Corporate Governance, Electricity Restructuring, and the Cost of Capital for Abatement Technologies*

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Abstract

A firm's cost of raising financial capital is important to its pollution abatement investment decisions and in turn to its environmental performance. The rapid growth in investor efforts to influence firms' Environmental, Social, and Governance (ESG) profiles has renewed interest in the extent to which investor preferences and oversight can affect firms' cost of capital. The ability of investors to directly influence firm-level decisions, however, depends on the corporate governance mechanisms in place—the provisions that determine the relative control rights of shareholders compared to those of managers. In this paper, we aim to answer whether the strength of corporate governance, relative to a firm's financial structure and regulatory environment, affects its cost of capital for abatement investment aimed at complying with environmental regulation. Specifically, we study the U.S. electricity industry's compliance with a major U.S. emissions trading program. We find that two of three well-known governance indices have no relationship to the implied cost of abatement capital. For the one index that does show a relationship, results suggest that limiting shareholder power—rather than giving shareholders more power—may reduce the cost of capital. These results are on contrary to the conventional wisdom that "the most important benefit of good governance is to raise capital at better terms" (Doidge et al., 2007). These also imply that investor activism aimed at improving firms' corporate governance might impede their environmental progress. That is, ESG investing might have goals that are in conflict with each other. We also find that the impacts of a firm's corporate governance on its cost of capital depend on the electricity restructuring status of plants the company owns. Improving governance raises the cost of capital for abatement investment in deregulated plants but has no significant impacts on regulated plants. This is consistent with the fact that regulated plants are allowed to recover capital costs through raising electricity prices, and are thus less dependent on governance quality to raise capital.

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1 Introduction

In the absense of stringent environmental regulation perhaps due to lack of political will, firms' voluntary environmental actions become important. What are firms' characteristics that make a firm more likely to reduce emissions? The literature has shown that management practices, ownership structures, financial status, and governance system matter (reviewed later). This study focuses on the linkage between corporate governance and the pollution control costs, specifically, the cost of raising financial capital for abatement investment. A firm's cost of raising financial capital is important for its investment decisions and thus its financial performance (Chava et al., 2009; Midrigan and Xu, 2014). Similarly, a firm's cost of capital could affect its pollution abatement investment and environmental performance (Andersen, 2016).[1] Further, a firm's project-specific cost of capital, including that for abatement projects, often differs from the firm's overall cost of capital. It is therefore important to understand the factors that determine a firm's cost of capital for abatement investment.

Corporate governance has been widely studied and shown to be important to firms' overall cost of capital (e.g. Himmelberg et al., 2004; Chen et al., 2009; Ashbaugh-Skaife et al., 2006). Its impacts on the cost of capital for abatement investment, however, are less understood. As mentioned, project-specific costs of capital often differ from a firm's overall cost of capital. A common measure of a firm's cost of capital is the weighted average cost of capital (WACC)—the weighted average of the cost of equity and the cost of debt across all projects of a firm. This measure, however, cannot represent the cost of capital for a specific project of the firm. The firm-wide cost of capital reflects the average risk of the firm's investments, while the project-based cost of capital reflects the idiosyncratic risk of a specific project (Brealey et al., 2009).[2] In addition, certain projects may be preferred by financial sectors and therefore enjoy lower costs of capital.[3]

The impact of corporate governance on the cost of capital for abatement investment may differ from its impact on the overall cost of capital for several reasons. First, the impact of corporate governance on the cost of debt and the cost of equity can be different, and abatement investment can involve a different composition of debt and equity than other investments. Second, abatement investment may have different risk than other projects and, as we will show later, corporate governance can affect managerial risk-taking behavior.

In this paper, we aim to determine whether the strength of corporate governance, relative to a firm's financial structure and regulatory environment, affects the cost of capital for

[1] According to Fowlie (2010), installing abatement technology for a coal-fired boiler can cost \$71.21 per kW for the most effective technology. Using a 10% average authorized rate of return in regulated markets in recent years as a cost of capital (Rode and Fischbeck, 2019) would yield a cost of financial capital of \$7.12 per kW. Given the average boiler capacity of 248 MW in Fowlie (2010)'s dataset and a common capacity factor 0.7, the cost of financial capital for the average boiler would be \$1.24 million per year—a not insignificant amount.

[2] In practice, financial managers usually calculate the WACC and send this to project managers to determine the cost of capital for a given project. Project managers may then adjust the WACC up or down to reflect the project's higher- or lower-than-average risk.

[3] The COP26 climate summit in Glasgow advocated for financial sectors to fund more clean energy projects.

abatement investment. Two notes on terminology: (i) because the cost of capital is the rate of return expected by suppliers of the capital, it thus is also the discount rate managers use to discount future cash flows generated by a project, we henceforth use the terms “cost of capital” and “discount rate” interchangeably; (ii) we will use the term “capital cost” to refer to the overall investment required to adopt an abatement technology, reserving the term “cost of capital” for the cost of raising financial capital to fund that investment.

We examine the effects of financial characteristics and corporate governance in the context of coal-fired power plants regulated by a major U.S. NO_x emissions trading program—the NO_x budget program. To comply with the program, power plant managers may invest in a range of different NO_x control technologies, purchase emission permits, or choose some combination of both. Each of these options entails a different tradeoff between capital costs and variable costs. Observing which option managers choose therefore allows us to infer the discount rate or cost of capital they apply when making compliance decisions.

Therefore, the main question addressed in this paper becomes: “Does a firm’s corporate governance affect the discount rate applied to abatement investment for compliance with a major U.S. NO_x emissions trading program?”

More specifically, using an engineering software program, we are able to calculate the expected unit-specific cost (both the physical capital cost and the variable operating cost) of adopting different NO_x control technologies for coal-fired boilers under the program, and match these costs to financial information on the firms that own the power plants operating these boilers. We then estimate a mixed logit model of the plant managers’ compliance choices that controls for boiler-level variations in each technology alternative’s costs, as well as for the firms’ financial characteristics and corporate governance quality, as measured by several well-known governance indices.

We find that two of three well-known governance indices have no relationship to the implied cost of abatement capital. For the one index that does show a relationship, results suggest that limiting shareholder power—rather than giving shareholders more power—may increase abatement investment. We find a much stronger relationship between abatement capital costs and fundamental corporate finance characteristics such as firm size (measured by book value of total assets), financial leverage, growth opportunities, and liquidity.

More specifically, we find that governance practices that shield CEOs from shareholder lawsuits have no effects on the cost of capital for abatement, while practices that are strong anti-takeover defenses reduce the cost of capital. At least two theories can explain why weaker governance, as indicated by more anti-takeover provisions, could lead to a lower cost of capital.First, managers tend to prefer lower-risk projects than do shareholders. In the face of uncertainty over future permit prices, adopting capital-intensive technologies is a less risky strategy than relying on permit purchases to comply with regulations. Because debt-holders dislike risk as well, stronger managerial entrenchment, skewing compliance decisions towards use of low-risk technologies, may lead to a lower cost of debt. Second, takeovers in the form of leveraged buyouts can significantly increase firms’ financial risk, by raising leverage ratios. Therefore, stronger anti-takeover defenses could lead to a lower cost of debt via this channel as well. Moreover, because electric utilities heavily rely on debt financing, it is plausible that a lower cost of debt implies a lower cost of capital overall.

We also examine whether electricity market regulation may moderate the effect of governance on abatement investment. The wave of electricity-sector restructuring during the sample period resulted in significant variation in regulatory status across plants. Importantly, traditional "regulated plants" are allowed to cover the cost of prudent capital investments through raising electricity prices, whereas "deregulated plants" have to rely on markets. Thus, governance quality should matter less to regulated plants' abatement investments. Consistent with this, we find that the effect of corporate governance is only significant for deregulated plants.

This paper makes several contributions to the environmental and finance literatures. First, previous literature has documented significant effects of corporate governance on firms' environmental performance, without demonstrating the underlying mechanisms. We argue that the cost of capital could be one channel. Second, to our knowledge this study is the first to examine how environmental regulation can interact with firms' financial characteristics to determine firms' pollution-control costs. Third, whereas the finance literature typically studies the effect of corporate governance on the overall cost of capital and rarely on the project-specific cost of capital. Finally, the paper uses tradeoffs between capital and variable costs implied by a firm's observed choices to estimate its cost of capital for specific projects. This is in contrast to the conventional method, which first estimates the overall cost of capital and then adjusts for project-specific risks estimated from investor surveys (Steffen, 2020).

The rest of the paper is organized as follows. Section 2 reviews the literature on governance, financial characteristics, cost of capital, environmental performance, and emissions regulation. Section 3 provides background on the NO_x regulatory environment studied in this paper. Section 4 presents a model to frame the interpretation of empirical results and Section 5 extends this model to the empirical methodology. Section 6 describes the data while Section 7 describes the estimation procedure. Section 8 presents and discusses the empirical results while Section 9 concludes.

2 Literature Review

2.1 Impacts of corporate governance on the cost of capital

The finance literature has supplied a number of theoretical arguments, supported by empirical evidence, for how corporate governance may affect the cost of capital. However, there is no agreement on the direction of the effect. More specifically, the literature has largely focused on the separate effects of corporate governance on either the cost of equity or the cost of debt. These effects are usually found to be in opposite directions, which may not be surprising given the existence of bondholder-shareholder conflicts.[4]

[4]Bondholders would like firms to undertake low-risk projects because their returns are concave in project profits: they receive any profits up to their fixed claim, but none above. Shareholders, in contrast, want firms to undertake more risky projects, because their returns are convex: they receive no profits up to the

It is intuitive that strong governance, which gives shareholders more control rights, should lead to lower cost of raising capital from them. John et al. (2008) propose a theory that poor shareholder protection entails the need for dominant owners, who then cannot be trusted to protect minority shareholder rights. The equilibrium result is a high cost of equity capital. Lombardo and Pagano (1999) argue that weak governance increases the monitoring cost of shareholders, who then demand a higher rate of return to compensate for that cost. The empirical evidence generally supports the negative association between corporate governance and the cost of equity. For example, McKinsey's surveys suggest that investors are willing to pay a significant premium for shares of firms with good governance (Coombes and Watson, 2000). Chen et al. (2009) demonstrates a significantly negative effect of corporate governance on the cost of equity in emerging markets. Using U.S. data, Cheng et al. (2006) find that firms with stronger shareholder rights and a greater level of financial transparency tend to have a lower cost of equity.

The impact of corporate governance on the cost of debt is less straightforward. On the one hand, managers prefer more conservative investments than shareholders, due to (i) costly managerial effort or difficult decisions related to risky investments—the so called "quiet life" preference of managers discussed by Bertrand and Mullainathan (2003), (ii) the concerns for private benefits that they could capture (John et al., 2008), and (iii) managers' nondiversifiable human capital (Himmelberg et al., 2004; Bradley and Chen, 2011; Holmstrom and Costa, 1986). Because bond-holders, too, prefer firms to take risk-averse strategies, weaker governance, which implies stronger manager entrenchment, may lead to a lower cost of debt. On the other hand, strong shareholder rights reduce opportunistic behavior by managers. This tends to increase overall firm value, resulting in gains to both shareholders and debtholders (Ashbaugh-Skaife et al., 2006). In addition, shareholders with strong rights can induce managers to disclose information that exposes the default risk of loans (Bhojraj and Sengupta, 2003). Stronger governance may thus lead to a lower cost of debt.

Evidence has largely pointed to a positive relation between corporate governance and cost of debt. Bradley and Chen (2011) find that firms with governance provisions that insulate managers from liability enjoy a lower cost of debt. The reason appears to be that managers of such firms have more power to enact their own preference for low-risk investment strategies. In addition, Klock et al. (2005), Ashbaugh-Skaife et al. (2006), and Chava et al. (2009) show that firms with more anti-takeover provisions tend to have a lower cost of debt. They argue that takeovers in the form of leverage buyouts can significantly increase firms' financial risk by adding debt to increase shareholder wealth (see also Warga and Welch (1993) for this argument). In contrast, Bhojraj and Sengupta (2003) find that governance quality indicated by board independence and institutional ownership share is negatively related to the cost of debt. Overall, it appears that different types of corporate governance practices may have heterogeneous effects on the cost of debt.

The main governance measure used in Klock et al. (2005), Ashbaugh-Skaife et al. (2006), and Chava et al. (2009) is the G-index, developed by Gompers et al. (2003). This index, described in more detail in section 6 below, identifies 24 different governance provisions that restrict shareholder rights, and counts how many of those provisions a firm has in place.

bondholders' claim, but all the profits above.

These provisions also in effect measure the level of takeover defenses (Chava et al., 2009). Bradley and Chen (2011) develop what they call the “L-index”: a subset of three of these 24 provisions that specifically protect managers from financial or legal liability from shareholder lawsuits. They find that these three provisions, which are arguably not strong anti-takeover mechanisms, are negatively associated with the cost of debt. More importantly, they find that after netting out the L-index provisions, the remaining G-index provisions are positively, not negatively associated with the cost of debt. This contrasts with findings in the earlier literature that found a negative association for the G-index as a whole. A third index, the “E-index” developed by Bebchuk et al. (2009), counts the subset of six of the 24 provisions that have systematically drawn substantial opposition from institutional shareholders. Bebchuk et al. show that this subset is largely responsible for the negative correlation between the G-index as a whole and shareholder value.

For our purposes, the papers above point to the possibility that the impact of governance on the cost of capital may be heterogeneous across different dimensions of governance. This is indeed what we find: shareholder rights measured by E-index are negatively related to the cost of capital for abatement investment, whereas both the G-index and L-index have insignificant effects.

2.2 Financial characteristics and the cost of capital

Like the corporate-governance literature, the literature relating firms’ financial characteristics to their cost of capital has largely focused separately on either the cost of equity or the cost of debt. The financial variables that are often studied are liquidity, firm size, financial leverage, and growth opportunities.

Liquidity, measured by various ratios of liquid assets to current liabilities, refers to a firm’s ability to meet its short-term debt obligations. Illiquid firms have high default risk and thus also high costs of capital. Focusing on different dimensions of liquidity, Ortiz-Molina and Phillips (2014) find that firms with more illiquid real assets have higher costs of capital, while Amihud and Mendelson (1986) and Saad and Samet (2017), focusing on stock illiquidity, find that the cost of equity increases in illiquidity.

Firm size, measured by the book value of assets, is generally negatively related to both the cost of debt (Petersen and Rajan, 1995; Rand, 2007; Chava, 2014) and the cost of equity (Chava, 2014). Larger firms are easier to monitor and tend to be more established. They can therefore access capital on better terms.

The evidence on the relationship between financial leverage and the cost of capital is mixed. Chava (2014), using a database covering the largest 3000 U.S. publicly traded companies in the U.S., find that higher leverage is associated with higher cost of both equity and debt. In contrast, Petersen and Rajan (1995), using a dataset of U.S. small businesses, do not find any significant effect of leverage on the cost of debt. Similarly, Chava and Purnanandam (2010), using data from firms that are publicly traded on the AMEX, NYSE, or NASDAQ, do not find a significant effect of leverage on the cost of equity.

The evidence on the relationship between growth opportunities and the costs of capital is also mixed. Some studies find that firms with high growth opportunities have higher costs of debt. A possible explanation is that such firms usually carry intangible assets, which are difficult for debtholders to monitor (Ethier and Horn, 1990; Ethier, 1986). Others find that firms with high growth opportunities tend to have lower costs of equity (La Porta, 1996; Gebhardt et al., 2001). One explanation is that these firms earn low subsequent returns, because of analysts' overoptimism in these firms. Chava and Purnanandam (2010), however, do not find a significant effect of growth opporunities on the cost of equity.

2.3 Firm characteristics and environmental performance

Our paper relates also to the literature on firm characteristics that affect firms' environmental performance. This literature has found that management practices (Bloom et al., 2010; Martin et al., 2012), foreign ownership (Cole et al., 2008), firm size (Arimura et al., 2008; Harrington et al., 2008), financial status (including liquidity, solvency and profitability) (Earnhart and Segerson, 2012), and geographic scope of operations (Ervin et al., 2013) can all significantly affect environmental performance. Of particular interest are studies that explore the impact of corporate governance on different environmental-performance measures. Amore and Bennedsen (2016) examine the impact of governance on green innovation, Gilbert et al. (2015) the impact on NO_x emissions rates, and Fisher-Vanden and Thorburn (2011) the impact on membership in the EPA's Climate Leaders program. These papers typically do not demonstrate a clear channel through which corporate governance affects environmental outcomes, however. Our paper proposes and tests such a channel—the cost of capital.

