% load (in thousand lbs/hour). It captures the capacity of a boiler. The actual use of a boiler in 1999 is captured by the variable *TotCoal* which measures annual coal consumption (in thousand short tons). *InsrvYearBoiler* gives the year the boiler went in operation. Further, the dummy variable *WetBottom* determines if the boiler is wet or a dry bottom. In case of a wet bottom boiler *WetBottom* has the value 1.

The technical specifications of scrubbers are captured by the following variables. A measure of the capacity of a scrubber is the ‘flue gas exit rate’ (in actual cubic feet/minute), denoted

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[8] Some Non-Table A boilers opted into the permit scheme but none of them installed a scrubber in the relevant period. They are treated as Non-Table A.

SpecExRate. Following Lange and Bellas (2005) the removal efficiency of the scrubber is specified in terms of standard removal units. A standard removal unit removes approximately 63.2% of the incoming sulfur. The variable *RemovalUnit* is calculated as follows

$$RemovalUnit = \ln \frac{1}{1-x}, \tag{12}$$

where x is the removal efficiency of the scrubber. The variable *InsrvYearScrubber* indicates the year the scrubber first went into service. The number of scrubber trains, denoted *TrainTot*, tells how many compartments the scrubber has and is a measure of redundancy. The dummy *Salable* equals 1 if the scrubber produces a salable by-product. *SharedScrub* is 1 if the scrubber is shared by more than one boiler and zero otherwise. The number of boilers a scrubber is attached to is captured by *NoBoilers*.

Installation costs of a scrubber *InstallCost* are deflated using the Handy-Whitman index for public utility construction costs (electric) and expressed in thousands of 1996 USD. *Cheap1* is a dummy that is one for the two boilers that report installation costs of less than 100,000 USD and *Cheap2* is one for the seven boilers reporting installation costs of less than 3 million. Mean installation costs in the sample are 76.8 million USD.

If the scrubber is linked to more than one boiler the variables *InstallCost*, *SpecExRate* and *TrainTot* are divided by the number of boilers the scrubber is attached to *NoBoilers*.

5.2 Regulatory and market structure variables

The dummy variable *TableA* tells whether or not a boiler is participating in Phase I of the tradable permit scheme (value of one if it is). A subset of Table A plants called ‘control units’ received additional permits conditional on installing a scrubber. This was public information.[9] The corresponding dummy variable is labeled *ControlUnit*. The variable *Dummy1992* is one for all scrubbers installed in or after 1992. This is the year the first scrubber was installed at a Table A boiler following the 1990 CAAA and is intended to capture any industry wide effect on scrubber costs like a discrete shift due to technological change.[10]

All boilers in the sample were subject to an emission standards denoted *Regulation*. They are measured in lbs of sulfur dioxide in the emission stream per mm Btu in the coal burned. For a non-Table A boiler the WTP for a scrubber is increasing in the stringency of the emission standard but not so for a Table A boiler (see Figure 1) as the emission standard has been

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[9] See EPA (1998).

[10] Note that the Table A boilers that installed a scrubber in 1992 are not part of the current sample since cost data was missing for them.

replaced by permit trading. Because of this an interaction variable, denoted *RegNonTableA*, which is zero for all non-Table A boilers is used.

For boilers that were subject to emission standards and for those for which the use of low-sulfur coal is cheaper than buying permits, the WTP is determined by the difference between the variable costs of scrubbing and the costs of using clean coal. Following Keohane (2005) and Frey (2008), the distance to the Powder River Basin, WY where the bulk of low-sulfur coal is mined is used as a proxy captured in the variable *DistancePRB.* The measure used is the 'as the crow flies' distance. In order to test whether scrubber producing firms differentiate the mark-up charged on the distance to the Powder River Basin between Table A and non-Table A boilers an interaction variable *lnDistPRBTableA* between *lnDistancePRB* and *TableA* is used.

