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Still your grandfather's boiler: Estimating the effects of the Clean Air Act's grandfathering provisions

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ABSTRACT

While vintage differentiation is a highly prominent feature of various regulations, it can induce significant biases. We study these biases in the context of New Source Review—a program within the US Clean Air Act imposing costly sulfur dioxide (SO_2) abatement requirements on new boilers but not existing ones. In particular, we empirically investigate how the differential treatment of coal boilers shaped the generation landscape by affecting unit utilization, retirement, and emissions. Leveraging a novel dataset covering state-level sulfur dioxide regulations for power plants, we show that the differentiation continued to have a strong effect even 30 years after its passage, raising the probability of surviving another year by 1.5 percentage points for grandfathered boilers and increasing their operations by around 800 hours annually. We estimate exempted units would have emitted a third fewer emissions per year, had they been subject to NSR. We run back-of-the-envelope calculations to assess the societal damages associated with the delayed retirements, higher utilization and higher emission rates of the grandfathered boilers. Focusing solely on the additional SO_2 emissions, we estimate annual costs of up to \$65 billion associated with the vintage differentiation in New Source Review.

Keywords: grandfathering, regulation design, Clean Air Act, power plants, coal.

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1 Introduction

Policymakers frequently condition regulatory stringency on the vintage of regulated units, with later entrants typically being subject to more stringent standards. Such vintage differentiated regulation (VDR) reduces investment uncertainty and can, in some cases, be justified on the grounds of efficiency or fairness (Nash, 2009). However, age differentiation is also likely to introduce distortions known as "new source bias" (Levinson, 1999). As differentiation tends to increase the relative cost of new units, it can lead to their decreased operation and profitability.[1] All else being equal, this can reduce the number of new entrants and lengthen the lifespan of existing units (Fraas et al., 2017, Heutel, 2011, Revesz and Westfahl Kong, 2011), potentially leading to perverse effects. These can be particularly severe when incumbents are completely exempted from new regulation, i.e., in case of grandfathering.[2] Despite VDR's high prevalence and its potential for perverse effects, especially across environmental regulations,[3] vintage differentiation remains understudied in economics (Damon et al., 2019).

We attempt to run a comprehensive empirical analysis of the unintended emission effects of VDRs in the context of the Clean Air Act, a seminal US environmental statute that has been touted as "one of the most significant federal interventions into markets in the postwar period" (Currie and Walker, 2019). While the statute comprises many elements, New Source Review (NSR) affects the vast majority of manufacturing facilities and power plants in the US. Introduced in 1977, this stringent and complex permitting process—applied to new units and to existing units having undergone substantial modifications—effectively grandfathered

[1] These effects can be partially mitigated through greater regulatory uncertainty—and thus, greater operational risk—facing grandfathered incumbents. For these units, additional, more stringent regulations passed without grandfathering provisions may be very hard to meet and, therefore, can can adversely affect their future profits.

[2] The etymology of the term "grandfathering" dates back to Jim Crow-era voting laws, when states created high barriers to voting, but allowed potential voters to sidestep the restrictions if the voter's grandparent had been an eligible voter, thus creating a separate set of rules for white citizens – whose grandparents had generally been eligible to vote – and Black citizens – whose grandparents were barred from voting. Since that time, the word has been used more generally to refer to differentiation in laws for new and existing entities. We use the term "grandfathering" in this paper, however, we wanted to acknowledge the term's racist roots.

[3] As Stavins (2006) notes, in the US, VDR appears "within the Clean Air Act in its standards for emissions from new versus existing stationary sources, motor vehicle and motor vehicle engines, non-road engines and vehicles, and commercial vehicles; within the Clean Water Act in a wide variety of aspects, including in effluent limits for public treatment plants; within the Safe Drinking Water Act; and within laws affecting the generation and disposal of hazardous and solid waste ... in a variety of occupational health and safety laws, automotive safety regulations, consumer product safety laws, and building codes." Vintage-differentiation is also present in drug approvals, underground storage tanks regulations, the Consumption Tax Act, the Affordable Care Act, the Federal Communications Commission's multiple ownership rules, financial regulations including the SHO Rule 201, etc.

all existing ones from federal regulation. As NSR is a program with major economic impacts and high compliance costs (Schmalensee and Stavins, 2019), a significant risk of adverse effects exists. Nevertheless, NSR has largely escaped comprehensive retrospective analyses (Aldy et al., 2020).

In our study, we focus on the program's effects on emissions of sulfur dioxide (SO_2)—a highly damaging pollutant targeted by NSR.[4] We investigate emissions in the context of coal boilers given they are the main source of SO_2 pollution and given the controversies around the effects of NSR grandfathering on the US power plant fleet (Revesz and Lienke, 2016). The operations of coal power plants are also well-documented with rich, publicly-available data permitting a more granular analyses.

Grandfathering increases emissions directly, with emissions rates differing widely between new and grandfathered units (GAO, 2012a, Cohan and Douglass, 2011, Ackerman et al., 1999). However, there may also be substantial additional impacts, such as through changes in boiler utilization (Stanton, 1993) or their survival. When Congress proposed the NSR provisions in 1977, the expectation was that most major stationary sources would quickly become subject to federal control notwithstanding the grandfathering provision. Lawmakers assumed units would be phased out over the course of their ordinary economic lives, which at the time were thought to be around 30 years.[5] However, the data shows that over 40 percent of the coal boilers active in 1977 were still operational in 2018,[6] suggesting that regulations may have incentivized older boilers to remain operational beyond their expected lifespan.

In order to properly assess these three impact channels, we first derive a framework that shows how differences in boiler survival, emission intensity, and utilization could drive changes in emissions. Next, we estimate grandfathering effects on the these impact channels. Finally, we use our estimates to perform a back-of-the-envelope calculation of the emissions and the associated damages that could have been avoided in the absence of NSR grandfathering provisions.

Our empirical approach compares the outcomes of interest for grandfathered boilers and

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[4] NSR also regulates nitrogen oxides and particulate matter emissions from power plants. However, compliance with these requirements is much cheaper than for sulfur dioxide—see, for instance Linn (2008) for the costs of nitrogen oxide abatement equipment. We, thus, expect limited impacts from units being shielded from these requirements through grandfathering provisions.