2.4 Economic regulations and abatement investment decisions under emissions trading programs

A final related strand of literature examines the impact of economic regulations on abatement investment decisions to comply with emissions trading programs (e.g., Fowlie, 2010; Keohane, 2006; Arimura, 2002). Closest to our paper is Fowlie (2010), who examines the effect of electricity regulation on the outcomes of the NBP program. She finds that rate-based regulated plants are more likely to choose capital-intensive compliance options and to emit less. While recognizing that regulated plants likely have lower costs of capital, because of their lower risk of default as well as certain tax advantages, she does not further examine what factors determine the cost of capital for abatement investment. Nor does she explore the role of corporate governance.

3 Background

3.1 The NO_x Budge Program

Transportation of NO_x from upwind states to downwind states significantly contributes to the nonattainment of federal ambient standard for ground-level ozone in the Northeastern United States. The EPA in late 1997 called on states that significantly contributed to ozone non-attainment in other states to amend their state implementation plan (SIP) and limit emissions from large stationary sources. This rule is referred to as the "NO_x SIP Call" (Burtraw and Szambelan, 2009). The rule assigns each state an emission budget and allows the states to participate in a cap-and-trade program, known as the NO_x budget trading program (NBP).[5] The NBP program mandates a more stringent emission allowance allocation, equivalent to achieving an emission standard of 0.15 lbs/MMbtu. In 2000, the SIP Call was upheld by the US Court of Appeals. Hence, firms made compliance decisions with this rule most likely between 2000 and 2004, right before the program started.

3.2 Compliance choices

Facing the stringent rules of the NO_x trading program, firms have several compliance options. They can invest in abatement technologies, buy emissions permits, retire generating units, and/or reduce unit utilization rates (Fowlie et al., 2012). In this paper, we ignore the compliance option of retiring generating units, because EPA modeling in 1998 indicated that less than 3% of the capacity would be retired because of the NBP program (U.S. EPA, 1998)

In addition, following (Fowlie et al., 2012) because coal-fired generating units, which account for 90% of the emissions, run continuously except for maintenance, we ignore the option to reduce unit utilization rates as well. Thus, in this paper, we assume that firms comply by investing in abatement technologies, buying permits, or some combination of both.

There are various NO_x abatement technologies a firm can choose from. They differ in their capital cost, variable operating cost, and also NO_x reduction efficacy. The main technologies are Overfire Air (OA), various Low NO_x Burners (LNB) technologies, Fuel Reburning/Combustion Modifications (CM), Selective Catalytic Reduction (SCR), and Selective Non-Catalytic Reduction (SNCR). Many firms employ combinations of these technologies. The set of technologies than can be applied to a given boiler differs by the boiler's firing type, however (Electric Power Research Institute, 1999; U.S. EPA, 1999). There are three main such types: wall firing, tangential firing, and cyclone firing.

Two factors that significantly affect a firm's compliance choices are the expected physical capital cost and variable cost of adopting a particular abatement technology (Fowlie, 2010).

[5] Prior to the NBP program, Congress formed the Ozone Transportation Commission (OTC), composed of representatives from 13 states and counties in the Northeast and Mid-Atlantic regions, to develop strategies to help the northeastern states achieve ozone attainment (U.S. EPA, 2003; Burtraw and Szambelan, 2009). The OTC also developed a NO_x emissions trading program for large point sources in these regions from 1999 to 2002. Our study focuses on the NBP pogram rather than this OTC program.

The expected variable cost includes the expected operating cost of the technology and the cost (benefit) of purchasing (selling) emissions permits. The latter depends on the NO_x reduction efficacies of a particular technology. The physical capital cost, operating cost, and reduction efficacies vary across different technologies and across boilers that adopt the same technology with different technical specifications. In general, the more capital-intensive a technology is, the higher is the NO_x reduction percentage that can be achieved, and thus the lower the cost of purchasing permits, which usually translates to lower variable costs. Among available technologies, Selective Catalytic Reduction (SCR) is the most capital-intensive technology, which can reduce NO_x emissions by up to 90%. Overfire Air (OA), the least capital-intensive technology, can reduce emissions by 10%-30%, depending on boiler technical characteristics. Figure 1 shows the capital cost (K) and variable cost (V) of several technologies available to a 217MW boiler in our sample. We can see that there is a clear tradeoff between the capital cost and variable cost. In particular, firms that choose the "no retrofit (NA)" option have the highest variable cost, because of the high cost of purchasing permits to offset their uncontrolled emissions. This capital cost/variable cost tradeoff is key to the analysis of this paper, as it can be used to estimate the discount rate applied by power plant managers when choosing among abatement technologies.

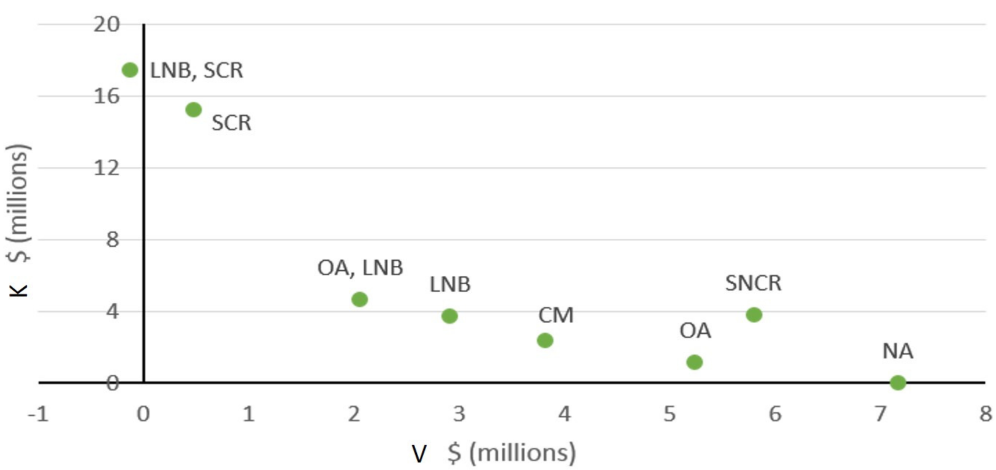

Figure 1: The tradeoff of calculated capital cost and variable cost for a 217MW Wall-fired boiler

3.3 Corporate governance provisions

In a publicly traded company, shareholders are the owners of a company and managers are delegated to maximize the shareholders' wealth. However, just like in any delegation setting, agency problems may arise. Managers have the tendency to cater to their own benefit (e.g., appropriate the capital provided by shareholders) at the cost of shareholders. Hostile takeovers and proxy fights are two common ways in which shareholders can exert their control rights and protect their benefits. A hostile takeover enables a company to acquire a target firm without the consent of the firm's directors but only the approval of its shareholders. This therefore subjects corporate control rights to market competition. Proxy fights enable a group of shareholders who are dissatisfied with some area of a firm's operations to impose change in that area. Shareholders typically try to vote out the board of directors that opposes the change. Firms, however, can install a variety of governance provisions to prevent shareholders from exercising control rights through the aforementioned channels. The Investor Responsibility Research Center (IRRC) tracks 22 of these governance provisions that appear in corporate charters, bylaws, or other rules of large corporations. In addition, it tracks whether the firms are covered under six state anti-takeover laws. Four of these anti-takeover laws overlap with firm-level provisions, which leaves 24 distinct provisions. Gompers et al. (2003) categorize these provisions into three main tactics: delaying tactics that deter hostile takeovers by, for example, slowing down replacement of board directors; voting tactics that restrict shareholders' voting rights in elections and bylaw/charter amendments; and protection tactics that shield directors/managers from financial and legal consequences of shareholder lawsuits. In this paper, we examine the aggregate effect of these 24 governance provisions on firms' NO_x abatement technology choices. Because some of these governance provisions may have different effects than others, we also separately examine the effects of specific dimensions of these 24 provisions. These dimensions are described in Section 6.

4 Theoretical model

We now introduce a stylized model based on Bohi and Burtraw (1992) and Fowlie (2010) to guide our empirical investigation. The model illustrates the important linkage between corporate governance and the cost of capital for abatement investment. Because the incentives of managers differ in deregulated versus regulated markets, the model must account for these differences.

Power plants in regulated electricity markets are allowed to earn a rate of return on investment of physical capital by adjusting their electricity price, provided the investment is "prudent."

They can also make rate adjustments to recover variable costs of purchasing emissions permits and operating abatement technologies. Plants in restructured electricity markets, however, have to depend on the market to recover these costs. These markets commonly conduct a uniform clearing price auction in which electricity generators place bids. An independent market administrator then orders the bids and dispatches the generators from the lowest to the highest bids, until electricity demand is satisfied. The electricity price is determined by the marginal cost of the generators that serve the last unit of electricity needed to satisfy the demand. These generators are referred to as price-setting units or marginal bidders. Generating units that have low variable costs relative to others supplying the market are usually never price-setting units and cannot pass through higher environmental compliance costs in the form of a higher price. Generating units in restructured electricity markets also cannot recover their fixed capital costs of investing in abatement technology. These differences between regulated and deregulated plants imply different incentives of managers of deregulated plants and regulated plants.

4.1 Deregulated plants

In principle, power plants in restructured electricity markets may be able to pass on some of their compliance costs through increases in the wholesale electricity price, namely if their generating units happen to be marginal. In practice, however, coal plants are rarely marginal, so that we can treat them as price taking.

If so, then the manager of any unit n, which produces a given amount of electricity q_n, will choose a compliance option with capital cost K_n and per-kWh variable cost v_n that minimizes the overall cost of complying with the emissions trading program. That is, the manager's optimization probem is

$$\min_{K_n, v_n} C_n = v_n q_n + l_n K_n, \tag{1}$$

subject to

$$v_n q_n = o_n q_n + [E(q_n) - A(K_n) - \widehat{E}]p^e, \tag{2}$$

where

$$l_n \equiv \frac{r_n(1+r_n)^{T_n}}{(1+r_n)^{T_n} - 1}. \tag{3}$$

The annual compliance cost includes annual variable cost $v_n q_n$ and amortized annual capital cost $l_n K_n$, where l_n is the annualized cost factor, which reflects amortization over a period of T_n; r_n is the cost of capital for the compliance option.

As mentioned, there is a capital cost/variable cost tradeoff in compliance decisions. This tradeoff is reflected in equation (2). The operating cost per kWh for the compliance choice is denoted o_n. The larger is the capital cost of the compliance choice, the higher is the associated abatement level, $A(K_n)$. This consequently leads to lower permit costs $[E(q_n) - A(K_n) - \widehat{E}]p^e$, where $E(q_n)$ represents the pre-retrofit emissions that depend on the amount of electricity generated, $\widehat{E}$ is the emissions rate standard, and p^e is the permit price. Given that a technology's annual operating cost per kWh is usually independent of its capital cost, a higher capital cost is typically associated with a lower variable cost. This capital cost/variable cost tradeoff, as illustrated by the least-compliance-cost frontier shown in Figure 1, can be expressed as $K_n = K(V_n)$, as implicitly defined by (2) for any given o_n, q_n, $\widehat{E}$, and p^e, with $V_n \equiv v_n q_n$ and $K'(V_n) < 0$.

The optimal compliance choice (K_n, V_n) will be determined by the tangency point between the lowest attainable isocost line $C_n = V_n + l_n K_n$ and the least-cost frontier, as shown in figure 2. Thus,

$$K'(V_n) = -\frac{1}{l_n}. \tag{4}$$

The manager will choose the compliance option with capital cost and variable cost on the least-cost frontier where the negative slope of the cost frontier equals the inverse of the levelized cost factor. This implies that an increase in the levelized cost factor leads to less capital-intensive investment.

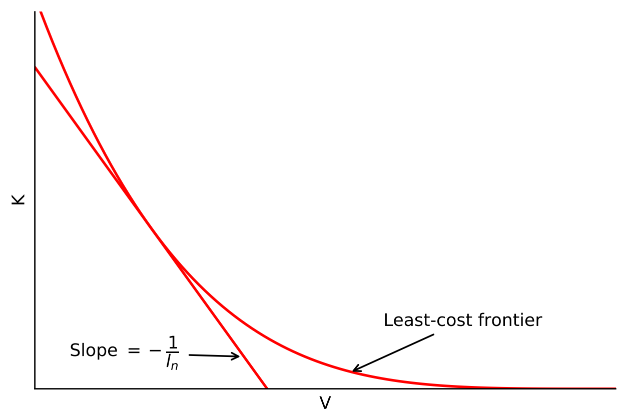

Figure 2: The optimal choices of capital and variable costs of adopting emissions control technologies.

Regulated plants

For regulated plants, too, the manager's objective is to minimize compliance costs borne by the shareholders.

The key difference, however, is that some of the overall compliance costs can be passed on to ratepayers. Let b^v and b^k denote the fractions of respectively the variable cost and capital cost that utilities can pass through to ratepayers, and therefore not borne by shareholders. Also, let R denote the allowed rate of return on undepreciated abatement assets $K_n - l_n K_n$, where $l_n K_n$ is the annual asset depreciation.

The manager's optimization problem can then be written as

$$\min_{K_n, v_n} C_n = v_n q_n + l_n K_n - \{b_k R[K_n - l_n K_n] + b_k l_n K_n + b_v v_n q_n\} \tag{5}$$

subject to the capital-variable cost tradoff constraint (2), where the terms in the braces are compliance cost that can be recovered by the revenue requirement. The revenue requirement consists of fraction of the return on undepreciated assets, the depreciated assets, and the variable cost that could pass through to consumers.

Letting again $V_n \equiv v_n q_n$, the optimal compliance choice (K_n, V_n) is again determined by the tangency point between the lowest attainable isocost line $C_n = (1 - b_v)V_n + [(1 - b_k)l_n - b_k R(1 - l_n)]K_n$ and the least-cost frontier. Thus we have

$$K'(V_n) = -\frac{1 - b_v}{(1 - b_k)l_n - b_k R(1 - l_n)}. \tag{6}$$

This condition implies that increasing the fraction of capital costs borne by the ratepayers increases investment in more capital-intensive compliance options, while the opposite occurs if the fraction of variable costs borne by ratepayers increases. In addition, a higher required rate of return and/or a lower levelized cost factor leads to more capital-intensive investment as well.

Link to the empirical analysis

In sum, our theory predicts that managers with different costs of capital r_n, leading to different levelized cost factors l_n, will choose systematically different optimal compliance options, which morever will vary by electricity-market regulation status. The empirical implication is that factors that affect the managers' cost of capital, such as the governance quality or financial characteristics of their plants' corporate owners, should systematically affect their compliance choices.

5 Empirical Model

Building on the theory above, we use a discrete-choice model to examine how corporate governance quality affects the discount rate that power plant managers apply when determining how much to invest in abatement to comply with the NO_x emissions regulations. The empirical analysis focuses on the compliance decisions made in the period 2000-2004 for the NBP program. Because boilers do not need to install technologies until the compliance deadline, and it is difficult to identify the exact year when compliance choices were made, we model the compliance decisions as static ones.[6,7] That is, we treat the final retrofit choices made between 2000 and 2004 for the NBP program as the compliance choices.[8]

In the discrete-choice model, it is assumed that power plant manager m chooses technology j from J_n types of technology alternatives ($j = 1, \ldots, J_n$) on boiler n to minimize a latent value

$$C_{mnj} = \alpha_j + \beta_m^k K_{nj} + \beta_m^v V_{nj} + \epsilon_{mnj}. \tag{7}$$

Variable K_{nj} is the expected capital cost of adopting technology j for boiler n, and V_{nj} is the expected annual variable cost of adopting the technology. We also include technology-type dummies α_j, to capture unobserved intrinsic features of technologies, such as their reliability or their potential side-effects on production.[9]

The expected variable cost, V_{nj}, is calculated as

$$V_{nj} = o_{nj} q_n + (E_{nj}^{\text{post}} - \widehat{E}) \times h_n \times p_t^e.$$

It includes the expected cost of operating the technology—the per-MWh operating cost o_{nj}

[6] It was reported for many plants that abatement technology installation had been delayed for several years because of labor and machinery shortages (Cichanowicz, 2004).