Whether the plant a boiler belongs to is an investor-owned (value 1) or a cooperatively/publicly owned municipal and federal utility (value 0) is captured in the dummy *IOU.* The dummy *IOUDrg* is 1 for all boilers part of an investor-owned utility that operates in a deregulated electricity market. More precisely it indicated whether the formal proceedings that eventually lead to a deregulated market had been started in 1999. Both variables are based on the ones used by Fabrizio et al. (2007) and extended to include all boilers of the current sample.

6 Results

6.1 Installation Costs

We start the analysis of scrubber installation costs with a set of OLS regressions bearing in mind that they might be subject to a selection bias. Note that both the effect on the price of a scrubber due to price discrimination and the selection effect for the policy and distance variables are always aligned. Both predict an increase in installation costs following an increase in WTP. More importantly there are no straightforward theoretical reasons as to why installation costs might depend on those factors other than price discrimination and selection effect. The results from the OLS regression can hence be interpreted as upper bounds on the real effects.

Table 1 presents the results of four OLS regressions. The set of explanatory variables is a result of a stepwise elimination of the variables with the highest p-values using a threshold of 0.05. Table 8 in the appendix gives the results for the regression including all explanatory variables. This elimination procedure allows to identify variables that can serve as potential exclusion restrictions in the Heckman model and increases the degrees of freedom. The most promising candidates for exclusion restrictions appear to be *ControlUnit* and the ownership status *IOU.* Both are available for all boilers and turn out not to significantly influence the

Table 1: OLS regressions

	(1)	(2)	(3)	(4)
	Cluster *PlantID*	No-clustering		
	All	All	Only *IOU*	No cheap
lnSpecExRate	0.675***	0.675***	0.665***	0.686***
	(0.000)	(0.000)	(0.000)	(0.000)
lnRemovalUnit	1.186***	1.186***	1.141***	1.157***
	(0.000)	(0.000)	(0.000)	(0.000)
lnTrainTot	0.556***	0.556***	0.627***	0.595***
	(0.001)	(0.000)	(0.000)	(0.000)
InsrvYearBoiler	-0.0424***	-0.0424***	-0.0471***	-0.0468***
	(0.000)	(0.000)	(0.000)	(0.000)
Dummy1992	-0.810**	-0.810***	-1.256***	-0.557*
	(0.005)	(0.000)	(0.000)	(0.038)
lnRegNonTableA	-0.437**	-0.437***	-0.395**	-0.389***
	(0.009)	(0.000)	(0.002)	(0.001)
lnDistPRBTableA	1.790**	1.790***	1.906**	1.718***
	(0.008)	(0.000)	(0.002)	(0.000)
TableA	-12.37*	-12.37***	-12.75**	-12.02**
	(0.015)	(0.001)	(0.005)	(0.001)
IOUDrg	-0.326*	-0.326*	-0.341*	-0.304*
	(0.049)	(0.021)	(0.038)	(0.036)
Cheap1	-5.180***	-5.180***	-5.206***	
	(0.000)	(0.000)	(0.000)	
Cheap2	-1.143***	-1.143***	-1.003***	
	(0.000)	(0.000)	(0.000)	
SharedScrub	-0.619	-0.619*	-0.647	-0.602*
	(0.106)	(0.030)	(0.067)	(0.034)
lnNoBoilers	0.639*	0.639*	0.635*	0.601*
	(0.026)	(0.013)	(0.028)	(0.018)
Constant	83.70***	83.70***	93.12***	92.24***
	(0.000)	(0.000)	(0.000)	(0.000)
Observations	65	65	54	58
Adjusted R^2	0.978	0.978	0.977	0.925
DoF	30	51	40	46

p-values in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

installation costs of scrubbers but might be reasonably expected to influence adoption decisions.