[5] Revesz and Lienke (2016) provide legislative records illustrating this expectation. For instance, during a hearing on NSR, Senator Howard Baker of Tennessee expressed the opinion that most of the 200 coal-fired power plants that were over twenty years of age at that time would be "phased out of operation in the next 5 to 20 years" (Revesz and Lienke, 2016, p. 48).

[6] The percent of coal boilers active across both 1977 and 2018 was estimated by combining information from Form EIA-767 with records from a proceeding into the age of boilers run by the Missouri Public Service Commission (2014).

boilers subject to NSR, while controlling for their characteristics, various state and federal sulfur dioxide regulations as well as spatial and temporal heterogeneity. The analysis is aided by variation in NSR rules, in particular through the differences in their applicability depending on boiler size and use. At the same time, the complex design of NSR and the existence of other SO_2 regulations could confound our estimates. To reduce this, we carefully account for other SO_2 regulations and their potential interactions with NSR. For instance, as the NSR rules differ between non-attainment and attainment counties—that is, those counties who have not met federal air quality standards versus those in compliance—we allow the grandfathering effects to depend on attainment status.

We find that initial assignment to NSR grandfathering increases boiler utilization, survival and emission rates. On average, grandfathered boilers are associated with around 787 additional hours under load annually, 2.05 pounds of additional sulfur dioxide emissions per MW of capacity per hour operated, and with a 1.5 percentage point increase in the probability of survival (reducing the likelihood of retirement in a given year by 84 percent compared to the sample average retirement rate).We also show that in areas with stringent state sulfur dioxide regulations and in non-attainment areas, new source bias is reduced. Our back-of-the-envelope calculations suggests that without grandfathering exemptions in NSR, SO_2 emissions from the pre-NSR boilers would have been lower by up to 70%. For instance, in 1998, when the absolute savings would be the highest, boilers belonging to investor-owned utilities and to commercial and industrial facilities would emit 1.6 million short tons less than the 5.2 million short tons observed. Based on marginal damage estimates from Holland et al. (2016), we translate these differences in sulfur dioxide emissions in 1998 into damages of $65 billion (in 2000 USD). Over time, as state and other federal environmental regulations became increasingly stringent, the damages associated with grandfathering decreased.

We contribute to the understanding of the effects of the Clean Air Act by providing easily interpretable estimates of the utilization, survival and emission rates influenced by NSR grandfathering. We also derive a comprehensive quantification of the emission impacts of grandfathering exemptions. Our results suggest substantial environmental harms due to VDR in this context. However, we also show that in regions with stringent local sulfur dioxide regulations, new source bias is reduced, emphasizing the complementarity between state and federal regulations. To our knowledge, our study represents the first empirical analysis to include state-level sulfur dioxide regulations. This was made possible, in part, by our development of a state regulation dataset with coverage from 1970 to the present. This novel contribution allows us to exploit variation in state regulations to more cleanly identify the effects of NSR grandfathering.

We also contribute to the literature on the merits of vintage differentiation. Existing studies are mostly confined to theoretical analyses within the legal literature (e.g., Kaplow, 1986, Stavins, 2006, Nash and Revesz, 2007, Nash, 2009, Revesz and Westfahl Kong, 2011, Huber, 2011, Serkin and Vandenbergh, 2018). In economics, studies have noted how grandfathering can help solve the tragedy of the commons (e.g., Damon et al., 2019, Anderson et al., 2011), and how grandfathering can be optimally used in the context of emissions trading (e.g., Hepburn et al., 2007, Böhringer and Lange, 2005). Empirically, Coysh et al. (2020) find in a cross-country panel that greater vintage differentiation is associated with significantly higher retirement age in the electricity sector. Another cross-country study, reports that the choice of entry modes in foreign direct investment (MA vs greenfield) is consistent with the existence of substantial grandfathering in environmental regulations. Bialek and Weichenrieder (2021)

The remainder of the paper is structured as follows. Section 2 provides background information on sulfur emissions occurring as a byproduct of coal combustion, available emission reduction strategies, and various sulfur dioxide regulations in the US. Section 3 reviews relevant literature and conducts a descriptive analysis to argue that a substantial new source bias is to be expected in the context of NSR. Section 4 delineates the conceptual framework for our empirical investigation, while Section 5 provides an overview of the data. We present the estimation results along with our back-of-the-envelope damages calculations in Section 6, while Section 7 concludes.

2 Background information on sulfur abatement and regulations

2.1 Sulfur Abatement

Burning coal is responsible for the majority of sulfur dioxide emissions.[7] The quantity of emissions produced from coal depends on its sulfur content and power plant abatement effort. The former usually ranges between 0.5 and 5.0 percent, with the most sulfur-intensive coal sourced from the Appalachian and Illinois basins. The small, acidic particulates released as a result of burning coal can penetrate human lungs, such that even short-term exposures to airborne sulfur dioxide has been linked with asthma, bronchitis and other adverse health effects (Chen et al., 2007). With respect to the environmental effects, sulfur dioxide contributes to acidic deposition—including acid rain—constitutes a major precursor

[7] In 1990, for instance, 70 percent of US sulfur dioxide emissions—around 16 million tons—were attributable to coal-fired generation (EPA, 2018).

to particulate matter, and impairs visibility.

To reduce the emissions intensity of sulfur dioxide, boiler owners rely on two main strategies: switching to less sulfur-intensive coal and installing sulfur-abatement equipment in the form of flue-gas desulfurization units. The latter, colloquially referred to as "scrubbers," remove sulfur dioxide from exhaust flue gases. As for the former, using low-sulfur coal can decrease emissions below 1.2 lbs of SO_2 per MMBtu, but it tends to be expensive as deposits are less geographically convenient. Scrubbers, on the other hand, are capable of removing between 50 to 98 percent of the pollutant, depending on the type of scrubber and its operation, but are very costly to install and run.

The negative impacts of SO_2 emissions drove a regulatory effort to curb them. Below, we outline the measures applicable to power plants.