[7] In principle, it would be possible to model a dynamic technology choice problem, whereby the managers' technology choice in each year up to 2004 depends on the engineering cost of installing technologies at that year as well as emission permits' futures prices. Unit managers did not need to make any technology choice decisions, however, until the compliance deadline.

[8] To illustrate what we mean by "final retrofit choice," if a boiler installed, for example, an LNB in 2002 and a SCR in 2004, then we code the final retrofit choice for the NBP program as "LNB+SCR." If a boiler did not install any new technology between 2000 and 2004, then we code the choice as "no retrofit."

[9] See Electric Power Research Institute (1999) for discussion of such side effects.

(\$/MWh) times the expected ozone-season electricity generation q_n (MWh)[10] —as well as the expected cost or benefit of emission-permit purchases or sales. The latter depends on the expected post-retrofit input emissions rate E_{nj}^{post} (lbs/MMBtu) (i.e., the emissions rate per unit of heat input after the chosen technology is installed), the expected heat input h_{nt} (MMBtu) and the expected NO_x emission permit price p_t^e (\$/lbs). The post-retrofit input emissions rate is in turn calculated as $E_{nj}^{\text{post}} = E_{nj}^{\text{pre}}(100 - R_{nj})/100$, where R_{nj} is the NO_x percentage reduction predicted to be achieved by technology j for boiler n, and E_{nj}^{pre} is the pre-retrofit input emissions rate. The emissions rate standard used to calculate the initial allocation of permits is $\widehat{E}_t$ (lbs/MMBtu); $\widehat{E}_t \times h_{nt}$ is thus the initial number of permits allocated to unit n. Finally, a stochastic component ϵ_{mnjt} is included to reflect unobserved factors that affect compliance choices.

As shown in the theory section, the weight of the capital cost in the overall compliance costs depends on the managers' levelized cost factor and cost recovery parameters (see (1) and (5)). These factors could differ across different managers. We thus allow the capital cost coefficient, β^k, to vary across managers. Since the levelized cost factor is determined by the managers' discount rate and the investment period (see (3)), any factor that affects the discount rate and investment period should affect β^k. As mentioned in the literature review section, corporate governance and firms' financial characteristics potentially affect the cost of capital. In addition, the older the boilers, the shorter the investment horizon for the chosen abatement technology. The capital-cost coefficient should therefore be a function of corporate governance, G_f, firms' financial charateristics, Z_f, and the boiler age, O_n, where G_f is the firm's measure of governance quality (hence the subscript "f").

We model the coefficient on the capital cost and variable cost respectively as

$$\beta_m^k(G_f) = \beta^{kc} + \beta^{kZ} Z_f + \beta^{kD} D + \beta^{kG} G_f + \beta^{kO} O_n + u_m^k \tag{8}$$

and

$$\beta_m^v = \beta^{vc} + u_m^v, \tag{9}$$

where β^{kc} and β^{vc} are constants, and D is a dummy indicator for whether a unit is regulated ($D = 1$) or not ($D = 0$). The final terms u_m^k and u_m^v capture unobserved factors that affect how managers weigh capital and variable costs in their compliance decisions. Examples include cost recovery rules of state Public Utility Commissions (PUCs), which affect managers' ability to pass on capital and variable costs to consumers, as captured by parameters b_v and b_k in the theoretical model. They also include the managers' inherent risk attitudes, which can affect compliance choices because of the uncertainty of future permit prices. Managers who are more risk averse might be more likely to adopt capital-intensive technologies to minimize the permit-price risks.

Rewriting (7) leads to the model for estimation:

$$C_{mnj} = \alpha_j + \beta_m^{kc} K_{nj} + \beta_m^v V_{nj} + \beta^{kZ} Z_f K_{nj} + \beta^{kD} D K_{nj} + \beta^{kG} G_f K_{nj} + \beta^{kO} O_n K_{nj} + \epsilon_{mnj}, \tag{10}$$

[10] We use the historical average of ozone-season electricity generation as a proxy for q_n, as anecdotal evidence suggests that power plant managers use past electricity generation to predict future generation (Electric Power Research Institute, 1999; Fowlie, 2010).

where

$$\beta_m^{kc} = \beta^{kc} + u_m^k. \tag{11}$$

5.1 Identifying the effects of corporate governance and financial characteristics on the cost of capital

To identify the effect of corporate governance on the cost of capital, recall from the theory section that at the optimum for deregulated power plants, we have

$$K'(V_n) = -\frac{1}{l_n} \tag{12}$$

and for regulated plants, we have

$$K'(V_n) = -\frac{1 - b_v}{(1 - b_k)l_n - b_k R(1 - l_n)}. \tag{13}$$

In the empirical model, the capital-variable cost tradeoff, $K'(V_n)$, can be calculated by taking the total derivative of (7) or (10):

$$K'(V_n) = -\frac{\beta_m^v}{\beta_m^k} = -\frac{\beta_m^{vc}}{\beta_m^{kc} + \beta^{kZ} Z_f + \beta^{kG} G_f + \beta^{kO} O_n}.$$

Combining this with (13) yields that for deregulated plants,

$$\frac{\beta_m^{kc} + \beta^{kZ} Z_f + \beta^{kG} G_f + \beta^{kO} O_n}{\beta_m^{vc}} = l_n(r_n) \tag{14}$$

Using the Implicit Function Theorem, we get

$$\frac{\partial r_n}{\partial G_f} = \frac{\beta^{kG}}{\beta_m^{vc}} \cdot \frac{1}{(\partial l_n / \partial r_n)}, \qquad \frac{\partial r_n}{\partial Z_f} = \frac{\beta^{kZ}}{\beta_m^{vc}} \cdot \frac{1}{(\partial l_n / \partial r_n)}. \tag{15}$$

Similarly, for regulated plants, we have

$$\frac{\beta_m^{kc} + \beta^{kZ} Z_f + \beta^{kG} G_f + \beta^{kO} O_n}{\beta_m^{vc}} = \frac{(1 - b_k)l_n - b_k R(1 - l_n)}{1 - b_v}. \tag{16}$$

If b_v, b_k, and R are independent of G_f and Z_f, we find that

$$\frac{\partial r_n}{\partial G_f} = \frac{\beta^{kG}}{\beta_m^{vc}} \frac{1 - b_v}{(1 - b_k + b_k R)} \cdot \frac{1}{(\partial l_n / \partial r_n)}, \qquad \frac{\partial r_n}{\partial Z_f} = \frac{\beta^{kZ}}{\beta_m^{vc}} \frac{1 - b_v}{(1 - b_k + b_k R)} \cdot \frac{1}{(\partial l_n / \partial r_n)} \tag{17}$$

Are b_v, b_k, and R independent of G_f and Z_f? We argue that this is likely the case. Fullerton et al. (1997) suggest that differences across firms in pass-through rates of compliance costs are driven by political and social factors that are not firm-specific. For example, some states, in order to protect the local environment, discourage utilities from buying emissions permits by letting ratepayers bear higher portions of scrubber costs. Conversely, because risk-averse utility managers often prefer to install abatement technology rather than face the uncertainty of future permit prices, PUC regulators, in order to incentivize participation in emissions trading markets, may raise the shareholder portion of abatement cost. This "allowance trading incentive" has been discussed widely in the literature (Bohi and Burtraw, 1991; Rose et al., 1992; Rose and Burns, 1993). Lastly, the governance measure used in the paper is to a large extent determined during the firms' IPO phase (which is much earlier than the compliance periods) and does not change much subsequently.

Since $\partial l_n / \partial r_n > 0$, equations (15) and (17) imply that the sign of the effect of governance on the cost of capital depends on the sign of β^{kG} and β_m^{vc}. To identify the effect of corporate governance, we therefore need to estimate these coefficients. To do so, we control for variables that could potentially correlate with both firms' quality of corporate governance and their cost of capital.

First, there may be financial characteristics of a firm that affect both its governance choices and its cost of capital. We include four such characteristics: liquidity, firm size, financial leverage, and growth opportunities.

Liquidity captures a firm's ability to repay especially its short-term debt.

Commonly, current ratio (current assets/current liabilities) and the quick ratio (current assets less inventory/current liabilities) are used to gauge this ability. However, (Mills and Yamamura, 1998) consider the ratio of free cash flow to current liabilities to be more reliable, since it focuses on assets that are readily available for repaying debts. Thus we use this ratio to measure liquidity.

We therefore use the ratio of free cash flow to current liabilities as our measure of liquidity, and conjecture that a higher ratio should lead to a lower cost of debt. At the same time, firms with more cash holdings are less dependent on external finance and are thus less in need of constraining governance practices in order to acquire capital (Doidge et al., 2007).

Firm size, as measured by total assets, may impact both the cost of capital and corporate governance quality as well. Larger firms attract more media attention, which reduces information asymmetry between shareholders/bondholders and the firm (El Ghoul et al., 2011). In addition, larger firms likely have already built up a reputation and may thus enjoy lower costs of debt (Chava et al., 2009). At the same time, larger firms are more likely to adopt better governance practices, because they enjoy economies of scale in doing so: they can spread the largely fixed costs of governance over a larger asset base (Doidge et al., 2007).

Financial leverage, as measured by the ratio of total debt to assets, also potentially correlates with both the cost of capital and corporate governance quality. Leverage can be used to increase the return of investors and thus may increase the cost of equity capital.

At the same time, according to Arping and Sautner (2010) and Zwiebel (1996), managers may voluntarily increase debt so as to reduce free cash flow, in order to signal to potential corporate raiders or creditors that they have no plans for future empire building. Improved corporate governance restricts manager rights and thus lowers the leverage ratio.

As for growth opportunities, evidence suggests that these correlate positively with firms' governance quality (Klapper and Love, 2004; Durnev and Kim, 2005; Francis et al., 2005). This is expected, as firms with strong growth opportunities all else equal need more capital, which adopting good governance practices facilitates. At the same time, as mentioned in the literature review section, growth opportunities may also correlate with firms' cost of capital, although evidence on the direction of that correlation is mixed. A widely used proxy for growth opportunities is sales growth (La Porta et al., 2002; Doidge et al., 2007), which we use in this paper as well.

Separate from these financial characteristics, a more direct source of correlation between corporate governance quality and the cost of capital is the passage of Sarbanes Oxley Act (SOX) and other disclosure-related financial regulations around 2002 in response to high-profile financial scandals in companies such as Enron and Worldcom.

These regulations aimed to improve firms' corporate governance, but could also affect their cost of capital. Protiviti (2011) reports that most firms spend around \$100,000 to \$1 million annually to comply with the SOX. To put these figures in perspective, note from Figure 1 that this is comparable in magnitude to the levelized capital cost of NO_x control technologies. The regulations therefore likely reduced firms' profitability and hence may have increased their cost of capital. To allay the resulting endogeneity concerns, the governance measures and financial charateristics used in our estimations are pre-2000 and therefore pre-SOX averages. Since compliance choices could be made in any year between 2000 to 2004, using the pre-2000 data also mitigates a direct reverse causality concern (e.g., installing technologies changes financial characteristics).

6 Data

6.1 Data description

The main data used in this paper are the NO_x permit price, the engineering costs of adopting different NO_x control technologies, various measures of firms' governance quality, and financial information on firms.

Permit price

The emissions permit price is assumed to be \$4500 per ton of $NO_x\dot{I}$t is the average future permit price during the compliance period(Fowlie, 2010).

Engineering cost data

In order to help utilities operating coal-fired boilers better comply with NO_x trading programs, the Electric Power Research Institute (EPRI) developed a software program called

"Umbrella" that generates estimates of the engineering cost (the capital and variable operating costs) of a range of NO_x control technologies. The software, which has been used by both regulators and power plant managers to predict coal-power plants' compliance costs (Fowlie, 2010), requires inputs of about 60 boiler-level and plant-level operating characteristics (e.g., boiler capacity, heat rate, and fuel heat content). These operating characteristics are obtained from Air Markets Program Data (AMPD), various Energy Information Agency (EIA) survey forms and other sources. Further details are provided in the Data Appendix. Because no similar software exists for estimating the cost of control technologies for oil and gas units, our paper focuses exclusively on coal-fired boilers. These boilers, however, account for over 90% of NO_x emissions in regions covered by the NBP (Fowlie et al., 2012).

Governance and financial data

We examine the effect of three governance measures on firms' compliance choices. The first one is the G-index, developed by Gompers et al. (2003), which the most widely used measure for governance quality. The index is a simple count of which of a maximum of 24 provisions that restrict shareholder rights a firm has in place. The index therefore ranges between zero and 24, with a higher score indicating weaker shareholder rights.

Importantly, the G-index treats the impact of each of the 24 provisions equally, even though some provisions may have a stronger impact on shareholder rights than others. We therefore also use the E-index (E for "Entrenchment"), constructed by Bebchuk et al. (2009), which has gained popularity because it drives most of the negative correlation between the overall G-index and firm valuation using only six of the 24 provisions. These six provisions are also the ones that have systematically drawn significant opposition from shareholders. Bebchuk et al. also view them as strong anti-takeover defenses. These six provisions include four provisions that restrict shareholder voting rights—the presence of classified boards, limits on bylaw amendments, supermajority requirements for mergers, and supermajority requirements for charter amendments—and two provisions that are the most salient anti-takeover measures—golden parachutes and poison pills. The index is bounded between zero and six, with a higher score indicating greater manager entrenchment and thus weaker shareholder rights.

The third measure for governance quality we use is the L-index developed by Bradley and Chen (2011). The index counts the three of the 24 provisions that protect managers from financial or legal consequences of shareholder lawsuits. Bradley and Chen find that this proxy for manager accountability has a different effect on firms' cost of debt than the remaining G-index provisions. The index ranges from zero to three, with a higher score indicating lower manager accountability and thus weaker shareholder rights.

Because the L-index and E-index are different subsets of G-index, we can use these indices to understand specific channels through which corporate governance affects cost of capital in abatement investment. The E-index measures shareholder rights in a way that affects managerial entrenchment, while the L-index indicates manager accountability. The difference is nuanced but not unimportant.

The governance provisions data are from the RiskMetrics database. Unfortunately, the

Table 1: Summary statistics for unit-level and firm-level characteristics

	Observations	Average	Standard deviation	Min	Max
Capacity (MW)	394	318.87	258.07	22	1310
Unit age (years)	394	39	10.77	0	60
Avg. NO_x Rate (lb/MMBtu)	394	.48	.20	.11	1.4418
Heat rate (Btu/kwh)	394	10123.28	1427.19	6188.9	18941.42
Regulatory status	394	.67	.47	0	1
Cash flow/debt	61	1.71	3.26	.16	44.11
Sales growth	61	.12	.13	-.13	.53
Debt/asset	61	.41	.07	.2	.65
Total asset ($billions)	61	15.14	8.91	0.9	36.62
G-index	61	8.12	2.51	4	16
E-index	61	1.82	1.24	0	5
L-index	61	1.14	.80	0	2.86

Notes: The table summarizes both boiler- and firm-level characteristics using the data for the 394 units used to estimate the model. Regulatory status is 1 if the plant is regulated and 0 otherwise.

database provides these data for only a limited number of publicly traded companies (see Gompers et al. (2003) for more detail).

The data on the financial variables mentioned are obtained from the Compustat database. Because the engineering-cost data are at the boiler level and the governance and financial data at the company level, the three datasets can only be matched using owner names. Gilbert et al. (2015) employ a fuzzy string-matching method to match the owner names of coal-fired power plants that appear in the the EPA's Emissions & Generation Resource Integrated Database (eGRID) to the corporate parent names that appeare in the Compustat and RiskMetrics databases.

Because the coal-fired power plants for which we have engineering cost data are also covered in eGRID, we match the engineering cost data to their matched dataset using a plant identifier. Thus we obtain a dataset that consists of data for engineering cost, financial information, and governance quality.

6.2 A first look at the data

Table 1 shows summary statistics of boiler-level and firm-level characteristics. The summary is based on only those firms for which governance data is available. Our dataset covers 818 coal-fired boilers subject to the NBP program. However, only 394 of these have both cost and governance data available. These 394 boilers belong to 150 power plants owned by 61 publicly traded companies.

Table 2 shows the average capital and variable costs for five major compliance choices. It also shows the mean and standard deviation of both boiler and firm level characteristics for boilers that adopt these five compliance options.