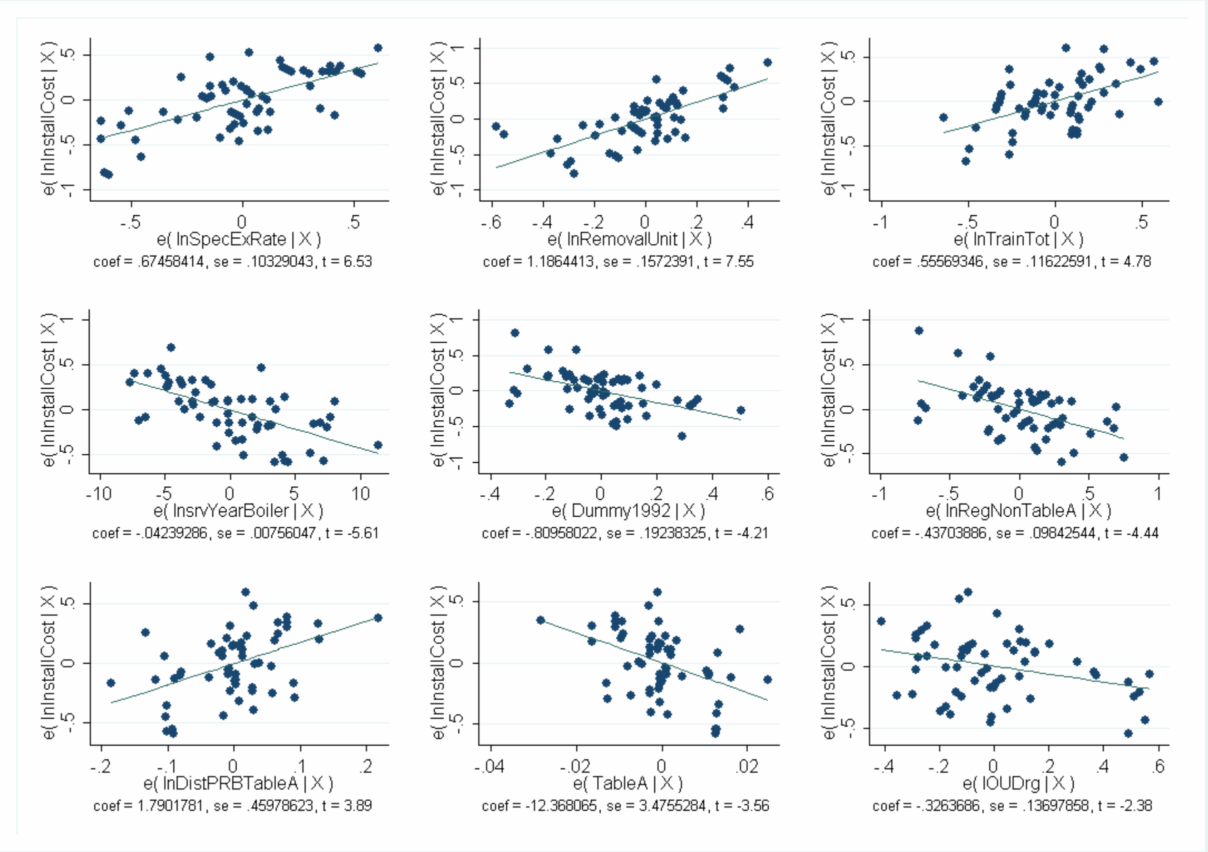

Figure 2: Added variable plots

Regressions (1) clusters observations at the plant level to correct for potentially different variations in installation costs between as opposed to within individual power plants. This procedure has the disadvantage of substantially reducing the degrees of freedom. Regression (2) repeats (1) but without clustering. The added variable plots for some of the variables in regression (2) are given in figure 2. Regression (2) does not suffer from heteroskedasticity or omitted variables.[11] Column (3) differs from (2) by including only those scrubbers that are installed at boilers of investor-owned utilities (IOU). Regressions (4) presents a robustness checks and excludes the outliers marked by *Cheap1* and *Cheap2*. The results of all four regressions are almost identical indicating a high robustness.