2.2 Federal regulations

The first federal effort to control sulfur dioxide emissions from major power plants was the 1970 Clean Air Act. It created emission intensity limits called the New Source Performance Standards (NSPS): boilers above 73MW whose construction commenced after 1971 or were modified thereafter were required to emit no more than 1.2 lbs of SO_2 per MMBtu of heat generated by the combustion of coal.

The 1977 Clean Air Act Amendments proposed a stricter set of rules for larger facilities, known as New Source Review. NSR subjected new or modified boilers to a permitting process[8] and imposed very stringent sulfur dioxide emission limits: boilers with capacity above 73 MW that generate electricity for utility sales were not only required to meet the 1.2 lbs/MMBtu standard, but were also required to abate their emissions by up to 90% relative to the potential emissions of the input fuel.[9] Effectively, this was tantamount to a scrubber installation mandate. In 1984, the regulations were extended to new or modified commercial and industrial boilers above 29 MW, with a grace period until 1986.[10] Then in 1989, these were further extended to new and modified commercial and industrial boilers with capacity above 2.9 MW.

[8] The permit application process is very complex and can involve up to five different stages: permit preparation, determination of application "completeness," public notice and comments, iterative responses to comments, and possible administrative and judicial appeals (Fraas et al., 2015). The process can be costly due to the large investment of time and resources, the associated uncertainties, and possible delays. Between 2002 and 2014, the permitting process for new coal boilers took, on average, 496 days or over 16 months (Fraas et al., 2015).

[9] For boilers with counterfactual sulfur dioxide emissions below 0.60 lbs of SO_2 per MMBtu, the boiler is only required to reduce emissions by 70%.

[10] Boilers of this size whose construction began between 1984 and 1986 were subject only to a 1.2 lbs/MMBtu performance standard and not required to install a scrubber.

Under NSR, facilities located in non-attainment areas—counties containing pollutant concentrations above threshold levels defined by the National Ambient Air Quality Standards (NAAQS)—must meet additional requirements. In order to gain a permit to build or modify a plant, facilities must generally obtain offsets for the resulting increase in emissions, potentially further dissuading new entrants (Shapiro and Walker, 2020). Depending on the region, these permits can be very expensive.[11] States are also required to make "reasonable further progress" on improving the air quality in their non-attainment areas, which can lead to additional state-level regulation beyond the federal requirements.[12]

The 1990 Clean Air Act Amendments, known as the Acid Rain Program, added the obligation to participate in a sulfur dioxide cap-and-trade program, first for the largest boilers, and after 1997 for all boilers with a capacity above above 25 MW.[13] In the years considered, the permit prices fluctuated between $0.01 and $860 per ton of SO_2.

In 2009, the Clean Air Interstate Rule (CAIR) became effective. For boilers located in upwind states, the Rule introduced obligations which effectively required obtaining two Acid Rain Program permits for each ton of emitted sulfur dioxide.[14] The Cross-State Air Pollution Rule (CSAPR) replaced CAIR in 2015 and introduced local sulfur dioxide emission trading programs. In the first phase, trades occurred separately for Group 1 and Group 2 states, which roughly correspond to upwind and downwind states, respectively. In the second phase of the program, starting in 2017, sulfur dioxide budgets were substantially tightened and additional trade restrictions between states were imposed. However, the emissions budgets under CSAPR were lenient. In most of the Group 1 states, for instance, the actual emissions in 2015 were already lower than the emission budgets for the second phase (Fotouhi et al., 2016). Consequently, emission allowances were available at relatively low prices between $1 to $5 per permit.

[11] EPA (2001) quotes the price range for 2001 sulfur dioxide offsets as between $6,000 to $7,667 per ton per year.

[12] In attainment areas, states are mandated only to avoid substantial degradation of air quality (Nash and Revesz, 2007).

[13] Some of the sulfur dioxide permits were allocated for free to incumbent power plants—i.e., some permits were grandfathered. Due to the design of the allocation process and the permits' inherent opportunity costs, the permit grandfathering policy likely did not affect boiler operations or retirement decisions. As Burtraw and Szambelan (2009) note, the law distributed emissions allowances to each affected unit on the basis of its heat input during a historical base period—from 1985 to 1987—multiplied by an emissions rate and adjusted to make aggregated emissions equal the target emissions cap. Only plants in existence over the base period received an allocation, and their owners continued to receive it even after retirement.

[14] CAIR created an additional SO_2 market for boilers in upwind states. Because the permit market was connected to the Acid Rain Program's market, this had the effect of requiring affected upwind boilers to purchase two permits.

2.3 State regulations

States are required to develop a regulatory plan setting out a trajectory to meet air quality standards within each county. These plans create a separate layer of sulfur regulation, complementing federal standards. States tended to develop regulations for coal boilers either by setting a performance standard of sulfur dioxide emissions per MMBtu or by limiting the allowable sulfur content of combusted coal. In a given state, regulatory stringency may depend not only on the vintage of a boiler, but also on its size, number of stacks, location, etc., with some states regulating individual counties—or even individual plants or boilers—separately. Generally, state regulations are more lenient than NSR requirements. Thus, for boilers already subject to NSR, state regulations rarely cause additional compliance costs. In some states, however, regulations may cause high compliance costs for boilers not subject to NSR, creating variation in compliance costs across boilers.

3 Possibility of new source bias in the context of NSR

Compliance with NSR necessitates the operation of a scrubber and is, thus, extremely costly. According to estimates from the EPA, the initial capital cost of installing a wet scrubber was between \$25 and \$150 million for a 100 MW boiler, with an annual operating cost between \$0.8 and \$2.0 million (EPA, 2003).[15] Moreover, flue-gas desulfurization equipment requires the use of corrosive chemicals and reagents which necessitate costly equipment maintenance and can significantly shorten boilers' lifespan (EIA, 2019).[16] Scrubbers also increase the fuel necessary to generate a unit of electricity, raising the heat rate of a coal-fired unit by around 2 percent (EPA, 2010).