It seems that older units tend to adopt less capital-intensive technologies, presumably due to the shorter time available to recover capital costs before the units are retired. Our main

Table 2: Boiler- and firm-level statistics by compliance choice

	(1) Low NOx burner	(2) No retrofit	(3) Overfire air	(4) SCR	(5) SNCR
Capital cost ($ millions)	3.85	0	2.21	27.5	4.21
	(1.96)	(0)	(0.59)	(12.86)	(1.33)
Operating cost ($ millions)	0.1	0	0.18	1.9	0.22
	(0.1)	(0)	(0.17)	(1.01)	(0.16)
Unit capacity (MW)	176.9	257.6	265.8	553.1	261.3
	(105.1)	(227.1)	(149.7)	(272.7)	(191.0)
Unit age	42.44	41.91	38.77	31.26	39.15
	(10.33)	(10.30)	(6.87)	(9.07)	(12.79)
Preretrofit emissions (lb/MMbtu)	0.49	0.44	0.68	0.49	0.440
	(0.17)	(0.19)	(0.33)	(0.15)	(0.22)
Heat rate (Btu/kwh)	10641.3	10203.3	10291.5	9600.3	9742.0
	(1483.6)	(1618.1)	(1254.2)	(790.2)	(1180.1)
Regulatory status	0.65	0.6	0.5	0.84	0.6
	(0.49)	(0.49)	(0.51)	(0.37)	(0.5)
Free cash flow/debt	1.75	2.03	1.31	1.26	1.54
	(1.35)	(4.51)	(0.71)	(1.08)	(1.58)
Total debt/asset	0.41	0.41	0.41	0.42	0.45
	(0.07)	(0.08)	(0.06)	(0.06)	(0.03)
Sales growth	0.08	0.14	0.1	0.1	0.15
	(0.12)	(0.14)	(0.13)	(0.11)	(0.12)
Total asset ($ billions)	16.08	14.46	17.08	15.03	16.03
	(10.97)	(8.17)	(11.8)	(8.8)	(6.52)
G-index	8.44	7.88	7.56	7.81	10.45
	(1.99)	(2.41)	(2.26	(2.79)	(2.33)
E-index	1.83	1.67	1.28	1.77	3.06
	(1.19)	(1.18)	(0.97)	(1.33)	(0.49)
L-index	1.58	0.99	1.47	1.170	1.24
	(0.83)	(0.79)	(0.96)	(0.71)	(0.74)
Number of units	48	191	22	95	20

Notes: Regulatory status is 1 if the plant is regulated and 0 otherwise. Standard deviations are in parentheses.

factors of interest, namely the corporate governance indices, do not show any systematic relationship with the technologies' capital intensity.

7 Estimation

Both conditional logit and mixed logit models of compliance choices are estimated. The mixed logit model, a generalization of the conditional logit model, can accommodate the possibility that individual agents have random variation in tastes. Instead of assuming homogeneous tastes and estimating a fixed parameter for each variable, the random coefficient logit model estimates the mean and variance of a random parameter for each variable. In addition, the conditional logit model is unbiased only if the assumption of *iid* structure of the error term holds. This assumption is unlikely to hold in the case of correlation in unobserved factors over multiple choices by each individual. The mixed logit model can, in contrast, accommodate a non-*iid* structure of the error terms.

In our setting, the coefficient on the capital cost may vary randomly across managers, due to randomly distributed unobserved factors such as Public Utility Commission (PUC) cost-recovery rules and managers' inherent risk attitudes. In addition, technology choices are observed at the boiler level. Because there can be up to ten boilers in a plant controlled by the same manager, the compliance choices may be correlated across boilers inside a plant.

Following Fowlie (2010), the coefficients β_m^{kc} and β_m^{vc} in (10) are assumed to be bivariate normally distributed, to capture the heterogeneous effect of the unobserved characteristics of a plant on the compliance choices. These coefficients are allowed to vary across plant managers but is assumed to be constant across choices made by the same plant manager.

The unobserved error term ϵ_{mnj} is assumed to be *iid* extreme value. Conditional on $\boldsymbol{\beta_m}$ and covariates $\boldsymbol{X_{mnj}}$, the probability of choosing technology j by manager m for boiler n is therefore

$$P(Y_{mn} = j|\boldsymbol{X_{mnj}}, \boldsymbol{\beta_m}) = \frac{e^{\boldsymbol{\beta_m}'\boldsymbol{X_{mnj}}}}{\sum_{i=1}^{J_n} e^{\boldsymbol{\beta_m}'\boldsymbol{X_{mni}}}},$$

where $\boldsymbol{\beta_m}'\boldsymbol{X_{mn\cdot}}$ is the right-hand side of the empirical cost function (10).

Assume the coefficients β_m^k and β_m^v are distributed according to bivariate normal density $\phi(\boldsymbol{\beta_m}|\boldsymbol{b}, \boldsymbol{W})$, where $\boldsymbol{b}$ is the mean and $\boldsymbol{W}$ is the covariance matrix. Integrating $\boldsymbol{\beta_m}$ over all its possible values then yields the unconditional (on $\boldsymbol{\beta_m}$) choice probability

$$P(Y_{mn} = j) = \int_{-\infty}^{\infty} \frac{e^{\boldsymbol{\beta_m}'\boldsymbol{X_{mnj}}}}{\sum_{i=1}^{J_n} e^{\boldsymbol{\beta_m}'\boldsymbol{X_{mni}}}} \phi(\boldsymbol{\beta_m}|\boldsymbol{b}, \boldsymbol{W}) d\boldsymbol{\beta_m}.$$

The unknown mean $\boldsymbol{b}$ and covariance matrix $\boldsymbol{W}$ along with the fixed coefficients in (10) are parameters that maximize the log likelihood function

$$l(\boldsymbol{b}, \boldsymbol{W}) = \sum_{m=1}^{M} \sum_{j=1}^{J_n} \ln \int_{-\infty}^{\infty} \frac{e^{\boldsymbol{\beta_m}'\boldsymbol{X_{mnj}}}}{\sum_{i=1}^{J_n} e^{\boldsymbol{\beta_m}'\boldsymbol{X_{mni}}}} \phi(\boldsymbol{\beta_m}|\boldsymbol{b}, \boldsymbol{W}) d\boldsymbol{\beta}.$$

These parameters can be estimated using the user-written Stata command "mixlogit", which uses Halton draws to simulate the likelihood function (Hole, 2007). We use 100 Halton draws instead of the commonly used 1000 draws to reduce the computational burden. The literature has found that using 100 draws can have performance close or even superior to that of using 1000 draws (Bhat, 2001; Train, 2009)

7.1 Accounting for residual variance differences across regulatory status

Recall that the objective is to examine the effect of governance on the cost of capital and whether the effects differ across different regulatory status. Logit models are not completely identified, because the coefficients are normalized by the variance (or scale) of the error term. Therefore, the variance and coefficients cannot be separately identified (Train and Sonnier, 2005). In our setting, if there are scale/variance differences across regulated and deregulated units, we cannot know whether any differences in estimated coefficients are due to differences in actual coefficients, scale differences, or both. The random unobserved characteristics that affect compliance choices are likely to vary across regulatory status. PUC rules are important in explaining the compliance choices in regulated plants, whereas in deregulated plants where PUC rules are nonexistent, unobserved financial structure, management style, and managerial risk attitude potentially play an important role.

Two methods can be used to address the identification problem (Fowlie, 2010). First, one can run a pooled model including samples of both regulated and deregulated units, while allowing the variance of the error term to vary across regulatory status. To do so, the model needs to estimate a new parameter δ^{reg}, which indicates the variance (scale) of the error term associated with the regulated units relative to that of the deregulated units. Stata commands "clogithet" and "gmnl" are readily available to estimate a pooled model accommodating scale differences for conditional and mixed logit models, respectively (Gu et al., 2013).

The second approach is to simply run the models separately for each group. This way the comparison of coefficients across groups already accounts for the variance difference. We will implement both approaches and discuss the results below.

8 Results

Table 3 reports the results from both the conditional logit and the mixed logit model using pooled data. All variables (except the indicator for regulatory status) that interact with the capital cost are demeaned to mitigate the multicollinearlity concerns (Iacobucci et al., 2016). The individual columns vary by the index used to measure governance quality, as indicated by the column headings.

First, all of the technology-type constants D_{CMOA}, D_{POST}, and D_{LNB} are negative and significant, indicating that plant managers in general favor the baseline option of no retrofit

Table 3: Conditional and mixed logit regression accounting for scale differences

	Conditional logit			Mixed logit		
	(1) G-index	(2) E-index	(3) L-index	(4) G-index	(5) E-index	(6) L-index
Mean						
D_{CMOA}	-2.769***	-2.790***	-2.822***	-2.649***	-2.661***	-2.638***
	(-10.49)	(-10.48)	(-10.39)	(-13.42)	(-13.28)	(-13.47)
D_{POST}	-2.955***	-2.910***	-2.946***	-2.817***	-2.769***	-2.730***
	(-9.59)	(-9.53)	(-9.26)	(-9.99)	(-9.72)	(-9.78)
D_{LNB}	-2.750***	-2.757***	-2.796***	-2.620***	-2.595***	-2.636***
	(-11.34)	(-11.34)	(-11.15)	(-15.07)	(-14.86)	(-15.37)
K	-0.00355	-0.00316	-0.00193	-0.0176**	-0.0180**	-0.0122*
	(-1.36)	(-1.21)	(-0.72)	(-2.43)	(-2.47)	(-1.82)
V	-0.0266***	-0.0278***	-0.0274***	-0.0623***	-0.0670***	-0.0510***
	(-5.02)	(-5.10)	(-5.08)	(-3.61)	(-3.74)	(-2.94)
K*Age	0.0000344	0.00000540	0.0000219	-0.000250	-0.000344	-0.000278
	(0.35)	(0.05)	(0.21)	(-1.11)	(-1.39)	(-1.49)
K*D^{reg}	0.00836***	0.00655***	0.00543***	0.0190*	0.0172*	0.00908
	(3.80)	(3.04)	(2.70)	(1.84)	(1.75)	(1.40)
K*Cash flow/debt	-0.00403***	-0.00407***	-0.00255**	-0.00761**	-0.00864**	-0.00380*
	(-3.13)	(-3.06)	(-2.21)	(-2.06)	(-2.16)	(-1.77)
K*Sales growth	-0.0268***	-0.0242***	-0.00810	-0.0569**	-0.0623**	-0.0239
	(-3.07)	(-2.85)	(-1.03)	(-2.18)	(-2.21)	(-1.37)
K*Debt/asset	0.0399**	0.0393**	0.0342**	0.114**	0.121**	0.0746**
	(2.34)	(2.28)	(2.12)	(2.31)	(2.39)	(2.01)
K*Asset	-0.00288**	-0.00228	-0.00465***	-0.00561*	-0.00443	-0.00589**
	(-2.13)	(-1.60)	(-3.61)	(-1.95)	(-1.51)	(-2.31)
K*G-index	0.000909			0.00180		
	(1.06)			(1.30)		
K*G-index*D^{reg}	0.000675			0.000916		
	(0.67)			(0.53)		
K*E-index		0.00313**			0.00692**	
		(1.98)			(2.29)	
K*E-index*D^{reg}		0.0000594			-0.000246	
		(0.03)			(-0.07)	
K*L-index			0.00197			0.00246
			(1.11)			(0.89)
K*L-index*D^{reg}			-0.000608			-0.00279
			(-0.28)			(-0.83)
δ^{reg}	-0.101	-0.111	-0.125	-0.464	-0.510	-0.0887
	(-1.06)	(-1.16)	(-1.29)	(-1.21)	(-1.37)	(-0.22)
Standard deviation						
K				0.000108	0.0000597	0.000178
				(0.03)	(0.01)	(0.04)
V				0.0424***	0.0481***	0.0333**
				(2.74)	(2.91)	(2.32)
Number of units	394	394	394	394	394	394
AIC	1108.2	1108.4	1119.2	1092.8	1088.4	1102.3
BIC	1196.5	1196.8	1207.5	1193.8	1189.4	1203.3
Log-likelihood	-540.1	-540.2	-545.6	-530.4	-528.2	-535.1

Notes: The table shows results from both conditional and mixed logit models that account for residual variance difference across regulatory status using pooled data. Column (1)-(3) show the results for the conditional logit models which examine the effect of G-, E-, and L-index respectively. Column (4)-(6) show the results for the mixed logit models which examine the effect of G-, E-, and L-index respectively. D_{CMOA}, D_{POST}, and D_{LNB} represent technology fixed effects for the three major technologies: combustion modification (CM and OA), Post-combustion technologies (SCR and SNCR), and Low NO_x/ Burners (LNB). δ^{reg} is the coefficient estimate for the scale parameter. t statistics are in parentheses. * ($p < 0.10$), ** ($p < 0.05$), *** ($p < 0.010$).

Table 4: Conditional logit regression results separated by regulatory status

	Deregulated			Regulated		
	(1)	(2)	(3)	(4)	(5)	(6)
	G-index	E-index	L-index	G-index	E-index	L-index
D_{CMOA}	-2.822***	-2.836***	-2.828***	-2.506***	-2.502***	-2.510***
	(-7.57)	(-7.52)	(-7.71)	(-11.20)	(-11.19)	(-11.19)
D_{POST}	-2.734***	-2.635***	-2.867***	-2.697***	-2.625***	-2.579***
	(-5.83)	(-5.68)	(-6.06)	(-9.62)	(-9.60)	(-9.61)
D_{LNB}	-2.660***	-2.639***	-2.737***	-2.471***	-2.457***	-2.445***
	(-8.20)	(-8.12)	(-8.47)	(-13.19)	(-13.21)	(-13.29)
K	-0.0149**	-0.0142**	-0.0112**	0.00505*	0.00396	0.00360
	(-2.36)	(-2.39)	(-2.00)	(1.84)	(1.48)	(1.37)
V	-0.0357***	-0.0382***	-0.0344***	-0.0216***	-0.0218***	-0.0224***
	(-3.77)	(-3.95)	(-3.64)	(-3.93)	(-3.97)	(-4.16)
K*Age	0.000357	0.000208	0.000291	0.0000222	-0.00000124	-0.00000789
	(1.20)	(0.73)	(1.00)	(0.22)	(-0.01)	(-0.08)
K*Cash flow/debt	-0.0146***	-0.0138***	-0.0115**	-0.00286**	-0.00284**	-0.00210*
	(-2.73)	(-2.67)	(-2.38)	(-2.30)	(-2.23)	(-1.76)
K*Sales growth	-0.0407*	-0.0423**	-0.0298	-0.0250**	-0.0183*	-0.00134
	(-1.89)	(-1.97)	(-1.55)	(-2.42)	(-1.90)	(-0.17)
K*Debt/asset	0.0471	0.0279	0.0233	0.0315**	0.0313**	0.0264*
	(0.75)	(0.42)	(0.40)	(2.01)	(1.98)	(1.76)
K*Asset	0.000632	0.00173	0.00205	-0.00216	-0.00230	-0.00465***
	(0.14)	(0.36)	(0.41)	(-1.45)	(-1.40)	(-3.57)
K*G-index	0.00218*			0.00141***		
	(1.80)			(2.66)		
K*E-index		0.00443**			0.00229*	
		(2.30)			(1.96)	
K*L-index			-0.000102			0.00167
			(-0.04)			(1.33)
Number of units	130	130	130	264	264	264
AIC	328.1	325.7	331.6	787.1	790.6	792.8
BIC	385.1	382.7	388.6	852.2	855.7	858.0
Log-likelihood	-153.0	-151.9	-154.8	-382.5	-384.3	-385.4

Notes: The table reports results from estimating the conditional logit model separately using data from regulated and deregulated plants, respectively. Column (1)-(3) show the results from estimating the conditional logit models which examine the effect of G-, E-, and L-index respectively using data from deregulated plants. Column (4)-(6) show the results from estimating the conditional logit models which examine the effect of G-, E-, and L-index respectively using data from regulated plants. t statistics are in parentheses. * ($p < 0.10$), ** ($p < 0.05$), *** ($p < 0.010$).