The technical variables have the expected sign and are highly significant. Installation costs increase with the capacity, removal efficiency, number of scrubber trains of the scrubber and the

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[11] A Breusch-Pagan / Cook-Weisberg test for heteroskedasticity yields a p-value of 0.6918 and a Ramsey RESET test one of 0.8411.

age of the boiler.

The results of Table 1 also indicate a clear link between the variables that affect the willingness-to-pay for a scrubber and the costs to install it. Stricter emission standards are associated with higher installation costs. Increasing the stringency by one percent (i.e. a one percent reduction in *lnRegNonTableA*), increases costs by 0.437%. Table A boilers pay a substantial premium of 1.79% for each percent the distance to the Powder River Basin increases. This more than outweighs the negative coefficient of *TableA* even for the adopting Table A boiler that is closest to the Powder River Basin, located some 1679 km (1043 miles) away at Petersburg, IN. The negative coefficient of *TableA* stems from an extreme extrapolation.

Boilers of investor-owned utilities located in states with deregulated electricity markets on average report installation costs about 27.8% ($= e^{-0.326} - 1$) lower than those subject to rate-of-return regulation. Boilers that adopted after 1992, which is the first year a Table A boiler adopted, pay lower installation costs than boilers that adopted earlier. The latter confirms findings by Lange and Bellas (2005) who interpret this drop in installation costs after the passing of the 1990 CAAA as an indication of technological progress triggered by the introduction of permit trading. This is an effect on top of an approximately 4% reduction in installation costs per year.

A Heckman model is used to test for the presence of a selection effect which could drive any correlation between variables affecting the WTP for a scrubber and installation costs in OLS regressions. Tables 2 and 3 present estimation results of four regressions.

The main exclusion restrictions used to identify the selection effect are *ControlUnit* and - to a much lesser extend - *IOU*. The former predicts adoption of Table A boilers very well since all but one of the eighteen control units installed a scrubber. At the same time the effect on installation costs seems to be driven by Table A status rather than a boilers being a control unit (see table 8).

The variables included in the adoption equation differ in a number of other ways from those in the cost equation. Instead of *SpecExRate*, which is only available if a scrubber has been installed, the selection equation includes *MaxFlow* and *TotCoal* as measures of the size of the boiler. *MaxFlow* measures the maximum continuous steam flow at 100% load (in thousand lbs/hour) and captures capacity while *TotCoal* gives annual fuel consumption in short tons and indicates actual use in 1999. The adoption equation also includes the variable *DummyFederal* and *DummyLocal* to control for the origin of the most stringent emission regulation. These differences help to identify a potential selection effect.

Regressions (1) is estimated using the simultaneous version of Heckman clustering at the

Table 2: Heckman regressions: Cost Equation

	(1)	(2)	(3)	(4)
	Simult. & Cluster		Two step	
	All	All	Only *IOU*	No cheap
lnInstallCost				
lnSpecExRate	0.674***	0.679***	0.659***	0.688***
	(0.000)	(0.000)	(0.000)	(0.000)
lnRemovalUnit	1.213***	1.218***	1.169***	1.177***
	(0.000)	(0.000)	(0.000)	(0.000)
lnTrainTot	0.572***	0.565***	0.637***	0.600***
	(0.000)	(0.000)	(0.000)	(0.000)
InsrvYearBoiler	-0.0412***	-0.0413***	-0.0460***	-0.0461***
	(0.000)	(0.000)	(0.000)	(0.000)
Dummy1992	-0.862***	-0.854***	-1.248***	-0.594*
	(0.001)	(0.000)	(0.000)	(0.014)
lnRegNonTableA	-0.491**	-0.485***	-0.432***	-0.413***
	(0.002)	(0.000)	(0.000)	(0.000)
lnDistPRBTableA	1.889***	1.903***	2.005***	1.791***
	(0.000)	(0.000)	(0.000)	(0.000)
TableA	-13.05**	-13.18***	-13.51***	-12.54***
	(0.001)	(0.000)	(0.000)	(0.000)
IOUDrg	-0.337*	-0.337**	-0.358**	-0.310*
	(0.016)	(0.005)	(0.010)	(0.014)
Cheap1	-5.318***	-5.311***	-5.279***	
	(0.000)	(0.000)	(0.000)	
Cheap2	-1.082***	-1.086***	-0.984***	
	(0.000)	(0.000)	(0.000)	
SharedScrub	-0.729*	-0.731**	-0.713*	-0.647*
	(0.023)	(0.005)	(0.020)	(0.013)
lnNoBoilers	0.753**	0.755**	0.712**	0.653**
	(0.003)	(0.002)	(0.006)	(0.006)
Constant	81.30***	81.47***	90.84***	90.75***
	(0.000)	(0.000)	(0.000)	(0.000)