As NSR substantially drives up operation and capital expenditures for regulated units, it advantages older, exempted units. The possibility of new source bias in the context of NSR has been a subject of contention for decades. In particular, economists, legal scholars, and environmental groups have argued that NSR increased the lifespan of incumbent boilers (Stavins and Gruenspecht, 2002, Ackerman et al., 1999, Hsu, 2006, Nash and Revesz, 2007, Schneider, 2001, Revesz and Westfahl Kong, 2011). Clean Air Act court cases have also indicated that grandfathered boilers' lifespans have been prolonged beyond their normal

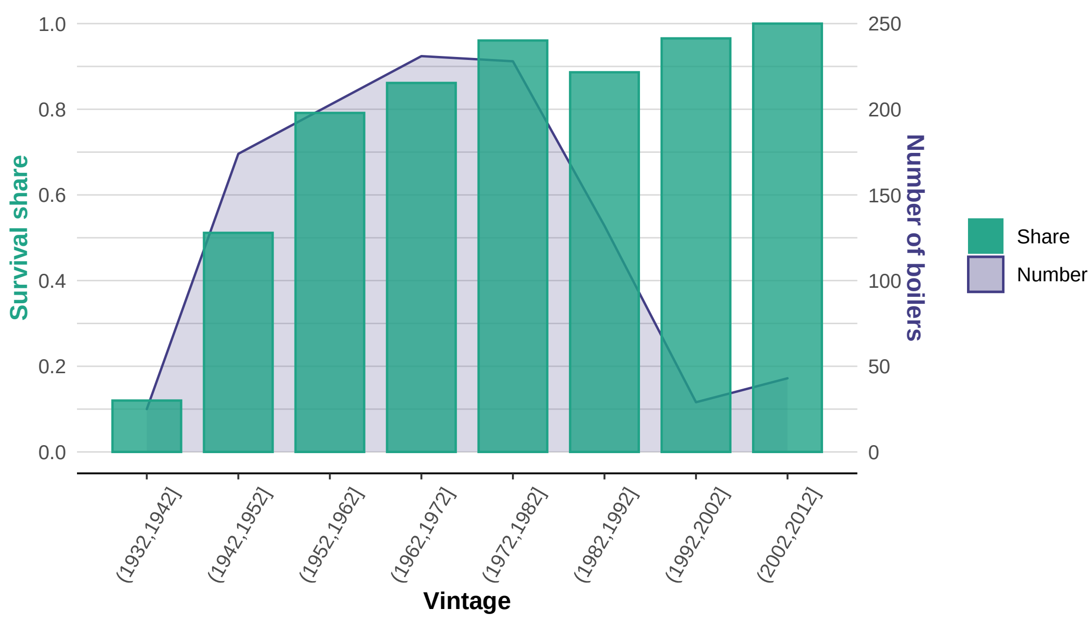
[15] Costs do not increase proportionally with the size of a boiler. A 650 MW boiler using a wet scrubber had capital costs between \$65 and \$162 million and an annual operating costs between \$1.3 and \$5.2 million (EPA, 2003).

[16] For such units, pollution control capital expenditures were estimated to account for around 20 to 27 percent of total capital costs, while annual pollution control expenditures account for about 23 to 31 percent of total annual generating costs (EPA, 2001).

economic life. For instance, according to the documents from a court case filed against Duke Energy Corp., a company representative admitted that by the late 1980s, some of Duke's grandfathered plants had deteriorated to the point of being often or always out of service. Although normally the plants would have been scrapped, these plants were not retired. Instead, between 1988 and 2000, Duke replaced or redesigned boiler elements, even though the cost of replacing them was several times the original cost of the entire generating unit (Rabinowitsh, 2008).

A naive analysis of the data is also suggestive of a grandfathering survival effect. Figure 1 shows that the probability to survive up to year 2014 is monotonically increasing for boilers with vintages up to 1982, i.e., boilers largely under grandfathered status.However, for the 1983-1992 cohort, where most boilers were subject to NSR, the probability to survive up to 2014 slightly declines. For the 1993-2002 cohort, the likelihood that a boiler survived to 2014 is only slightly higher than for a boiler from the 1973-1982 period. Such non-monotonicity in the propensity to survive is counter-intuitive: one would expect the share of surviving boilers be higher for younger boilers, especially if the technology improves over time. It indicates that NSR grandfathering could have affected boiler retirements substantially. Establishing whether this pattern in survival rates is indeed driven by NSR grandfathering provisions requires further empirical investigation.

Figure 1: Propensity to survive until 2014 for boilers from different vintages



Notes: Boilers that retired before 1985 are not included.

To the best of our knowledge, the implications of NSR grandfathering for boiler survival have not been studied empirically. However, there exist studies on closely related issues. Levinson (1999) looks at the effects of NSR grandfathering on the age of facilities in the commercial printing and paint manufacturing industries and finds no significant relationship. Heutel (2011) develops a structural model of boilers' scrapping, emissions and investment decisions. He uses the model to show that grandfathering provisions in NSPS increased both boilers' emissions and survival. Maloney and Brady (1988) and Nelson et al. (1993) find a positive correlation between more stringent regulation—measured as expenditures of the state air quality management agency—and the age of power plant capital. Both studies are frequently cited as support for the proposition that grandfathering delayed retirements.

As for differences in emissions rates, only a few studies have attempted an empirical analysis. Apart from Heutel (2011), who focuses on emission effects of NSPS, the relevant studies include: Nelson et al. (1993), who find no correlation between emission rates and age of capital; and, Raff and Walter (2020), who find that non-attainment status can cause regulatory avoidance in grandfathered boilers through voluntary decreases in emissions. The impact of grandfathering on utilization, on the other hand, has largely escaped public attention with the exception of Stanton (1993), who finds that plants subject to NSR or NSPS are less utilized than exempted plants.

A response channel that has also attracted interest, but is beyond our analysis, relates to potential adjustments in capital investments associated with the sunsetting provisions for NSR grandfathering. According to these provisions unit becomes exposed to NSR if it undergoes substantial modification in a way that increases emissions. Bushnell and Wolfram (2012) documents that increased enforcement of this requirement may have led to distortions in capital investments by power plants, seeking to avoid investments that could lead to a finding that the plant had been modified. List et al. (2004) show how NSR distorted modification decisions in manufacturing plants. Other studies used changes in the modification rule's enforcement to estimate the value of grandfathering provisions for existing power plants (Lange and Linn, 2008). We believe that the modification rule, by distorting capital investments, affected survival and utilization of the boilers, and thereby affected emissions. It could also directly affect emissions as documented in Keohane et al. (2009) who shows that power plants decreased their emissions when it became likely they would be targeted by the Environmental Protection Agency in relation to the modification rule. In our framework, we abstain from explicitly modeling the sunsetting provisions and instead acknowledge that part of the emission effects we estimate may be driven by them.