Table 5: Mixed logit regression results separated by regulatory status

	Deregulated			Regulated		
	(1)	(2)	(3)	(4)	(5)	(6)
	G-index	E-index	L-index	G-index	E-index	L-index
Mean						
D_{CMOA}	-2.820***	-2.857***	-2.806***	-2.571***	-2.570***	-2.566***
	(-7.14)	(-7.07)	(-7.27)	(-11.08)	(-11.05)	(-11.03)
D_{POST}	-2.624***	-2.528***	-2.768***	-2.798***	-2.768***	-2.686***
	(-4.64)	(-4.43)	(-4.93)	(-8.26)	(-8.18)	(-8.11)
D_{LNB}	-2.535***	-2.513***	-2.640***	-2.610***	-2.607***	-2.590***
	(-7.34)	(-7.22)	(-7.50)	(-12.91)	(-12.87)	(-12.86)
K	-0.0339***	-0.0296***	-0.0248**	-0.00205	-0.00315	-0.00388
	(-3.01)	(-2.98)	(-2.56)	(-0.52)	(-0.81)	(-0.96)
V	-0.0565***	-0.0599***	-0.0530***	-0.0467***	-0.0482***	-0.0488***
	(-3.19)	(-3.22)	(-3.14)	(-4.68)	(-4.77)	(-4.70)
K*Age	0.000249	-0.00000755	0.000198	-0.000275	-0.000307*	-0.000344*
	(0.54)	(-0.02)	(0.46)	(-1.53)	(-1.70)	(-1.84)
K*Cash flow/debt	-0.0270***	-0.0230***	-0.0189***	-0.00326*	-0.00343*	-0.00269
	(-3.15)	(-3.11)	(-2.58)	(-1.88)	(-1.89)	(-1.53)
K*Sales growth	-0.103***	-0.107***	-0.0749**	-0.0288*	-0.0251*	-0.0103
	(-2.58)	(-2.59)	(-2.08)	(-1.88)	(-1.67)	(-0.80)
K*Debt/asset	0.168*	0.159	0.0949	0.0666***	0.0682***	0.0644***
	(1.83)	(1.63)	(1.11)	(2.75)	(2.77)	(2.59)
K*Asset	0.000597	0.000169	0.00268	-0.00374*	-0.00358	-0.00589***
	(0.10)	(0.03)	(0.40)	(-1.71)	(-1.48)	(-3.00)
K*G-index	0.00470**			0.00135*		
	(2.31)			(1.78)		
K*E-index		0.00906**			0.00266	
		(2.54)			(1.53)	
K*L-index			-0.000839			0.000294
			(-0.21)			(0.15)
Standard deviation						
K	0.000225	0.0000858	0.000143	-0.000289	-0.000336	-0.000170
	(0.04)	(0.02)	(0.02)	(-0.10)	(-0.11)	(-0.06)
V	0.0498***	0.0545***	0.0438**	0.0287***	0.0304***	0.0305***
	(2.67)	(2.69)	(2.28)	(3.48)	(3.60)	(3.55)
Number of units	130	130	130	264	264	264
AIC	324.4	322.0	330.6	774.9	775.6	778.0
BIC	391.8	389.3	398.0	851.9	852.6	855.0
Log-likelihood	-149.2	-148.0	-152.3	-374.4	-374.8	-376.0

Notes: The table reports results from estimating the mixed logit model separately using data from regulated and deregulated plants, respectively. Column (1)-(3) show the results from estimating the mixed logit models which examine the effect of G-, E-, and L-index respectively using data from deregulated plants. Column (4)-(6) show the results from estimating the mixed logit models which examine the effect of G-, E-, and L-index respectively using data from regulated plants. t statistics are in parentheses. * ($p < 0.10$), ** ($p < 0.05$), *** ($p < 0.010$).

and dislike undertaking emission control technology projects.[11]

These constants represent the average effect of unobservable characteristics of the technologies that affect plant managers' preference for using these technologies as compliance options relative to the option of buying permits. As mentioned earier, these factors might include the technologies' reliability, or side effects on production. They may also reflect differences in the complexity of adoption (plausibly, constructing capital projects is considerably more complex than buying permits).

The coefficient on the capital and variable costs are statistically significant and have the expected negative sign. Notice the large coefficient differences between the mixed logit and conditional logit model for the capital cost variable: the mixed-logit estimates are about an order of magnitude larger in absolute value. Notice also that the estimate for the standard deviation of the variable cost is statistically significant. In addition, the AIC and BIC are lower and the log likelihoods are higher for the mixed logit model. This suggests that the results from the conditional logit model are biased, possibly because the assumption of the *iid* structure of the error term does not hold. As mentioned, the errors may correlate across units because a plant manager makes choices for multiple units that s/he operates.

The negative coefficient for the interaction between capital cost and unit age in the mixed logit model indicates that older boilers are less likely to install capital-intensive technologies. This makes sense because older units have less time to recover the installation cost. Note, however, that the coefficient is insignificant, indicating that the remaining lifespan of boilers does not materially constrain the payback period on capital investments. Plausibly, this is because of the short average lifespan of abatement technologies compared to the remaining lifespan of most boilers in our sample. It may also reflect short-sightedness on the part of managers, whose tenure is likely to be shorter than the remaining lifespan of boilers and who may not care about payback beyond their tenure.

The positive coefficient for the interaction between capital cost and regulatory-status dummy D^{reg} indicates that regulated plants are more likely to invest in more capital-intensive technologies than deregulated plants, although the effect is only marginally significant in the mixed logit model. This is consistent with the main result of Fowlie (2010) and the fact that regulated plants are allowed to earn a rate of return on their capital investments, whereas deregulated plants have to recover their capital costs from the market.

As for the financial characteristics, the negative coefficient on the interaction between capital cost and the cash flow/debt ratio implies that firms with more liquidity have a higher cost of capital, and are thus less likely to invest in capital-intensive technologies. To see this, recall from equations (15) and (17) that the sign of dr_n/dZ^f is equal to that of the ratio of β_m^{kZ} and β_m^v. Because β_m^{kZ} is negative for this interaction term and β_m^{vc} (in the fifth row of the table) is negative as well, the ratio of these two coefficients is positive.

Ideally, one would want to formally test whether β_m^{kZ}/β_m^v is significantly different from zero.

[11] We include technology fixed effects for the three categories of technologies: combustion modification and overfire air (CMOA) (CM and OA), Post-combustion technologies (SCR and SNCR), and Low NO_x/ Burners (LNB). Although there are other types of technologies, such as four different types of Low NO_x/ Burners for tangential-firing boilers. Including these types doesn't significantly improve the model fit.

However, to form this test, we need to know the variance of the ratio. As is well known in statistics and has been pointed out by several economic studies, such as Fowlie (2010), Carson and Czajkowski (2013) and Hanemann and Kanninen (2001), since the support of the normally distributed denominator spans zero, the variance of the ratio is not well defined. The literature has not proposed an appropriate method to deal with this problem.[12]

Despite this issue, however, previous literature continues to use the ratio of coefficients in discrete choice models to estimate discount rates (Hausman, 1979; Gately et al., 1980).

In other discrete choice models, the ratio of coefficients has also been widely used to estimate willingness to pay (WTP) (e.g., Haab and McConnell, 2002; Train, 2009; Viscusi et al., 2008). We follow suit and focus on the point estimates of the ratio, $\beta_m^{kG}/\beta_m^{vc}$, and leave the estimation of the variance for future research.

To interpret the finding of a negative interaction effect, recall that a higher ratio of free cash flow to current debt suggests a stronger ability of the firm to pay back short-term debt, which all else equal should lower the cost of debt. On the other hand, however, the higher ratio might also indicate higher expected future cash flows and therefore higher expectations of return by equity investors. This would imply a higher cost of equity capital. The empirical finding suggests that the latter effect dominates.

The positive coefficient on the capital cost/debt to asset ratio interaction term implies that firms with higher leverage weigh capital costs less heavily, and thus are more likely to invest in capital-intensive technologies. Our later results reported in Table 5 indicate that this finding is primarily driven by the regulated plants. One reason might be that higher leverage of regulated plants indicates willingness on the part of PUCs to accommodate higher debt. This may allay concerns of bondholders and lead to a lower cost of capital.

The negative coefficient on the capital cost/sales growth interaction term implies that firms with more growth opportunities have higher costs of capital. This is consistent with the notion that higher-growth firms usually carry intangible assets and thus are difficult for debtholders to monitor (Ethier, 1986; Ethier and Horn, 1990). Moreover, we find this effect is significant at 5% only among deregulated units as shown by Table 5.

Lastly, the coefficient on the capital cost/asset interaction term is negative, indicating that larger firms are less likely to invest in capital-intensive technologies. This result is surprising given the argument of El Ghoul et al. (2011) that larger firms gain more media attention, which reduces information asymmetry between shareholders/bondholders and the firm and thus reduces the cost of capital.

The later results reported in Table 5 indicate, however, that this counter-intuitive result

[12] There have been several attempts to mitigate the problem. One approach is to assume that β^{vc} is a fixed parameter. Carson and Czajkowski (2013) argue that this does not rule out uncertainty of the *estimate* of that parameter, which may still span zero and lead to the non-existence of variance. Train and Sonnier (2005) also add that restricting a parameter to be fixed when it is actually random leads to an overestimate of the variance, even if the true variance is small. In a recent paper, Carson and Czajkowski (2013) propose a new approach by restricting the estimate of the denominator to be lognormally distributed and bounded above zero. However, this method cannot be applied to situations like ours where β^{vc} (not its estimate) is random across individuals.

applies mainly to regulated plants.

This may be because larger firms are under stronger scrutiny from PUCs, and thus are less likely to engage in excessive capital spending to raise profits. For deregulated plants, the coefficient is positive as predicted (albeit insignificant), indicating that larger firms are more likely to invest in capital-intensive technologies.

We now turn to the main interest of this paper. The coefficients on the capital cost/governance interaction terms are all positive, but are significant only for the E-index. This implies that firms with a higher E-index have lower costs of capital and are more likely to invest in capital-intensive technologies.

This result is somewhat surprising given the belief that "perhaps the most important benefit of good governance is access to capital markets on better terms" (Doidge et al., 2007). Stronger governance enhances shareholder rights and should thereby reduce the cost of equity capital. However, at least two theories mentioned in the literature review section can explain why weaker governance, as indicated by higher E-index might lead to a lower cost of debt. First, managers prefer lower-risk projects (i.e., they prefer a "quiet life") than do shareholders. Adopting capital-intensive technologies is a less risky strategy in the face of uncertainty of future permit prices. Stronger managerial entrenchment will therefore lead to adoption of capital-intensive technologies, which is less risky than buying permits. Because debt-holders dislike risky investments, stronger managerial entrenchment thus leads to a lower cost of debt. Second, takeovers in the form of leveraged buyouts can significantly increase firms' financial risk by raising leverage ratios. Therefore, stronger anti-takeover defenses could lead to a lower cost of debt via this channel as well. Because electric utilities rely heavily on debt financing, it is plausible that a lower cost of debt implies a lower cost of capital overall.

Our finding that, out of all three governance indices, only the E-index has a significant effect indicate that anti-takeover provisions—the main focus of the E-index—are particularly important to the cost of debt used to finance abatement technologies. This is consistent with the literature finding that anti-takeover laws induce managers to take on less-risky projects.

Table 3 also attempts to estimate the differential effects of governance by regulatory status. The insignificant coefficients on the triple interaction terms seem to suggest that there is no such differential effects in the pooled regression.

While Table 3 shows results from a restrictive specification forcing many coefficients to be the same regardless of regulatory status, Tables 4 and 5 show the results from running the model separately for regulated and deregulated plants, thereby allowing all coefficients to vary. Using a nested likelihood ratio test, the null hypothesis that all coefficients are the same across regulatory status is rejected (p-value < 0.01), indicating that the less restrictive models are preferred. Note that in both 4 and 5, the coefficients across regulated and deregulated plants differ by more than a multiplicative scalar, suggesting that the difference in the variance of the error term cannot account for all differences in the coefficients.

Table 5 shows that in the mixed logit model specification, the estimated standard deviations of the distributions of the random coefficients are significant, implying that plant managers indeed have idiosyncratic unobserved random preference towards costs. The mixed logit model is therefore more appropriate. Notice also that the mixed logit specification significantly improves the fit of the model relative to the conditional logit, as indicated by the generally lower AIC and BIC and higher log-likelihood. Thus we focus on table 5 in discussing the heterogeneous effects across regulatory status.

First, the coefficient on the capital cost variable is negative and significant only for deregulated plants, mirroring the main result of Fowlie (2010).

Second, unit age negatively affects decisions to choose capital-intensive technologies in regulated plants but not in deregulated plants. One possible explanation is that regulated plants' rate base from which companies are allowed to make a return explicitly excludes depreciation of capital. Thus higher depreciation lowers rate base. While older units implies shorter investment horizon and thus higher depreciation rate, they will have smaller rate base.

Finally, the coefficients on the governance indices suggest that firms with a higher G-index or E-index have a lower cost of capital for abatement investment, but this effect is significant only for deregulated plants. This implies that if a company with mainly regulated plants wants to raise capital for abatement investment, improving corporate governance will have little effect. For deregulated plants, corporate governance does matter, but—for reasons touched upon earlier, in our discussion of Table 3—in an unexpected direction: improving governance quality might for these plants be counterproductive, resulting in a higher cost of debt and overall cost of capital.

8.1 Robustness checks

Our main results on the effects of governance are robust to the choices of financial variables as controls. In an alternative specification, we use market-to-book as an alternative measure of growth opportunities and ratio of debt to equity as an alternative measure of financial leverage. The results are shown in table 6 - 8.

Since the compliance choices could be made in any year between 2000 and 2004, in the main analysis we use financial and governance variables that are averages across 1997-1999. The results are also robust to instead using financial variables that are averages across 1998-2000, 1999-2001, and 2000-2002.[13]

9 Conclusion

The cost of financial capital to fund abatement investment figures importantly in firms' abatement choices and thus their environmental performance. In this paper, we examine the impact of corporate governance, relative to a firm's financial structure and regulatory environment, on this cost. We use engineering software to estimate the cost profile of NO_x abatement technologies for coal-fired boilers, and use the observed technology choices of

[13]Here we only show the result for using the financial variables that are averages of 1998-2000 to save spaces. The results are shown in table 9 - 11. Futher robustness checks will be provided upon request.

power plant managers subject to a major U.S. NO_x emissions trading program to infer how these managers traded off costs of physical capital and variable costs. The cost of financial capital plays a key role in this tradeoff. By matching the plant managers' choices to financial and governance information on the firms that own their plants, we are able to infer how corporate governance provisions in the firms' corporate charters and bylaws impact the cost of financial capital, thereby indirectly affecting the managers' abatement choices.

We find that two of three well known governance indices have no relationship to the implied cost of abatement capital. For the one index that does show a relationship, results suggest that limiting shareholder power – rather than giving shareholders more power – may increase abatement investment. We find a much stronger relationship between abatement capital costs and fundamental corporate finance characteristics such as firm size measured by book value of total assets, financial leverage, growth opportunities and liquidity. More specifically we find that governance practices that shield CEOs from shareholder lawsuits have no effects on the cost of capital for abatement, while practices that are strong anti-takeover defenses reduce the cost of capital.

A plausible explanation for the latter finding is that anti-takeover defenses reduce pressure on managers to take on risk, and also deter risky leveraged buyouts. Reducing risk aligns with the interests of debt-holders, and because electric utilities heavily rely on debt financing, promoting those interests can drive down utilities' cost of capital.

We also find that the impacts of corporate governance provisions depend crucially on the power plants' electricity restructuring status. Improving governance raises the cost of capital for abatement investment in deregulated plants but has no significant impacts on the regulated plants. This is consistent with the fact that regulated plants are allowed to recover capital costs through raising electricity prices and are thus less dependent on financial capital.

Because the cost of capital is a part of the cost of pollution control, our results also imply that corporate governance quality affects the cost of pollution control. This has important policy implications. First, environmental regulations have been argued to reduce firms' competitiveness. Our findings, paradoxically, imply that poorly-governed firms are less affected. Moreover, results from this study may provide guidence on what governance can help firms comply with at lower cost, which should be attractive to investors. Lastly, financial regulations that are intended to improve governance across the board, such as the Business Combination laws that deter takeovers and the Sarbanes-Oxley Act (SOX), may unintentionally affect firms' pollution control costs.

Several caveats are in order, however. First, we do not observe cost recovery parameters. These parameters are essential to quantify the relationship between corporate governance and the cost of capital in abatement investment and in turn environmental compliance cost. We here nevertheless document a qualitative relationship between corporate governance and the cost of capital.