p-values in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 3: Heckman regressions: Adoption Equation

	(1)	(2)	(3)	(4)
Adopt				
lnMaxFlow	0.115	0.136	-0.0781	0.204
	(0.634)	(0.534)	(0.753)	(0.404)
InsrvYearBoiler	-0.00948	-0.00946	-0.00387	-0.00691
	(0.613)	(0.526)	(0.823)	(0.698)
lnDistancePRB	0.229	0.214	0.149	0.176
	(0.232)	(0.316)	(0.481)	(0.439)
lnDistPRBTableA	1.512	1.410	1.745	2.042*
	(0.095)	(0.089)	(0.059)	(0.032)
lnTotCoal	-0.0701	-0.0824	-0.0577	-0.0344
	(0.437)	(0.460)	(0.620)	(0.778)
lnRegNonTableA	-1.994***	-1.983***	-1.877***	-1.988***
	(0.000)	(0.000)	(0.000)	(0.000)
TableA	-12.42	-11.63	-14.10*	-16.51*
	(0.072)	(0.064)	(0.045)	(0.022)
ControlUnit	3.047***	2.992***	2.869***	3.178***
	(0.000)	(0.000)	(0.000)	(0.000)
IOU	0.287	0.289		0.0870
	(0.332)	(0.258)		(0.755)
IOUDrg	-0.645**	-0.629**	-0.577*	-0.439
	(0.002)	(0.005)	(0.011)	(0.074)
DummyFederal	-0.608	-0.615*	-0.476	-1.472*
	(0.147)	(0.043)	(0.131)	(0.015)
DummyLocal	0.535	0.562	0.700*	0.722*
	(0.165)	(0.067)	(0.028)	(0.021)
WetBottom	0.450	0.422	0.245	0.545*
	(0.105)	(0.089)	(0.407)	(0.040)
Constant	15.76	15.73	6.868	10.27
	(0.662)	(0.585)	(0.835)	(0.765)
athrho				
Constant	0.328			
	(0.345)			
mills				
lambda		0.0717	0.0529	0.0324
		(0.235)	(0.452)	(0.593)
Observations	838	838	687	831

p-values in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

level of the power plant while regressions (2) - (4) use the two step procedure. Again, column (3) focuses on investor-owned utilities while (4) excludes unusually cheap scrubbers (see above).

There is no significant selection effect in any of the regressions which indicates that the technological and regulatory variables used include the main drivers of installation costs. Table 2 therefore confirms the results of the OLS regressions. Hence, the effects of the regulatory variables are indeed due to price discrimination and not an artifact caused by an selection effect based on the adoption decision.

The main result is therefore that the scrubber producing upstream industry price discriminates on the basis of downstream (environmental) regulation. The size of the mark-up paid by boilers participating in permit trading depends on how far away they are located from the Powder River Basin.

As a further robustness check of this result table 9 in the appendix presents results for the same regressions contained in table 1 but without the interaction variable *lnDistPRBTableA*. It therefore assumes that any mark-up on scrubbers installed at Table A boilers is a constant percentage increase in installation costs. The results confirm that scrubbers installed at Table A boilers are indeed (about three times) more expensive than those at non-Table A boilers.