4 Conceptual framework

We would like to estimate SO_2 emissions in a world with no VDR, that is all boilers are subject to NSR from the time of the passage of the 1977 Clean Air Act Amendments. To answer that question, we first need a framework that connects the direct effects of NSR on boilers' operations through to emissions. We construct that framework by assuming that the amount of electricity needed to be produced each year is fixed and that boilers subject to NSR deliver the residual energy not provided by grandfathered boilers. This allows us to define the total annual boiler emissions as follows:

$$
\begin{aligned}
E^j_{total} =& E^j_O + E^j_N = H^j_O \cdot EI^j_O + (H_{total} - H^j_O) \cdot EI_N && (1)\\
=& H^j_O(EI^j_O - EI_N) + H_{total} EI_N && (2)\\
=& h^j_O \cdot N^j_O (EI^j_O - EI_N) + \bar{C}, && (3)
\end{aligned}
$$

where the upper index j denotes the scenarios considered: the status quo and our counterfactual without grandfathering. The lower index represents types of boilers, with old boilers grandfathered if NSR is passed with VDR exemptions and young boilers always subject to NSR, $i \in \{O,\ N\}$. Here, H_{total} is the total number of boiler-hours needed for coal power plants to serve load in a given year. The variables E_i and H_i denote respectively the emissions per hour under load and the total number of hours served by power plants of type i, while EI_i represents the average emission per hour operated or, alternatively, the emissions intensity. Finally, $\bar{C}$ denotes a constant. When moving from Equation (2) to (3), we approximate the total number of hours served by grandfathered boilers as a product of the hours under load for an average plant, h_i, times the number of grandfathered plants, N_i. Based on that we decompose the total emission effects of grandfathering into the following elements:

$$
\begin{aligned}
\varDelta E_{total} &= \Bigg(\underbrace{\frac{\mathrm{d}\ h_O}{\mathrm{d}\ Gf} N_O}_{\substack{\text{increased utilization}\\ \text{mechanism}}} + \underbrace{\frac{\mathrm{d}\ N_O}{\mathrm{d}\ Gf} h_O}_{\substack{\text{delayed retirement}\\ \text{mechanism}}} \Bigg)(EI_O - EI_N) + H_O \underbrace{\frac{\mathrm{d}\ EI_O}{\mathrm{d}\ Gf}}_{\substack{\text{change in}\\ \text{emission}\\ \text{intensity}}}. \\
&= \beta_{hours} N_O\ (EI_O - EI_N) + \ \beta_{surv} h_O\ (EI_O - EI_N) + \beta_{emit} H_O. && (4)
\end{aligned}
$$

The first term captures emission effects associated with grandfathered boilers increasing utilization, the second – the potential rise in grandfathered boilers survival rates that slows down the turnover of the boiler fleet. The third term captures the higher emission intensity of grandfathered boilers, compared to non-grandfathered boilers.

Because we assume constant electricity generation from coal boilers in both scenarios, we likely underestimate emission savings that would result from removing grandfathering. Namely, the increased costs would likely depress the cost competitiveness of coal boilers and, thus, lower their share in total generation. Removing the assumption would require adding an additional effect proportional to $\frac{\mathrm{d}\, H_{total}}{\mathrm{d}\, Gf}$ to Equation (4).

To translate the emissions to damages, we multiply the estimated difference in emissions by the marginal damages from sulfur dioxide. As SO_2 is a non-uniformly mixed pollutant, the emission damages depend on the location of the emission source. We assume that the geographical location of generation is not affected by grandfathering and compute emission effects at the county level, $\Delta E_{total,c}$. We then multiply these by county-level estimates of marginal damages of SO_2 emissions from Holland et al. (2016). To obtain a measure of the total SO_2 damages associated with grandfathering, we sum over all counties.

In the reminder of this section, we discuss our approach to estimating the β parameters delineated in Equation (4). Since it forms such a large part of our identification strategy, we also outline our approach to each potentially confounding environmental regulation in detail. Finally, we discuss threats to causal identification.

4.1 Estimating survival effects

We want to estimate the relationship between NSR grandfathering and the turnover of the coal-fired fleet, i.e. the parameter β_{surv}. Coal-fired power plants subject to NSR effectively have to install and run a scrubber, adding substantial investment, maintenance and generation costs. These additional costs were largely avoided by grandfathered plants, even in the presence of stringent state regulations.

To understand how this cost advantage could affect the survival of grandfathered boilers, we build a framework that reflects the retirement decision faced by boiler owners. In theory, a boiler will be retired if the cost of its continued operation is sufficiently higher than that of its replacement, such that the lower operational costs outweigh the capital costs of demolishing and replacing the existing boiler. Assuming a replacement boiler is identical in size, location and fuel source, the retirement decision at time t for boiler i in location j made by owner type m is modelled as follows:

$$\pi_{it}^{E} = R_{it}^{E} - C^{E}\left(GF_{it},\ \mathbf{\Omega}_{it},\ size_i,\ \mathbf{X}_{it}^{S},\ \mathbf{Z}_{jt}^{S},\ \mu_m\right)\ +\ \epsilon_{it}^{E} \tag{5}$$

$$\pi_{it}^{R} = R_{it}^{R} - C^{R}\left(\boldsymbol{\Omega}_{it},\ size_i,\ \mathbf{Z}_{jt}^{S},\ \mu_m\right) - \kappa\left(\boldsymbol{\Omega}_{it},\ size_i,\ \mu_m,\ \eta_t\right) - S_{ijmt}\ +\ \epsilon_{it}^{R}, \tag{6}$$

where π_{it}^{E} represents profits associated with the continued operation of the existing boiler and π_{it}^{R} is the profit associated with replacement. The operating costs for an existing boiler, $C^{E}(\cdot)$, depend on its pollution control equipment, which is driven by: its grandfathering status, GF_{it}; its generation capacity, $size_i$; and, the remaining characteristics of the boiler, $\mathbf{X}_{it}^{S}$, including age. These costs are also influenced by environmental regulations applicable to the specific boiler, $\boldsymbol{\Omega}_{it}$, where grandfathering status may attenuate some of their effects. Local cost determinants, such as regional demand and competitive pressure but also location-level fixed effects, are captured by $\mathbf{Z}_{jt}^{S}$. As there may be differences in decision-making between owner types—e.g., state-regulated investor-owned utilities face the cost of service regulation and, therefore, have somewhat different boiler replacement incentives than do co-ops or industrial owners—we allow μ_m to capture the costs specific to the owner type.