Second, there are other important aspects of corporate governance not explored in terms of their impact on cost of capital in abatement investment, such as board independence, ownership structure and financial transparency.

Third, we do not claim that the relationship between corporate governance and the cost of capital is causal in our findings. Future research could study the causal relationship by using natural experiments such as the passage of Sarbanes Oxley Act or the passage of state anti-takeover legislations to evaluate their impacts on the cost of capital.

References

Amihud, Y. and Mendelson, H. (1986). Asset pricing and the bid-ask spread. *Journal of financial Economics*, 17(2):223–249.

Amore, M. D. and Bennedsen, M. (2016). Corporate governance and green innovation. *Journal of Environmental Economics and Management*, 75:54–72.

Andersen, D. C. (2016). Credit constraints, technology upgrading, and the environment. *Journal of the Association of Environmental and Resource Economists*, 3(2):283–319.

Arimura, T. H. (2002). An empirical study of the SO_2 allowance market: Effects of PUC regulations. *Journal of Environmental Economics and Management*, 44(2):271–289.

Arimura, T. H., Hibiki, A., and Katayama, H. (2008). Is a voluntary approach an effective environmental policy instrument? A case for environmental management systems. *Journal of Environmental Economics and Management*, 55(3):281–295.

Arping, S. and Sautner, Z. (2010). Corporate governance and leverage: Evidence from a natural experiment. *Finance Research Letters*, 7(2):127–134.

Ashbaugh-Skaife, H., Collins, D. W., and LaFond, R. (2006). The effects of corporate governance on firms' credit ratings. *Journal of Accounting and Economics*, 42(1):203–243.

Bebchuk, L., Cohen, A., and Ferrell, A. (2009). What matters in corporate governance? *Review of Financial Studies*, 22(2):783–827.

Bertrand, M. and Mullainathan, S. (2003). Enjoying the quiet life? Corporate governance and managerial preferences. *Journal of Political Economy*, 111(5):1043–1075.

Bhat, C. R. (2001). Quasi-random maximum simulated likelihood estimation of the mixed multinomial logit model. *Transportation Research Part B: Methodological*, 35(7):677–693.

Bhojraj, S. and Sengupta, P. (2003). Effect of corporate governance on bond ratings and yields: The role of institutional investors and outside directors. *The Journal of Business*, 76(3):455–475.

Bloom, N., Genakos, C., Martin, R., and Sadun, R. (2010). Modern management: Good for the environment or just hot air? *The Economic Journal*, 120(544):551–572.

Bohi, D. R. and Burtraw, D. (1991). Avoiding regulatory gridlock in the Acid Rain Program. *Journal of Policy Analysis and Management*, 10(4):676–684.

Bohi, D. R. and Burtraw, D. (1992). Utility investment behavior and the emission trading market. *Resources and Energy*, 14(1-2):129–153.

Bradley, M. and Chen, D. (2011). Corporate governance and the cost of debt: Evidence from director limited liability and indemnification provisions. *Journal of Corporate Finance*, 17(1):83–107.

Brealey, R. A., Myers, S. C., and Marcus, A. J. (2009). *Fundamentals of Corporate Finance*. McGraw-Hill/Irwin.

Burtraw, D. and Szambelan, S. J. F. (2009). US emissions trading markets for SO_2 and NO_x. *Resources for the Future Discussion Paper*, (09-40).

Carson, R. T. and Czajkowski, M. (2013). A new baseline model for estimating willingness to pay from discrete choice models. In *International choice modelling conference, Sydney*.

Chava, S. (2014). Environmental externalities and cost of capital. *Management science*, 60(9):2223–2247.

Chava, S., Livdan, D., and Purnanandam, A. (2009). Do shareholder rights affect the cost of bank loans? *The Review of Financial Studies*, 22(8):2973–3004.

Chava, S. and Purnanandam, A. (2010). Is default risk negatively related to stock returns? *The Review of Financial Studies*, 23(6):2523–2559.

Chen, K. C., Chen, Z., and Wei, K. J. (2009). Legal protection of investors, corporate governance, and the cost of equity capital. *Journal of Corporate Finance*, 15(3):273–289.

Cheng, C. A., Collins, D., and Huang, H. H. (2006). Shareholder rights, financial disclosure and the cost of equity capital. *Review of Quantitative Finance and Accounting*, 27(2):175–204.

Chesner, W. H., Collins, R. J., and MacKay, M. (1998). User guidelines for waste and byproduct materials in pavement construction. Technical report, U.S. Department of Transportation Federal Highway Administration, Washington D.C.

Cicala, S. (2014). When does regulation distort costs? Lessons from fuel procurement in US electricity generation. *The American Economic Review*, 105(1):411–444.

Cichanowicz, J. E. (2004). Why are SCR costs still rising? *Power*, 148(3):32–40.

Cole, M. A., Elliott, R. J., and Strobl, E. (2008). The environmental performance of firms: The role of foreign ownership, training, and experience. *Ecological Economics*, 65(3):538–546.

Coombes, P. and Watson, M. (2000). Three surveys on corporate governance. *McKinsey Quarterly*, (4; SPI):74–77.

Doidge, C., Karolyi, G. A., and Stulz, R. M. (2007). Why do countries matter so much for corporate governance? *Journal of Financial Economics*, 86(1):1–39.

Durnev, A. and Kim, E. H. (2005). To steal or not to steal: Firm attributes, legal environment, and valuation. *The Journal of finance*, 60(3):1461–1493.

Earnhart, D. and Segerson, K. (2012). The influence of financial status on the effectiveness of environmental enforcement. *Journal of Public Economics*, 96(9):670–684.

El Ghoul, S., Guedhami, O., Kwok, C. C., and Mishra, D. R. (2011). Does corporate social responsibility affect the cost of capital? *Journal of Banking & Finance*, 35(9):2388–2406.

Electric Power Research Institute (1999). Application of methodology for identification of least cost NO_x control combinations. Technical Report TE-112860, Electric Power Research Institute, Palo Alto, CA.

Ervin, D., Wu, J., Khanna, M., Jones, C., and Wirkkala, T. (2013). Motivations and barriers to corporate environmental management. *Business Strategy and the Environment*, 22(6):390–409.

Ethier, W. J. (1986). The multinational firm. *The Quarterly Journal of Economics*, 101(4):805–833.

Ethier, W. J. and Horn, H. (1990). Managerial control of international firms and patterns of direct investment. *Journal of international Economics*, 28(1-2):25–45.

Fisher-Vanden, K. and Thorburn, K. S. (2011). Voluntary corporate environmental initiatives and shareholder wealth. *Journal of Environmental Economics and Management*, 62(3):430–445.

Fowlie, M. (2010). Emissions trading, electricity restructuring, and investment in pollution abatement. *The American Economic Review*, 100(3):837–869.

Fowlie, M., Knittel, C. R., and Wolfram, C. (2012). Sacred cars? Cost-effective regulation of stationary and nonstationary pollution sources. *American Economic Journal: Economic Policy*, 4(1):98–126.

Francis, J. R., Khurana, I. K., and Pereira, R. (2005). Disclosure incentives and effects on cost of capital around the world. *The accounting review*, 80(4):1125–1162.

Fullerton, D., McDermott, S. P., and Caulkins, J. P. (1997). Sulfur dioxide compliance of a regulated utility. *Journal of Environmental Economics and Management*, 34(1):32–53.

Gately, D. et al. (1980). Individual discount rates and the purchase and utilization of energy-using durables: Comment. *Bell Journal of Economics*, 11(1):373–374.

Gebhardt, W. R., Lee, C. M., and Swaminathan, B. (2001). Toward an implied cost of capital. *Journal of accounting research*, 39(1):135–176.

Gilbert, B., Gogineni, S., van 't Veld, K., and Xu, C. (2015). Overlapping environmental and financial regulations: The role of corporate governance. In *2015 ASSA Annual Meeting, Boston, MA*. American Economic Association.

Gompers, P., Ishii, J., and Metrick, A. (2003). Corporate governance and equity prices. *The Quarterly Journal of Economics*, 118(1):107–155.

Gu, Y., Hole, A. R., and Knox, S. (2013). Fitting the generalized multinomial logit model in stata. *The Stata Journal*, 13(2):382–397.

Haab, T. C. and McConnell, K. E. (2002). *Valuing Environmental and Natural Resources: The Econometrics of Non-market Valuation*. Edward Elgar Publishing.

Hanemann, M. and Kanninen, B. (2001). The statistical analysis of Discrete-Response CV data. *Valuing environmental preferences: theory and practice of the contingent valuation method in the US, EU, and developing countries*, page 302.

Harrington, D. R., Khanna, M., and Deltas, G. (2008). Striving to be green: The adoption of total quality environmental management. *Applied Economics*, 40(23):2995–3007.

Hausman, J. A. (1979). Individual discount rates and the purchase and utilization of energy-using durables. *The Bell Journal of Economics*, pages 33–54.

Himes, R. (2015). Electric Power Research Institute. Telephone conversation. March 8, 2015.

Himmelberg, C. P., Hubbard, R. G., and Love, I. (2004). Investor protection, ownership, and the cost of capital. *World Bank Policy Research Working Paper*, (2834).

Hole, A. R. (2007). Estimating mixed logit models using maximum simulated likelihood. *Stata Journal*, 7(3):388–401.

Holmstrom, B. and Costa, J. R. I. (1986). Managerial incentives and capital management. *The Quarterly Journal of Economics*, pages 835–860.

Iacobucci, D., Schneider, M. J., Popovich, D. L., and Bakamitsos, G. A. (2016). Mean centering helps alleviate "micro" but not "macro" multicollinearity. *Behavior research methods*, 48(4):1308–1317.

John, K., Litov, L., and Yeung, B. (2008). Corporate governance and risk-taking. *The Journal of Finance*, 63(4):1679–1728.

Keohane, N. (2006). Cost savings from allowance trading in the 1990 Clean Air Act: Estimates from a choice-based model. *Moving to markets in environmental regulation: Lessons from twenty years of experience*, pages 194–229.

Klapper, L. F. and Love, I. (2004). Corporate governance, investor protection, and performance in emerging markets. *Journal of corporate Finance*, 10(5):703–728.

Klock, M. S., Mansi, S. A., and Maxwell, W. F. (2005). Does corporate governance matter to bondholders? *Journal of Financial and Quantitative Analysis*, 40(4):693.

La Porta, R. (1996). Expectations and the cross-section of stock returns. *The Journal of Finance*, 51(5):1715–1742.

La Porta, R., Lopez-de Silanes, F., Shleifer, A., and Vishny, R. (2002). Investor protection and corporate valuation. *The journal of finance*, 57(3):1147–1170.

Lombardo, D. and Pagano, M. (1999). Law and equity markets: A simple model. *Stanford Law and Economics Olin Working Paper*.

Martin, R., Muûls, M., de Preux, L. B., and Wagner, U. J. (2012). Anatomy of a paradox: Management practices, organizational structure and energy efficiency. *Journal of Environmental Economics and Management*, 63(2):208–223.

Midrigan, V. and Xu, D. Y. (2014). Finance and misallocation: Evidence from plant-level data. *The American Economic Review*, 104(2):422–458.

Mills, J. and Yamamura, J. H. (1998). The power of cash flow ratios. *Journal of Accountancy*, 186(4):53.

Nehring, R. (2015). U.S. Department of Agriculture. E-mail correspondence. April 7, 2015.

Ortiz-Molina, H. and Phillips, G. M. (2014). Real asset illiquidity and the cost of capital. *Journal of Financial and Quantitative Analysis*, 49(1):1–32.

Petersen, M. A. and Rajan, R. G. (1995). The effect of credit market competition on lending relationships. *The Quarterly Journal of Economics*, 110(2):407–443.

Protiviti (2011). 2011 Sarbanes-Oxley compliance survey. https://www.protiviti.com/en-US/Documents/Surveys/2011-SOX-Compliance-Survey-Protiviti.pdf. Accessed: 2015-08-20.

Rand, J. (2007). Credit constraints and determinants of the cost of capital in vietnamese manufacturing. *Small Business Economics*, 29(1):1–13.

Rode, D. C. and Fischbeck, P. S. (2019). Regulated equity returns: A puzzle. *Energy Policy*, 133:110891.

Rose, K. and Burns, R. E. (1993). Regulatory policy issues and the Clean Air Act: Issues and papers from the state implementation workshops. Technical report, National Regulatory Research Inst., Columbus, OH (United States).

Rose, K., Burns, R. E., Coggins, J. S., Harunuzzaman, M., and Viezer, T. W. (1992). Public Utility Commission implementation of the Clean Air Act's allowance trading program. Technical report, National Regulatory Research Inst., Columbus, OH (United States).

Saad, M. and Samet, A. (2017). Liquidity and the implied cost of equity capital. *Journal of International Financial Markets, Institutions and Money*, 51:15–38.

Sargent Lundy (2013). IPM model updates to cost and performance for APC technologies: SCR cost development methodology. Technical report, Sargent Lundy, Chicago, IL.

Steffen, B. (2020). Estimating the cost of capital for renewable energy projects. *Energy Economics*, 88:104783.

Stevens, W. (2015). U.S. Environmental Protection Agency. Telephone conversation. May 15, 2015.

Toupin, K. (2015). Babcock Power, Inc. Telephone conversation. March 12, 2015.

Train, K. and Sonnier, G. (2005). Mixed logit with bounded distributions of correlated partworths. *Applications of Simulation Methods in Environmental and Resource Economics*, pages 117–134.

Train, K. E. (2009). *Discrete choice methods with simulation*. Cambridge University Press.

U.S. EPA (1994). Alternative control techniques document: NO_x emissions from utility boilers. Technical Report EPA-453/R-94-023, Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, Washington DC.

U.S. EPA (1995). Compilation of air pollutant emission factors, volume I stationary point and area sources. Technical Report AP-42 Supplement D, U.S. Environmental Protection Agency, Washington DC.

U.S. EPA (1998). Regulatory impact analysis for the NOx SIP Call. Technical Report A.98.4 A, Office of Air and Radiation, Washington DC.

U.S. EPA (1999). Nitrogen oxides (NO_x), why and how they are controlled? Technical Report EPA-456/F-99-006R, U.S. Environmental Protection Agency, Washington DC.

U.S. EPA (2003). NO_x Budget Program: 1999-2002 progress report. Technical Report EPA-430-R-03-900, U.S. Environmental Protection Agency, Washington DC.

Viscusi, W. K., Huber, J., and Bell, J. (2008). Estimating discount rates for environmental quality from utility-based choice experiments. *Journal of Risk and Uncertainty*, 37(2-3):199–220.

Warga, A. and Welch, I. (1993). Bondholder losses in leveraged buyouts. *Review of Financial Studies*, 6(4):959–982.

Zwiebel, J. (1996). Dynamic capital structure under managerial entrenchment. *The American economic review*, pages 1197–1215.

Robustness Check Tables

Data Appendix

This appendix describes the data used to generate the capital cost and variable cost of adopting different NO_x abatement technologies for coal-fired boilers.

In the late 90s, the Electric Power Research Institute (EPRI) developed a software program called "Umbrella" to help power plant managers calculate the cost of adopting different NO_x control technologies and thereby help them comply with NO_x-related regulations. About 60 input variables are needed for Umbrella to calculate both the capital and the operating cost for each technology. These input variables can be categorized as boiler specific and technology specific.

Boiler-specific input variables

The main boiler-specific input variables required by Umbrella are boiler capacity, ozone season capacity factor, ozone season total generation, firing type, ozone heat input, furnace exit emissions rates, coal type, fuel heat content, fuel sulfur content, fuel ash content, heat rate, calcium oxide in coal ash, number of burners, number of burner columns, furnace depth, furnace width, flue gas temperature at air heater outlet, labor cost, water price, reagent cost, electricity price, and fuel cost. Below, we describe data sources for each of these variables and potential problems with the data.

Data on **boiler capacity** are from the "U.S. EPA National Electric Energy System (NEEDS)" database. The NEEDS database uses Energy Information Administration (EIA) Form 767 and Form 860 as its primary data source and contains data such as capacity, heat rate, on-line year, and firing types for model plants that represent existing units and plan-committed units used for EPA Integrated Planning Modeling.