6.2 The Adoption Decision

The Heckman regressions also reveal what drives adoption decisions (see table 3). In terms of the adoption decision, the main drivers appear to be policy and not technical factors. The stricter the emission standard a boiler is subject to the higher its propensity to install a scrubber - despite the higher costs due to price discrimination. Table A boilers are (weakly) significantly less likely to have scrubbers than similar boilers subject to emission standards - unless they are also control units. Note that this does not imply that the switch from emission standards to permits has reduced adoption incentives for Table A boilers. None of the Table A boilers had a scrubber installed before the permit scheme was initiated, but two dozen boilers in our sample operated one within just five years of permit trading. Nevertheless, Table A boilers were less likely to install a scrubber than comparable non-Table A boilers due to some unobserved differences between the two. The propensity to adopt of Table A boilers increases (significant at the 10% or 5% level) in the distance to the Powder River Basin, again despite the substantial increase in mark-ups this brings about.

Boilers in states which had deregulated electricity markets in 1999 were less likely to install scrubbers. This reflects the distorted incentives to increase the capital base under rate-of-return regulation (Averch and Johnson 1962). It thereby confirms recent findings by Fowlie (2010) who provides evidence that heterogeneity in state-level electricity market regulation distorts power plants' adoption of abatement technologies for nitrogen oxides (NO_x). She also establishes that due to the positive correlation between restructuring of markets and high population density this distortion effectively shifts pollution toward areas where they create more damage. Since SO_2, like NO_x, is a non-uniformly mixed pollutant this result carries over to the present case.

The above results present clear evidence - robust to variations in explanatory variables, estimation technique, sample and model specification - that price discrimination is prevalent in the market for scrubbers installed at coal-fired power plants in the U.S.

6.3 Implications for Diffusion, R&D and Welfare

Market power in an upstream eco-industry has been linked to suboptimal diffusion of abatement technologies in the theoretical literature (David and Sinclair-Desgagne 2005, Requate 2005, Perino 2010, David et al. 2010). The empirical evidence presented above suggests that mark-ups on scrubbers are substantial and hence adoption of scrubbers could be expected to be well below the socially optimal level which, if indeed the case, would make a strong point to take such effects into account in policy design. However, and maybe more importantly, mark-ups are very sensitive to the type and stringency of environmental regulation.

In general the effects of third-degree price discrimination on diffusion and welfare are ambiguous. However, the nature of the market for scrubbers allows to draw some conclusions. Because for most adopting boilers in the sample there is exactly one scrubber, the simple reservation price model presented by Varian (1985), where each buyer demands one unit of the good if the price is below a given reservation price, is a reasonably good approximation of the market for scrubbers. Varian (1985) shows that in such a setting third-degree price discrimination increases output and welfare as it constitutes a move toward perfect price discrimination which redistributes rents but does not distort the allocation.

The degree of sophistication of price discrimination revealed above shows that the upstream eco-industry makes effective use of observable information about power plants' willingness-to-pay. This suggests that price discrimination is likely to increase the number of scrubbers installed compared to non-discriminatory pricing. The higher degree of diffusion reduces the welfare costs of market power, increases the upstream industry's profits and thereby research incentives for improvements in abatement technology.

There are also implications for the relative effectiveness of instruments in environmental regulation. The introduction of tradable permits increased the demand for scrubbers among the participating boilers. This effect and hence the attractiveness of permits over emission standards is dampened by the increase in mark-ups for Table A boilers. However, this effect is smaller than it would be under a less or non discriminatory pricing because the increase in mark-ups is contingent on the location of the power plant.

7 Conclusion

Using the regulation of sulfur dioxide emissions from U.S. coal fired power plants as an example, it is shown that market power in the upstream eco-industry interacts with the instrument used to regulate pollution externalities. The imperfectly competitive upstream eco-industry charges different mark-ups on the primary abatement technology depending on the type of regulatory instrument a boiler is subject to. Power plants regulated by tradable permits face substantially higher prices than their counterparts that are subject to emission standards. This constitutes an additional channel by which instrument choice in environmental regulation affects abatement costs.