The operating costs for a new unit are given by $C^{R}(\cdot)$ and its investment cost, $\kappa(\cdot)$, can be affected by year-specific effects captured by η_t. Changes in operation costs associated with boiler replacement affect the amount of electricity generated and revenue, $R(\cdot)$, such that $R_{it}^{R} = R_{it}^{E} + \psi\left(C^{R}(\cdot) - C^{E}(\cdot)\right)$. Finally, $S_{ij}(\cdot) = S + e_{it}$ captures the scrappage costs for boiler i and idiosyncratic effects are captured by ϵ_{it}^{E} and ϵ_{it}^{R}. If the difference between Equations (6) and (5) is positive, it is more profitable to replace the boiler, such that its survival can be represented by the function:

$$survive_{it} = g\left(GF_{it},\ \boldsymbol{\Omega}_{it};\ size_i,\ \mathbf{X}_{it}^{S},\ \mathbf{Z}_{jt}^{S},\ \alpha_j,\ \mu_m,\ \eta_t,\ \epsilon_{it}^{E},\ \epsilon_{it}^{R}\right) \tag{7}$$

We do not separately model upgrade decisions for existing units, e.g., turbine upgrades or condenser optimization. Instead, we assume that the profits of an existing plant are based off an optimal upgrades plan and that the possibility of improvement is not limited by grandfathering status. In other words, we assume that the sunsetting rule did not affect the boilers' behavior and profits. This assumption is motivated by the fact that for much of our sample period, the modification rule was lightly enforced.[17]

4.2 Estimating utilization effects

NSR grandfathering affects boiler utilization through the additional generation costs imposed on regulated units by the *de facto* scrubber requirement and, in non-attainment

[17] The effects of the modification provision could be proxied within our framework, for instance by interacting the age of boilers with grandfathering status. However, this relationship would need to be time dependent as the enforcement of the provision changed over time. See Lange and Linn (2008) and EELP Regulatory Tracker New Source Review.

regions, by the obligation to offset any net increase in emissions when building a new or modified source (Shapiro and Walker, 2020). *Ceteris paribus*, NSR grandfathering provisions, thus, provide a substantial variable cost advantage, which should translate to higher utilization rates. Under cost minimization, boilers with lower marginal costs should be dispatched more frequently both in wholesale market settings and in the context of regulated, vertically integrated utilities. With utilization driven by cost minimization considerations, we define the following function to explain the number of hours boiler i runs in year t:[18]

$$hours_{it} = f\left(GF_{it},\ \mathbf{\Omega}_{it};\ \mathbf{X}^H_{it},\ \mathbf{Z}^H_{jt},\ \alpha_j,\ \mu_m,\ \eta_t,\ \epsilon^h_{it}\right) \tag{8}$$

where indices as well as terms GF_{it}, $\mathbf{\Omega}_{it}$, α_j, μ_m and η_t are similarly defined in Equation (7). Boiler-level and location-specific characteristics relevant for utilization are given by the terms $\mathbf{X}^H_{it}$ and $\mathbf{Z}^H_{jt}$, respectively.

Some of the factors that affect boiler utilization, such as market conditions, including load duration curves, market structure, and market conduct are not observable to us. We, thus, rely on the assumption that there are no systematic differences between the demand and competition faced by grandfathered and non-grandfathered boilers.[19]

A significant and positive coefficient on grandfathering status would indicate a marginal cost advantage associated with NSR exemption but would not explain the mechanism through which that advantage occurs. One potential driver of this difference in marginal cost is that operating a scrubber requires electricity, decreasing the amount of electricity a boiler can deliver to the grid. Consequently, systematic differences in generation ratios between grandfathered and non-grandfathered boilers could be indicative of the electricity expense associated with scrubber operations driven by NSR. We measure this advantage through the net-to-gross generation ratio, i.e. net generation measured at the power plant's connection to the grid compared to gross generation measured at the generator. The generation ratios are captured by the following naive regression:

$$GR_{it} = \alpha + \beta GF_i + \mathbf{X}^{GR}_{it}\boldsymbol{\gamma} + \epsilon^{GR}_{it} \tag{9}$$

where GR_{it} is the net-to-gross generation ratio for boiler i during time t. The set of covariates, $\mathbf{X}^{GR}_i$, represent various boiler characteristics, α is the intercept, while the ϵ^{GR}_{it} term

[18] We define utilization as hours under load, that is the number of hours a unit operates.

[19] Potentially problematic is that both market structure and conduct are related to the electricity regime, and many regions in the US underwent restructuring from vertically-integrated monopolies to liberalized markets during the analyzed time horizon (Borenstein and Bushnell, 2015). For our approach, we require that market restructuring affected grandfathered and non-grandfathered boilers symmetrically.

represents i.i.d. idiosyncratic effects.

4.3 Estimating emission effects

As boilers regulated by NSR face stricter sulfur regulations, we can expect their emission rates—the amount of emissions released per unit of generation—to be lower than those for grandfathered units. This does not imply, however, that grandfathered units went unregulated. Boilers built before 1978 may be exempt from NSR but still subject to NSPS or state regulation, which could create incentives or requirements to use low-sulfur coal and, in some cases, even to install scrubbers. In addition, the 1990 Clean Air Act Amendments launched a sulfur dioxide cap-and-trade market, which made it economically desirable for coal plants to take some steps to reduce their sulfur emissions. And indeed, over time, many grandfathered boilers found it profitable to use low-sulfur coal or install scrubbers.