[14] The NEEDs database contains capacity data for boilers in all plants that are 100MW or larger, excluding mobile and distributed generators as well as non-utility onsite generators that do not sell electricity to the grid. The U.S. EPA official website only has recent versions of NEEDS (NEEDS3.02, NEEDS4.10 and NEEDS5.13). (Is this up to date?) Earlier versions of NEEDS that trace back to as early as 1998 were obtained from EPA staff through email correspondence.

[15,16]

[14] Plan-committed units are units that have not yet operated but are guaranteed to operate in the future and units that have already received funds for construction and/or have started construction.

[15] The capacity data in EIA form 767 and EIA form 860 are generator specific and not boiler specific. To obtain boiler capacity, NEEDS develops a parsing algorithm using each boiler's maximum steam flow and mapping between boilers and generators to deduce boiler capacity.

[16] We observe that the boiler capacity data for some boilers changes from year to year, although the change is small. This could be attributed to the parsing algorithm, if new boilers or generators are added to the

Table 6: Conditional and mixed logit regression accounting for scale differences

	Conditional logit			Mixed logit		
	(1) G-index	(2) E-index	(3) L-index	(4) G-index	(5) E-index	(6) L-index
main						
D_{CMOA}	-2.887***	-2.881***	-2.922***	-2.712***	-2.728***	-2.708***
	(-10.65)	(-10.57)	(-10.59)	(-13.55)	(-13.27)	(-13.51)
D_{POST}	-3.010***	-2.949***	-2.973***	-2.823***	-2.772***	-2.775***
	(-9.40)	(-9.44)	(-9.32)	(-10.10)	(-9.78)	(-9.93)
D_{LNB}	-2.801***	-2.772***	-2.839***	-2.644***	-2.591***	-2.663***
	(-11.32)	(-11.31)	(-11.29)	(-15.34)	(-14.81)	(-15.50)
K	-0.00421	-0.00494*	-0.00342	-0.0139**	-0.0196***	-0.0108*
	(-1.49)	(-1.74)	(-1.24)	(-2.11)	(-2.59)	(-1.78)
V	-0.0260***	-0.0273***	-0.0274***	-0.0476***	-0.0610***	-0.0423***
	(-4.89)	(-4.99)	(-5.02)	(-3.32)	(-3.84)	(-2.98)
K*Age	0.0000560	0.0000271	0.0000380	-0.000167	-0.000247	-0.000198
	(0.55)	(0.26)	(0.37)	(-0.99)	(-1.08)	(-1.38)
K*Cash flow/debt	-0.00379***	-0.00485***	-0.00231*	-0.00487**	-0.00841***	-0.00311*
	(-2.89)	(-3.40)	(-1.93)	(-2.19)	(-2.64)	(-1.95)
K*Sales growth	-0.00475	-0.00685*	-0.00560*	-0.00631	-0.0121*	-0.00694
	(-1.54)	(-1.92)	(-1.71)	(-1.43)	(-1.72)	(-1.50)
K*Debt/asset	0.0268	0.0316*	0.0388**	0.0543**	0.0841**	0.0532**
	(1.63)	(1.83)	(2.44)	(1.98)	(2.11)	(2.20)
K*Asset	-0.000351	0.00156	-0.00256**	-0.000669	0.00288	-0.00242
	(-0.23)	(0.85)	(-2.09)	(-0.29)	(0.80)	(-1.57)
K*D^{reg}	0.00982***	0.00927***	0.00753***	0.0152*	0.0216**	0.00911
	(4.22)	(3.92)	(3.52)	(1.88)	(2.12)	(1.55)
K*G-index	0.00127			0.00193		
	(1.37)			(1.54)		
K*G-index*D^{reg}	-0.00000908			-0.000612		
	(-0.01)			(-0.42)		
K*E-index		0.00500***			0.0102***	
		(2.99)			(3.06)	
K*E-index*D^{reg}		-0.00111			-0.00383	
		(-0.55)			(-1.06)	
K*L-index			0.0000379			-0.000160
			(0.02)			(-0.06)
K*L-index*D^{reg}			-0.000229			-0.00144
			(-0.11)			(-0.51)
δ^{reg}	-0.125	-0.120	-0.140	-0.159	-0.486	0.116
	(-1.31)	(-1.26)	(-1.45)	(-0.42)	(-1.39)	(0.30)
Standard deviation						
K				-0.000123	-0.0000735	-0.000106
				(-0.03)	(-0.02)	(-0.03)
V				0.0294***	-0.0402***	-0.0265**
				(2.72)	(-3.03)	(-2.56)
Number of units	394	394	394	394	394	394
AIC	1088.1	1078.9	1097.3	1077.2	1062.4	1082.3
BIC	1176.4	1167.3	1185.6	1178.2	1163.4	1183.3
Log-likelihood	-530.0	-525.5	-534.6	-522.6	-515.2	-525.2

Notes: The table shows results from both conditional and mixed logit models that account for residual variance difference across regulatory status using pooled data. Here we use alternative financial variables market to book ratio and ratio of debt to equity to measure growth opportunities and financial leverage respectively. t statistics are in parentheses. * ($p < 0.10$), ** ($p < 0.05$), *** ($p < 0.010$).

Table 7: Conditional logit regression results separated by regulatory status

	Deregulated			Regulated		
	(1)	(2)	(3)	(4)	(5)	(6)
	G-index	E-index	L-index	G-index	E-index	L-index
techchoice						
D_{CMOA}	-2.804***	-2.678***	-2.852***	-2.615***	-2.617***	-2.619***
	(-7.96)	(-7.18)	(-7.99)	(-11.02)	(-11.02)	(-11.00)
D_{POST}	-2.949***	-2.427***	-2.956***	-2.625***	-2.622***	-2.556***
	(-6.22)	(-5.02)	(-6.26)	(-9.50)	(-9.49)	(-9.44)
D_{LNB}	-2.830***	-2.526***	-2.860***	-2.433***	-2.432***	-2.423***
	(-8.81)	(-7.55)	(-8.97)	(-12.98)	(-12.97)	(-13.00)
K*Age	0.000324	0.000143	0.000278	0.0000166	0.0000121	0.00000764
	(1.17)	(0.46)	(1.03)	(0.16)	(0.12)	(0.07)
K*Cash flow/debt	-0.00620*	-0.00925**	-0.00685**	-0.00253*	-0.00332**	-0.00156
	(-1.94)	(-2.33)	(-2.09)	(-1.71)	(-2.07)	(-1.02)
K*Sales growth	-0.00993	-0.0279***	-0.0127*	0.000893	-0.000952	0.00219
	(-1.55)	(-2.62)	(-1.66)	(0.20)	(-0.21)	(0.40)
K*Debt/asset	0.0277	0.157**	0.0327	0.0254	0.0242	0.0340**
	(0.52)	(2.25)	(0.77)	(1.62)	(1.53)	(2.24)
K*Asset	0.00198	0.00682	0.00548	-0.000430	0.000509	-0.00267**
	(0.48)	(1.18)	(1.18)	(-0.26)	(0.26)	(-2.02)
K	-0.0103*	-0.0241***	-0.0108*	0.00554**	0.00508*	0.00477*
	(-1.86)	(-2.96)	(-1.94)	(2.06)	(1.91)	(1.80)
V	-0.0341***	-0.0396***	-0.0358***	-0.0207***	-0.0207***	-0.0213***
	(-3.44)	(-3.73)	(-3.69)	(-3.85)	(-3.83)	(-3.97)
K*G-index	0.00162			0.000976**		
	(1.51)			(2.14)		
K*E-index		0.0100***			0.00266**	
		(3.76)			(2.11)	
K*L-index			-0.00362			0.000884
			(-1.51)			(0.62)
Number of units	130	130	130	264	264	264
AIC	337.2	321.3	337.2	761.5	761.4	765.7
BIC	394.8	379.0	394.9	826.2	826.2	830.5
Log-likelihood	-157.6	-149.7	-157.6	-369.7	-369.7	-371.9

Notes: The table reports results from estimating the conditional logit model separately using data from regulated and deregulated plants, respectively. Here we use alternative financial variables market to book ratio and ratio of debt to equity to measure growth opportunities and financial leverage respectively. t statistics are in parentheses. * ($p < 0.10$), ** ($p < 0.05$), *** ($p < 0.010$).

Table 8: Mixed logit regression results separated by regulatory status

	Deregulated			Regulated		
	(1)	(2)	(3)	(4)	(5)	(6)
	G-index	E-index	L-index	G-index	E-index	L-index
Mean						
D_{CMOA}	-2.794***	-2.691***	-2.839***	-2.682***	-2.683***	-2.681***
	(-7.47)	(-7.02)	(-7.54)	(-10.88)	(-10.86)	(-10.84)
D_{POST}	-2.757***	-2.362***	-2.844***	-2.766***	-2.777***	-2.715***
	(-4.97)	(-4.39)	(-5.17)	(-8.08)	(-8.06)	(-7.98)
D_{LNB}	-2.698***	-2.523***	-2.774***	-2.568***	-2.568***	-2.565***
	(-7.27)	(-7.18)	(-7.44)	(-12.60)	(-12.58)	(-12.56)
K*Age	0.000270	0.0000891	0.000242	-0.000293	-0.000299	-0.000319*
	(0.73)	(0.23)	(0.67)	(-1.62)	(-1.64)	(-1.72)
K*G-index	0.00193			0.000926		
	(1.34)			(1.33)		
K*Cash flow/debt	-0.00904*	-0.0107**	-0.0103**	-0.00280	-0.00373*	-0.00239
	(-1.83)	(-2.21)	(-1.97)	(-1.38)	(-1.69)	(-1.07)
K*Sales growth	-0.0130	-0.0357**	-0.0167	0.00594	0.00419	0.00505
	(-1.44)	(-2.45)	(-1.54)	(0.87)	(0.61)	(0.61)
K*Debt/asset	0.0523	0.201**	0.0327	0.0556**	0.0538**	0.0646***
	(0.76)	(2.28)	(0.59)	(2.37)	(2.29)	(2.79)
K*Asset	0.00377	0.00725	0.00930	-0.000620	0.000664	-0.00288
	(0.67)	(1.07)	(1.36)	(-0.24)	(0.22)	(-1.39)
K	-0.0194*	-0.0322***	-0.0187*	-0.000510	-0.000938	-0.00148
	(-1.69)	(-2.82)	(-1.84)	(-0.13)	(-0.24)	(-0.38)
V	-0.0423**	-0.0552***	-0.0454***	-0.0455***	-0.0457***	-0.0471***
	(-2.42)	(-3.24)	(-2.91)	(-4.59)	(-4.58)	(-4.62)
K*E-index		0.0133***			0.00289	
		(3.22)			(1.59)	
K*L-index			-0.00526			0.0000345
			(-1.38)			(0.02)
Standard deviation						
K	0.00903	-0.0000254	0.00714	-0.000225	-0.000247	-0.000281
	(1.39)	(-0.00)	(0.88)	(-0.07)	(-0.08)	(-0.09)
V	0.00883	0.0291*	0.0179	0.0295***	0.0300***	0.0308***
	(0.24)	(1.67)	(0.80)	(3.63)	(3.65)	(3.69)
Number of units	130	130	130	264	264	264
AIC	339.8	323.1	339.6	747.8	747.0	749.6
BIC	407.9	391.3	407.7	824.4	823.6	826.2
Log-likelihood	-156.9	-148.6	-156.8	-360.9	-360.5	-361.8

Notes: The table reports results from estimating the mixed logit model separately using data from regulated and deregulated plants, respectively. Here we use alternative financial variables market to book ratio and ratio of debt to equity to measure growth opportunities and financial leverage respectively. t statistics are in parentheses. * ($p < 0.10$), ** ($p < 0.05$), *** ($p < 0.010$).

Table 9: Conditional and mixed logit regression accounting for scale differences using alternative financial variables

	Conditional logit			Mixed logit		
	(1) G-index	(2) E-index	(3) L-index	(4) G-index	(5) E-index	(6) L-index
main						
D_{CMOA}	-2.908***	-2.927***	-2.875***	-2.673***	-2.692***	-2.652***
	(-10.74)	(-10.68)	(-10.54)	(-13.94)	(-13.85)	(-13.86)
D_{POST}	-3.158***	-3.107***	-3.054***	-2.863***	-2.844***	-2.826***
	(-9.52)	(-9.58)	(-9.33)	(-10.61)	(-10.45)	(-10.48)
D_{LNB}	-2.912***	-2.921***	-2.865***	-2.699***	-2.696***	-2.691***
	(-11.56)	(-11.56)	(-11.28)	(-16.09)	(-16.02)	(-16.08)
K	0.000554	0.00117	-0.000505	-0.00502	-0.00368	-0.00498
	(0.21)	(0.44)	(-0.18)	(-1.04)	(-0.81)	(-0.96)
V	-0.0285***	-0.0306***	-0.0277***	-0.0379***	-0.0391***	-0.0334**
	(-5.27)	(-5.50)	(-5.12)	(-2.78)	(-3.03)	(-2.48)
K*Age	0.0000468	0.0000159	0.0000375	-0.000151	-0.000186	-0.000154
	(0.45)	(0.15)	(0.36)	(-1.20)	(-1.43)	(-1.35)
K*Cash flow/debt	-0.00484***	-0.00452***	-0.00330***	-0.00427**	-0.00407**	-0.00280**
	(-3.66)	(-3.54)	(-2.90)	(-2.09)	(-2.37)	(-1.99)
K*Market-to-Book	0.0325***	0.0325***	0.0160*	0.0274**	0.0280**	0.0141
	(3.32)	(3.39)	(1.83)	(2.22)	(2.50)	(1.55)
K*Debt/equity	-0.000235	0.000642	0.000899	0.00155	0.00235	0.00222
	(-0.16)	(0.44)	(0.61)	(0.92)	(1.40)	(1.46)
K*Asset	-0.000356	0.000653	-0.00309**	-0.000839	0.0000183	-0.00248
	(-0.24)	(0.40)	(-2.24)	(-0.51)	(0.01)	(-1.54)
K*D^{reg}	0.00455**	0.00231	0.00456**	0.00404	0.00157	0.00317
	(2.30)	(1.14)	(2.18)	(0.83)	(0.38)	(0.69)
K*G-index	0.00220***			0.00226**		
	(2.62)			(2.12)		
K*G-index*D^{reg}	-0.000999			-0.00146		
	(-1.10)			(-1.39)		
K*E-index		0.00557***			0.00673***	
		(3.11)			(2.92)	
K*E-index*D^{reg}		-0.00276			-0.00467**	
		(-1.42)			(-2.03)	
K*L-index			0.00216			0.00270
			(1.25)			(1.24)
K*L-index*D^{reg}			-0.000220			-0.00171
			(-0.10)			(-0.70)
δ^{reg}	-0.150	-0.151	-0.139	0.188	0.223	0.371
	(-1.59)	(-1.60)	(-1.44)	(0.44)	(0.59)	(0.84)
Standard deviation						
K				-0.00000554	-0.0000119	-0.0000379
				(-0.00)	(-0.01)	(-0.02)
V				-0.0202**	-0.0217**	-0.0187**
				(-2.26)	(-2.43)	(-2.14)
Number of units	394	394	394	394	394	394
AIC	1113.3	1110.3	1123.5	1107.0	1100.7	1112.4
BIC	1202.0	1199.0	1212.2	1208.4	1202.1	1213.7
Log-likelihood	-542.7	-541.2	-547.7	-537.5	-534.3	-540.2

Notes: The table shows results from both conditional and mixed logit models that account for residual variance difference across regulatory status using pooled data. The data for financial and governance variables are the average of 1998-2000. t statistics are in parentheses. * ($p < 0.10$), ** ($p < 0.05$), *** ($p < 0.010$).