Mark-ups on new technology are a crucial driver not only of diffusion but also of research incentives, which has repercussions on dynamic efficiency of environmental regulation. The sophistication of third-degree price discrimination evident in the market for scrubbers suggests that diffusion, R&D incentives and welfare are higher than under non-discriminatory price setting.

The interplay between downstream regulation and price discrimination in the market for abatement technology is substantiated by evidence that state-level electricity market restructuring also affects the price power plants pay for a scrubber. Investor-owned utilities in states with deregulated electricity markets pay less than their counterparts that are subject to rate-of-return regulation.

So far price discrimination by an imperfectly competitive eco-industry has been ignored both by the theoretical and empirical literature studying the link between environmental instrument choice and diffusion of abatement technologies. The evidence presented suggests that this practice is empirically relevant at least in some markets and requires further theoretical and empirical research to better understand how market power and price discrimination in the eco-industry should be reflected in the design of environmental regulation.

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Table 4: Summary Statistics: Table A Units with Scrubbers

Variable	Mean	Std. Dev.	Min	Max
Boiler				
MaxFlow	3200.2	2587.1	840	9300
InsrvYearBoiler	1968.3	6.72	1954	1974
WetBottom	.25	.4423	0	1
TotCoal	1203.6	966.6	254	3819.9
Regulation	4.33	2.05	.2	6.5
DummyFederal	.125	.3378	0	1
DummyLocal	0	0	0	0
DistancePRB	2027.6	314.4	1679	2663
IOU	.8333	.3807	0	1
IOUDrg	.3333	.4815	0	1
Scrubber				
SpecExRate	1450788	1123581	145000	4206000
RemovalUnit	3.03	.4245	2.3	3.91
InsrvYearScrubber	1995.1	1.33	1994	1999
Salable	.75	.4423	0	1
TrainTot	1.25	.8076	.5	3
ControlUnit	.5	.5108	0	1
Dummy1992	1	0	1	1
SharedScrub	.3333	.4815	0	1
NoBoilers	1.33	.4815	1	2
InstallCost	102342.4	83809.4	51	270408
Observations: 24				

Table 5: Summary Statistics: Non-Table A Units with Scrubbers

Variable	Mean	Std. Dev.	Min	Max
Boiler				
MaxFlow	2031.2	1648.5	215	5410
InsrvYearBoiler	1961.1	10.7	1935	1978
WetBottom	.0488	.2181	0	1
TotCoal	779.2	863.3	0	2905.9
Regulation	.9458	.8244	.1	4
DummyFederal	.0732	.2637	0	1
DummyLocal	.2439	.4348	0	1
DistancePRB	1582.5	700.6	183	2588
IOU	.8292	.3809	0	1
IOUDrg	.3415	.4801	0	1
Scrubber				
SpecExRate	1072774	869699.3	123333.3	3006814
RemovalUnit	1.85	.5909	.59	3
InsrvYearScrubber	1981	7.31	1971	1999
Salable	.1463	.3578	0	1
TrainTot	2.02	1.39	.3333	6
ControlUnit	0	0	0	0
Dummy1992	.1220	.3313	0	1
SharedScrub	.3171	.4711	0	1
NoBoilers	1.78	1.24	1	4
InstallCost	61925.7	50864.7	1262	175927
Observations: 41				

Table 6: Summary Statistics: Table A Units without Scrubbers

Variable	Mean	Std. Dev.	Min	Max
Boiler				
MaxFlow	2120.6	1519.7	375	8000
InsrvYearBoiler	1962.3	7.56	1949	1978
WetBottom	.2422	.4293	0	1
TotCoal	748.0	548.9	21.5	2772.4
Regulation	5.12	2.00	1.125	9
ControlUnit	.0045	.0670	0	1
DummyFederal	.2108	.2108	0	1
DummyLocal	.0583	.2348	0	1
DistancePRB	1901.3	374.9	848	2797
IOU	.8341	.3728	0	1
IOUDrg	.4170	.4942	0	1
Observations: 223				