To study the difference in emissions associated with NSR grandfathering, we assume the average emissions rate of boiler i in year t can be represented by the following function:

$$emissions_{it} = h\left(GF_{it},\ \mathbf{\Omega}_{it};\ \mathbf{X}^{E}_{it},\ \mathbf{Z}^{E}_{jt},\ \alpha_j,\ \mu_m,\ \eta_t,\ \epsilon^{e}_{it}\right), \tag{10}$$

with $\mathbf{X}^{E}_{it}$ and $\mathbf{Z}^{E}_{jt}$ being the relevant boiler- and location-level characteristics. All other variables are defined equivalently above.

4.4 Controlling for SO_2 regulations

We are interested in the effects of NSR grandfathering provisions on coal boiler operations, survival, and emissions. Our empirical approach must account for other sulfur dioxide regulations described in Section 2 as they could otherwise pollute the inference. Above, we left unspecified how environmental policies, $\mathbf{\Omega}_{it}$, are modeled in Equations (8), (7), and (10) and how they interact with grandfathering status, GF_{it}. We provide the empirical implementation details for the relevant programs below.

New Source Review and National Ambient Air Quality Standards As there is no indication that NSR compliance costs have substantially changed over time, we model the NSR status of the boiler through an indicator variable, GF_{it}, which equals one for grandfathered boilers and zero otherwise. With the fixed and variable costs of scrubbers varying with boiler size, we adopt interactions between grandfathering and boiler capacity, $GF_{it} \cdot size_i$. Additionally, we introduce a NAAQS attainment indicator variable, $NAAQS_{jt}$ and interact it with grandfathering status, $GF_{it} \cdot NAAQS_{jt}$ to reflect the fact that NSR prescribes additional obligations for units located in non-attainment areas.

New Source Performance Standards and state regulations NSPS and state regulations typically limit the amount of sulfur dioxide that regulated boilers can emit per MMBtu. If a unit is subject to both NSPS and state regulations, it must comply with both. We capture these two regulatory regimes using one continuous variable, $MMBTU_{it}$, which we construct as the inverse of the more stringent standard.[20]

Sulfur cap-and-trade programs Boilers could face participation obligations for the sulfur dioxide cap-and-trade programs: the Acid Rain Program, CAIR, and CSARP. We expect these programs to affect boilers through their price on emissions. We, thus, control for boiler-specific cap-and-trade emission prices, $price_{it}$. The absence of permit requirements is modeled as $price_{it} = 0$. As the permit prices for the Cross-State Air Pollution Rule have been negligible (see Section 2.2), while the program participation rules are highly complex, we assume the permit prices for that program to equal zero. However, the effect of permit requirements may differ across boilers. Those capable of emitting relatively little pollution should be less responsive to permit prices. The level of emissions is in turn largely driven by the sulfur content of utilized coal. We, therefore, allow for heterogeneous price effects by interacting permit prices with a variable capturing coal sulfur content, $price_{it} \cdot SO2cont_{it}$.

Unfortunately, sulfur content is endogenous. This is most evident in the context of the survival analysis. Given an inefficient boiler with a high likelihood of retirement, an owner would prefer to avoid the high fixed costs of scrubber installation and, thus, to reduce the sulfur content of the combusted coal when facing high emission permit prices. In contrast, an owner of a highly efficient boiler may find scrubber installation optimal. To deal with the arising endogeneity, we take advantage of the fact that the relative profitability of these two strategies depends on the geographical location of the plant. As coal transport is expensive, where its cost can exceed those of the commodity itself, we expect the proximity of low-sulfur coal reserves to lead to lower average sulfur content. Hence, we instrument the sulfur content variable using the mean sulfur content of close-proximity coal, $SO2contIV_i$.[21]

4.5 Empirical specification

Below, we present the functional form for our empirical specification. Given the relationships outlined above along with the description of the various sulfur dioxide regulatory programs, we apply a similar linear model for each outcome variable, y_{it}: utilization, survival and emissions. We estimate the following regression for boiler i and owner type m

[20] If the unit is not regulated, we code it as facing a limit of 10 lbs of SO_2 per MMBtu—a standard far in excess of typical boiler operations. By using the inverse of this standard, we reduce the potential that our dummy value for non-regulation could affect the results.

[21] For further details on the construction of the close-proximity coal instrument, see Section 5.3.

located in region j during year t:

$$\begin{aligned} y_{it} = & \beta_1^y GF_{it} + \beta_2^y NAAQS_{jt} + \beta_3^y NAAQS_{jt} \cdot GF_{it} \\ & + \beta_4^y MMBTU_{it} + \beta_5^y MMBTU_{it} \cdot GF_{it} \\ & + \beta_6^y price_{it} + \beta_7^y \widehat{SO2cont}_{it} + \beta_8^y price_{it} \cdot \widehat{SO2cont}_{it} \\ & + \mathbf{X}_{it}^y \mathbf{\Gamma}_x^y + \mathbf{Z}_{jt}^y \mathbf{\Gamma}_z^y + \alpha_j^y + \mu_m^y + \eta_t^y + \varepsilon_{it}^y, \end{aligned} \tag{11}$$

where $\widehat{SO2cont}$ is the instrumented variable capturing coal sulfur content; $\mathbf{X}_{it}^y$ and $\mathbf{Z}_{jt}^y$ are the sets of boiler-specific and location-specific explanatory variables relevant for outcome variable y; and, ε_{it}^y is an i.i.d. error term. Below we drop the upper index y for brevity.

Our variable of interest is the NSR grandfathering indicator GF_{it}. Assuming our framework captures the causal effects of grandfathering, coefficient β_1 is interpreted as the direct effect of grandfathering status on the particular outcome variable for small boilers located in attainment areas that do not face additional requirements through NSPS or state regulations.[22] For larger boilers located in non-attainment areas or subject to other sulfur regulations, additional grandfathering effects occur.