Table 10: Conditional logit regression results separated by regulatory status using alternative financial variables

	Deregulated			Regulated		
	(1) G-index	(2) E-index	(3) L-index	(4) G-index	(5) E-index	(6) L-index
techchoice						
D_{CMOA}	-2.984***	-3.033***	-2.925***	-2.496***	-2.496***	-2.497***
	(-8.10)	(-8.10)	(-8.00)	(-11.16)	(-11.16)	(-11.15)
D_{POST}	-3.169***	-3.076***	-3.062***	-2.674***	-2.656***	-2.595***
	(-6.57)	(-6.55)	(-6.39)	(-9.60)	(-9.59)	(-9.56)
D_{LNB}	-2.910***	-2.927***	-2.868***	-2.469***	-2.467***	-2.438***
	(-9.14)	(-9.18)	(-8.90)	(-13.19)	(-13.18)	(-13.27)
K*Age	0.000419	0.000287	0.000331	-0.00000123	-0.00000646	-0.0000147
	(1.60)	(1.11)	(1.20)	(-0.01)	(-0.06)	(-0.14)
K*Cash flow/debt	-0.0149***	-0.0101***	-0.0104***	-0.00376***	-0.00419***	-0.00326***
	(-3.22)	(-2.84)	(-2.73)	(-2.83)	(-3.03)	(-2.58)
K*Market-to-book	0.0323	0.0150	-0.000103	0.0462***	0.0492***	0.0299***
	(1.46)	(0.94)	(-0.01)	(3.51)	(3.55)	(2.60)
K*Debt/equity	-0.00386	0.000650	-0.00126	0.00144	0.00160	0.00225
	(-0.98)	(0.18)	(-0.32)	(0.93)	(1.04)	(1.43)
K*Asset	0.00502	0.00474	0.00469	0.00105	0.00188	-0.00246
	(1.34)	(1.31)	(1.23)	(0.60)	(0.93)	(-1.62)
K	-0.00664	-0.00725	-0.00872	0.00464*	0.00413	0.00389
	(-1.21)	(-1.42)	(-1.57)	(1.71)	(1.54)	(1.45)
V	-0.0361***	-0.0399***	-0.0350***	-0.0230***	-0.0231***	-0.0222***
	(-3.95)	(-4.28)	(-3.75)	(-4.18)	(-4.18)	(-4.10)
K*G-index	0.00310**			0.00112***		
	(2.13)			(2.73)		
K*E-index		0.00517**			0.00268***	
		(2.29)			(2.60)	
K*L-index			0.000516			0.00180
			(0.25)			(1.53)
Number of units	130	130	130	264	264	264
AIC	331.4	330.1	335.8	781.8	782.5	787.2
BIC	389.3	387.9	393.6	847.0	847.6	852.3
Log-likelihood	-154.7	-154.1	-156.9	-379.9	-380.2	-382.6

Notes: The table reports results from estimating the conditional logit model separately using data from regulated and deregulated plants, respectively. The data for financial and governance variables are the average of 1998-2000. t statistics are in parentheses. * ($p < 0.10$), ** ($p < 0.05$), *** ($p < 0.010$).

Table 11: Mixed logit regression results separated by regulatory status using alternative financial variables

	Deregulated			Regulated		
	(1) G-index	(2) E-index	(3) L-index	(4) G-index	(5) E-index	(6) L-index
Mean						
D_{CMOA}	-2.984***	-3.013***	-2.917***	-2.549***	-2.550***	-2.552***
	(-7.87)	(-7.82)	(-7.78)	(-11.09)	(-11.07)	(-11.05)
D_{POST}	-3.159***	-3.076***	-3.054***	-2.715***	-2.717***	-2.670***
	(-5.85)	(-5.72)	(-5.69)	(-8.34)	(-8.30)	(-8.21)
D_{LNB}	-2.846***	-2.852***	-2.820***	-2.589***	-2.591***	-2.577***
	(-8.35)	(-8.26)	(-8.19)	(-12.94)	(-12.92)	(-12.90)
K*Age	0.000344	0.000199	0.000302	-0.000276	-0.000287	-0.000309*
	(0.97)	(0.53)	(0.85)	(-1.55)	(-1.61)	(-1.69)
K*G-index	0.00405**			0.000968*		
	(2.02)			(1.66)		
K*Cash flow/debt	-0.0194***	-0.0131***	-0.0138**	-0.00459**	-0.00510***	-0.00411**
	(-2.89)	(-2.60)	(-2.49)	(-2.45)	(-2.58)	(-2.20)
K*Market-to-book	0.0401	0.0117	-0.0000993	0.0510***	0.0555***	0.0377**
	(1.29)	(0.51)	(-0.00)	(2.71)	(2.77)	(2.11)
K*Debt/equity	-0.00502	0.000597	-0.00223	0.00445*	0.00469*	0.00527**
	(-0.95)	(0.12)	(-0.42)	(1.68)	(1.76)	(1.97)
K*Asset	0.00828	0.00761	0.00771	0.000207	0.00124	-0.00277
	(1.54)	(1.45)	(1.41)	(0.08)	(0.43)	(-1.24)
K	-0.0120	-0.0125	-0.0145*	-0.00205	-0.00262	-0.00296
	(-1.51)	(-1.61)	(-1.73)	(-0.51)	(-0.66)	(-0.73)
V	-0.0451***	-0.0489***	-0.0448***	-0.0451***	-0.0461***	-0.0460***
	(-3.11)	(-3.28)	(-3.02)	(-4.37)	(-4.45)	(-4.40)
K*E-index		0.00645**			0.00260*	
		(2.09)			(1.77)	
K*L-index			0.000729			0.00135
			(0.26)			(0.75)
Standard deviation						
K	0.0000141	-0.0000358	-0.000889	-0.000102	0.000161	-0.0000333
	(0.00)	(-0.01)	(-0.06)	(-0.04)	(0.06)	(-0.01)
V	0.0272	0.0294	0.0262	0.0253***	-0.0265***	0.0270***
	(1.59)	(1.57)	(1.49)	(2.95)	(-3.05)	(3.17)
Number of units	130	130	130	264	264	264
AIC	333.3	332.3	337.7	774.3	773.3	776.4
BIC	401.7	400.7	406.0	851.3	850.3	853.4
Log-likelihood	-153.7	-153.2	-155.9	-374.2	-373.6	-375.2

Notes: The table reports results from estimating the mixed logit model separately using data from regulated and deregulated plants, respectively.The data for financial and governance variables are the average of 1998-2000. t statistics are in parentheses. * ($p < 0.10$), ** ($p < 0.05$), *** ($p < 0.010$).

The **ozone season capacity factor** variable is calculated using **ozone season total generation** divided by boiler capacity. We obtain the latter data from the EPA's Air Market Data Program (AMPD) for the years 1997–2008, which spans three NO_x emission trading programs—the OTC, the NBP, and the Clean Air Interstate Rule (CAIR). One issue is that some boilers in the AMPD did not report their total generation, but reported steam load instead. This results in some missing data. EIA767 has net generation data (total generation minus electricity used onsite). We used these net generation data and imputed the total generation for each boiler using the non-missing total generation data of the AMPD.

Data on **firing type** and **ozone heat input** come directly from the Air Markets Program Data (AMPD). Umbrella distinguishes seven firing types: single-wall, opposed-wall, tangential, twin-tangential, cell-fired, cyclone and other. The AMPD contains a few more firing types. The engineering literature and consultations with engineers from boiler manufacturers enabled us to map those firing types from the AMPD into the seven firing types distinguished by Umbrella.

The mapping details are as follows. If the AMPD's firing-type variable name contains the string "Wall," then the boiler is wall-fired. If additionally the boiler's capacity exceeds 300MW, then the firing type is opposed-wall; otherwise it is single-wall (Toupin, 2015). If the AMPD's firing-type variable name contains the string "Cyclone," then the boiler is cyclone-fired. If the firing-type variable is either Circulating fluidized bed or Stoker, then the boiler is treated as cyclone-fired as well. This is because boilers with these two firing types have the same technology feasible set as cyclone-fired boilers. If the firing type-variable name contains the string "Tangential," then the boiler is tangentially-fired. If additionally the boiler's capacity exceeds 615MW, then the firing type is twin-tangential; otherwise it is tangential. The full mapping between AMPD firing type and Umbrella firing type is as shown in Table 12.

Table 12: Mapping between AMPD firing type and Umbrella firing type

AMPD Firing Type	**"Umbrella" Firing Type**	Source
Wall-fired boilers with capacity less than 300MW	Single Wall	Kevin Toupin, Babcock Power, Inc.
Wall-fired boilers with capacity greater than 300MW	Opposed Wall	Kevin Toupin, Babcock Power, Inc.
Cyclone, Stoker and Circulating fluidized bed boilers	Cyclone	U.S. EPA (1994)
Tangential-fired boilers with capacity less than 615MW	Tangential	U.S. EPA (1994)[17]
Tangential-fired boilers with capacity less than 615MW	Twin-Tangential	U.S. EPA (1994)
Cell burner boiler	Cell-fired	

The AMPD also contains boilers that are either vertically-fired, arch-fired or turbo-fired. Umbrella cannot be used to calculate the cost for these firing types. These boilers, however, are inconsequential (Himes, 2015). We remove these boilers from our dataset. Indeed, the dataset indicates that these firing types account for only about 3.5% of aggregate installed capacity. Our dataset also indicates that arch-fired boilers are usually very old and do not

original mapping. Correspondence with EPA staff suggests that the stakeholders and utilities sometimes make mistakes and update their information. Following this hint, we use the boiler capacity of the most recent year.

[17]The article states that about 10% of tangentially-fired boilers have twin furnaces, and they are generally greater than 400MW. 615MW is used as a threshold because 90% tangentially-fired boilers have capacity less than 615MW.

generally install any NO_x control technology.

Furnace exit emission rates data are only needed when calculating the cost of post-combustion technologies such as Selective Catalytic Reduction (SCR) and Selective Non-catalytic Reduction (SNCR). The AMPD lists post-retrofit emissions rates for each boiler.

Calculating furnace exit emission rates for these technologies requires data on pre-retrofit emissions rates, which we do not observe for firms that installed NO_x control technologies. These data, however, can be approximated using emissions factors that relate emissions rates to an emissions-generating activity, such as fuel consumption. These emissions factors are obtained from the EPA's AP-42 Compilation of Air Pollutant Emission Factors (U.S. EPA, 1995).

Coal type data are collected from EIA Form 767. This data source does not have coal-type data for year 2000. It only lists general fuel types such as gas, oil or coal. After that year, however, EIA Form 767 categorizes coal type into BIT (Bituminous), SUB (Subbituminous), LIG (Lignite), WC (Waste/Other Coal), and SC (Coal-based Synfuel). We impute the coal type for 2000 by assuming that boilers did not switch coal type between years 2000 and 2001. Importantly, Umbrella distinguishes only four coal types: Anthracite, BIT, SUB and LIG. To map between the EIA Form 767's coal types and Umbrella's coal types, we use information provided in the instructions for EIA Form 767, which note that WC and LIG have a similar range of heating values, as do SC and BIT. Because the heating value is a key reason for why coal type matters for SCR capital cost (Sargent Lundy, 2013), we map EIA category WC to Umbrella category LIG, and EIA category SC to Umbrella category BIT. In addition, EIA views Anthracite to be BIT. We follow suit.

We also collect **fuel heat content**, **fuel ash content** and **fuel sulfur content** from EIA Form 767. It provides these data at the boiler level.

Heat rate is calculated as ozone heat input divided by ozone season total generation.

Calcium oxide in coal ash differs by coal type. We gather this data from Federal Highway Administration report (Chesner et al., 1998). The source lists a range of Calcium Oxide levels in coal ash for major types of coal—BIT, SUB, and LIG. Since WC is a mix of waste from BIT and LIG, we use the average calcium level of BIT and LIG as the calcium level of WC.

The way to obtain data on the number of burners, burner columns, furnace depth, furnace width, and flue gas temperature at air heater outlet is provided by Toupin (2015).

Number of burners is calculated using a rule of thumb:

$$\text{number of burners} = \frac{\text{maximum heat input rate in MMbtu/hr}}{\text{200 MMbtu/hr per burner}},$$

where the maximum heat input rate is the ozone heat input rate from the AMPD.

Number of burner columns is interpolated from the following data points:

$$60\text{MW} = 2\text{columns}$$
$$150\text{MW} = 4\text{columns}$$
$$400\text{MW} = 8\text{columns}$$
$$600\text{MW} = 10\text{columns}.$$

Furnace depth is interpolated from the following data points:

$$60\text{MW} = 30\text{feet}$$
$$150\text{MW} = 32\text{feet}$$
$$400\text{MW} = 40\text{feet}$$
$$600\text{MW} = 50\text{feet}$$

Furnace width is the number of burners times 12 feet.

Flue gas temperature at air heater outlet equals 300 °F if the fuel sulfur content is less than 1% and 320 °F otherwise.

Labor cost includes wages and benefits. We collect wage and benefits data from "Occupational Employment and Wage Statistics" at *https://www.bls.gov/oes/tables.htm*

The labor benefits for construction and extraction workers accounted for about 32.3% of total employee compensation in 2003.[18] Some state-year wage data are missing. We interpolated these using the non-missing wage data.

Water price is collected from Raftelis Financial Consultants' (RFC) Water and Wastewater Rate Survey and from American Water Works Association (AWWA) surveys. These surveys publish data biennially from 2000 to 2008. Not all of the water utilities have consistently participated in the surveys each year. We interpolated the missing data using the non-missing water price data

Reagent cost is collected from a dataset provided by Nehring (2015). The dataset contains state-by-year fertilizer prices from 1960 to 2012.

For the **electricity price** we use wholesale electricity price data from Whole Electricity and Natural Gas Market Data at *https://www.eia.gov/electricity/wholesale/*.

These prices are only available for some regions, for limited years. We impute missing values from a regression of wholesale prices on electricity retail prices that we have for all states and all years in our sample. The retail prices are obtained from "state electricity profiles" at *https://www.eia.gov/electricity/state/*.

Fuel cost is calculated from FERC-423 data on fuel purchasing contracts for all power plants.

[18] We use the benefits of construction and extraction workers because boilermakers belong to this occupation category.

Contracted fuel need not be used in the year in which it was purchased, however. For plants without contracts in a given year we used the previous year's price. Divested plants were not required to report to FERC before 2002 and fuel-cost data for non-utility plants have not been released to the public after 2002. So our dataset contains fuel cost data for regulated utilities from FERC-423. We use 88% of the average fuel cost for regulated utilities as the fuel cost for deregulated plants. This is because Cicala (2014) finds that deregulated plants paid 12% less for coal than regulated plants. A sensitivity test finds that our technology cost calculation is not sensitive to a wide range of fuel costs.

Technology-specific input variables

The main technology-specific input variables required by Umbrella are number of overfire air (OFA) ports, number of walls with OFA ports, heat input as gas, choice of reagent for SCR and SNCR, and NO_x reduction percentage for each technology other than SNCR. The NO_x reduction percentage for SNCR depends on boiler characteristics and can be generated by Umbrella. The other input variables may differ across boilers as well. It is difficult, however, to obtain information on precisely how they depend on boiler characteristics, since this involves proprietary information. We thus use typical values suggested by Toupin (2015).

The NO_x reduction percentages for technologies other than SNCR are proprietary. The sources below provide percentages voluntarily disclosed by some boiler makers or obtained from experiments undertaken by EPRI and the EPA. The sources provide a range of NO_x reduction percentages for each specific technology. We use the mid point of this range, which is generally used by power plants managers too (Stevens, 2015).

1. Electric Policy Research Institute. 1999. "Application of Methodology for Identification of Least Cost NO_x Control Combinations."

2. Electric Policy Research Institute. 1999. UMBRELLA: "Software for Assessing NO_x Control Technology Combinations, Version 1.0."

3. Farzan, H. Maringo, G.J. Johnson, D.W. Wong, D.K. 1999. "B&W's Advances on Cyclone NO_x Control Via Fuel and Air Staging Technologies," EPRI_DOE_EPA Combined Utility Air Pollutant Control Symposium, Atlanta GA.

4. Retrofit NO_x Controls for Coal-Fired Utility Boilers - 2000 Update. 2000. http://www.epri.com/search/Pages/results.aspx?k=Retrofit%20NO$_x$%20Controls%20for%20Coal-Fired%20Utility%20Boilers%20-%202000%20Update

5. Staudt, J. "Technologies and Cost Effectiveness of Post-Combustion NOx Controls." Andover Technology Partners, http://www.netl.doe.gov/publications/proceedings/99/99scr-sncr/staudt.pdf.

6. U.S. Department of Energy. 2002. Full-Scale Demonstration of Low-NO_x Cell Burner Retrofit. https://www.netl.doe.gov/File%20Library/Research/Coal/major%20demonstrations/cctdp/Round3/LNCB2.PDF

7. US EPA Office of Research and Development. 2001. EPA-600/R-01-087. Cost of Selective

Catalytic Reduction (SCR) Applications for NO_x Control on Coal-Fired Boilers. http://nepis.epa.gov/Adobe/PDF/2000CYYO.pdf