Table 7: Summary Statistics: Non-Table A Units without Scrubbers

Variable	Mean	Std. Dev.	Min	Max
Boiler				
MaxFlow	1400.5	1397.1	95	9775
InsrvYearBoiler	1959.1	9.52	1906	1978
WetBottom	.1	.3003	0	1
TotCoal	518.7	635.2	0	3573.9
Regulation	3.05	2.02	.3	9
ControlUnit	0	0	0	0
DummyFederal	.1236	.3295	0	1
DummyLocal	.0218	.1462	0	1
DistancePRB	1827.8	585.4	76	2875
IOU	.8127	.3905	0	1
IOUDrg	.3727	.4840	0	1
Observations: 550				

Table 8: OLS regressions with all explanatory variables (no clustering)

	(1)	
lnSpecExRate	0.588***	(0.000)
lnRemovalUnit	1.076***	(0.000)
lnTrainTot	0.468*	(0.016)
WetBottom	-0.279	(0.089)
lnTotCoal	-0.00815	(0.821)
InsrvYearBoiler	-0.0336***	(0.001)
InsrvYearScrubber	0.00694	(0.762)
Salable	0.289*	(0.036)
Dummy1992	-0.881	(0.056)
lnRegNonTableA	-0.420*	(0.024)
lnDistancePRB	0.0491	(0.739)
lnDistPRBTableA	2.311***	(0.000)
TableA	-16.48***	(0.000)
ControlUnit	0.000276	(0.999)
IOU	-0.149	(0.430)
IOUDrg	-0.412*	(0.022)
Cheap1	-5.129***	(0.000)
Cheap2	-1.293***	(0.000)
SharedScrub	-0.864	(0.065)
lnNoBoilers	0.863*	(0.033)
Constant	53.82	(0.312)
Observations	65	
Adjusted R^2	0.978	
DoF	44	

p-values in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 9: OLS regressions without *lnDistPRBTableA*

	(1)	(2)	(3)	(4)
	Cluster *PlantID*	No-clustering		
	All	All	Only *IOU*	No cheap
lnSpecExRate	0.821***	0.821***	0.821***	0.824***
	(0.000)	(0.000)	(0.000)	(0.000)
lnRemovalUnit	1.201***	1.201***	1.149***	1.157***
	(0.000)	(0.000)	(0.000)	(0.000)
lnTrainTot	0.384*	0.384**	0.510**	0.442***
	(0.043)	(0.003)	(0.005)	(0.001)
InsrvYearBoiler	-0.0418***	-0.0418***	-0.0453***	-0.0461***
	(0.000)	(0.000)	(0.000)	(0.000)
Dummy1992	-0.841**	-0.841***	-1.336***	-0.517
	(0.002)	(0.000)	(0.001)	(0.085)
lnRegNonTableA	-0.388*	-0.388***	-0.314*	-0.324**
	(0.014)	(0.001)	(0.018)	(0.010)
TableA	1.124**	1.124***	1.752***	0.867*
	(0.010)	(0.000)	(0.000)	(0.015)
IOUDrg	-0.0383	-0.0383	-0.0435	-0.0165
	(0.845)	(0.769)	(0.769)	(0.902)
Cheap1	-5.653***	-5.653***	-5.889***	
	(0.000)	(0.000)	(0.000)	
Cheap2	-1.010***	-1.010***	-0.785**	
	(0.000)	(0.000)	(0.004)	
SharedScrub	-0.412	-0.412	-0.271	-0.396
	(0.365)	(0.187)	(0.460)	(0.202)
lnNoBoilers	0.367	0.367	0.300	0.337
	(0.301)	(0.178)	(0.308)	(0.212)
Constant	80.65***	80.65***	87.42***	89.01***
	(0.000)	(0.000)	(0.000)	(0.000)
Observations	65	65	54	58
DoF	30	52	41	47

p-values in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$