The remainder of the covariates with β coefficients are sulfur regulations as described in Subsection 4.4. Boiler-level characteristics—age, capacity and the instrumented sulfur content of utilized coal—are included in the vector $\mathbf{X}_{it}$. The vector $\mathbf{Z}_{jt}$ represents the characteristics of location j. The variables included here depend on the specification. For utilization and survival regressions, we include state-level load growth in the estimations. The intuition is that with increasing electricity demand more units need to be online at the same time, and in the long-run, participants may decide to expand generation capacity. An investment in new capacity may not preclude keeping existing boilers operational, even if they are expensive compared to a new unit. We also include measures of competitive pressure for our survival and utilization regressions, including: generation capacity growth at the state-level and coal-gas price ratios.

Time fixed effects, η_t, control for changes in other policies and market-level changes, such as investment costs of alternative technologies. We account for time-invariant local characteristics using state-level fixed effects, α_j. Finally, by imposing i.i.d. standard errors, we can estimate Equation (11) using two-staged least squares.

[22] For a discussion on the appropriateness of the causal interpretation of coefficients, see Subsection 4.6.

4.6 Causal interpretation of the results

There are two main threats to the causal interpretation of the β parameters: potential endogeneity of grandfathering status and systematic differences between grandfathered and non-grandfathered units.

First, thresholds in regulations always raise concerns about bunching behavior. In our setting, this would mean boiler owners manipulating their construction commencement date in order to gain grandfathering status. However, the grandfathering cutoff date was coincident with the establishment of the regulation, leaving little chance for manipulation post-announcement. There still exists the possibility of boiler owners anticipating the regulation—given the passage of the Clean Air Act Amendments—along with the grandfathering provisions and manipulating their construction date. While theoretically possible, it is rather unlikely given the long lead times that coal boilers require.[23] This is due to their substantial capital requirements and extensive regulatory approvals process, which limits the opportunity to accelerate construction decisions. Unfortunately, we are unable confirm the absence of construction manipulation empirically as we lack comprehensive data on commencement dates.

However, grandfathering status could also be endogenous due to the sunsetting provision stipulating that boilers lose their grandfathering status if they undergo substantial modifications that result in a net increase in emissions. Under such conditions, only boilers that gain the most from upgrades perform them and lose their grandfathering status. For a boiler approaching the end of its useful life, performing an upgrade that exposes it to NSR may not be profitable.

For the majority of our sample period, the modification rule was weakly enforced. This implies that upgrades are unlikely to introduce bias into our regressions. However, in later periods, boilers performing significant upgrades were exposed to NSR (Lange and Linn, 2008, Bushnell and Wolfram, 2012). This was especially true during the Clinton and Obama administrations, such that in later years we expect a correlation between grandfathering status and unobserved variables determining boiler survival and operations. We address this selection issue by disregarding changes in grandfathering status, and instead, we adopt initial assignment to grandfathering. That is, we define grandfathering as the status the unit had at the inception of NSR or when the unit commenced operation. Consequently, we estimate the impact of initial assignment to later survival, utilization, and emissions. This is equivalent to dropping the t subscript on our grandfathering indicator.

[23] The CAA amendments were passed in August 1977, and the regulatory cutoff for electric utility boilers greater than 73MW was set for September 1978.

Unfortunately, this modeling choice compounds the second problem we face: the possibility that grandfathered and non-grandfathered units are systematically different. By design, only boilers that commenced construction before the relevant regulation was proposed received grandfathering status. This results in the two groups—grandfathered boilers and these subject to NSR—differing in terms of age and underlying technology. If boilers became more efficient over time, our estimates will be biased downwards and the finding of a significant effect is at worst understated.

This problem is partly mitigated by the varying applicability of NSR across boilers of different size and type. We also attempt to control for boiler heterogeneity by using various boiler-level controls. These can capture differences, such as age and boiler size, but will not reflect all possible technological change over time. As the efficiency of coal boilers improved over time (Rode et al., 2017), we can expect our estimates of the effect of grandfathering on survival to be biased downwards. In one of our robustness checks, we limit our sample to boilers with in-service years between 1975 and 1988, leading to higher overlapping support between the two groups.[24] This technique is appropriate for utilization and emissions regressions, where there is sufficient variation in the outcome variables. Unfortunately for survival, too few boilers from that vintage have retired, such that we cannot restrict our sample without losing statistical power.

5 Data

We synthesize a variety of electricity and regulatory data in order to assess the effect of NSR grandfathering. Our panel of coal-fired boilers encompasses 1985-2017, but based on the availability of other controls, we are limited to years 1990-2017 for survival and 1995-2017 for utilization and emission analyses. Below, we discuss the sourcing and preparation for our most important variables. Table 4 in Appendix A summarizes our dataset.

5.1 Federal regulations

Datasets with comprehensive federal regulatory status information do not exist, making it difficult to ascertain which units have been subject to NSR and for how long.[25] Two sources—the Environmental Protection Agency (EPA) and the Energy Information Administration (EIA)—provide some information that is indicative of grandfathering status.

[24] During the eighties, we also observe both grandfathered and non-grandfathered units commencing service concurrently, further increasing the similarity of grandfathered and non-grandfathered boilers. See Section 5.1 for a detailed explanation of which boilers were exempted from NSR.

[25] This is a known problem acknowledged by the Government Accountability Office (GAO, 2012b).

However, their records are inconsistent and incomplete, and it is challenging to establish which units were exempted from NSR at which time.[26] To assign the grandfathering status to the boilers, we use the date defined in the regulation as a cutoff for grandfathering. For instance, for boilers generating electricity for utility sales to be grandfathered, construction must have commenced prior to September 18, 1978.[27] Given the construction time for coal boilers we assume that all boilers are exposed to NSR if, according to the the EIA-767 form, they started generating electricity after:

- 1988 - for boilers with capacity above 73 MW generating electricity for utility sales[28] and for commercial and industrial boilers with capacity above 29 MW
- 1992 - for commercial and industrial boilers with capacity between 2.9 and 29 MW.

For commercial and industrial boilers we thus assume they became subject to NSR if they start generating electricity two years after the cutoff date for the relevant regulation. For boilers with capacity above 73 MW generating electricity for utility sales with operating dates between 1981 and 1988, it is unclear whether the commencement of their construction occurred before September 1978. We, thus, manually gather information on their construction commencement date. This included inquiries with state environmental departments and, in some cases, directly contacting individual power plants. Figure 2a presents the final set of boilers along with their grandfathering status.

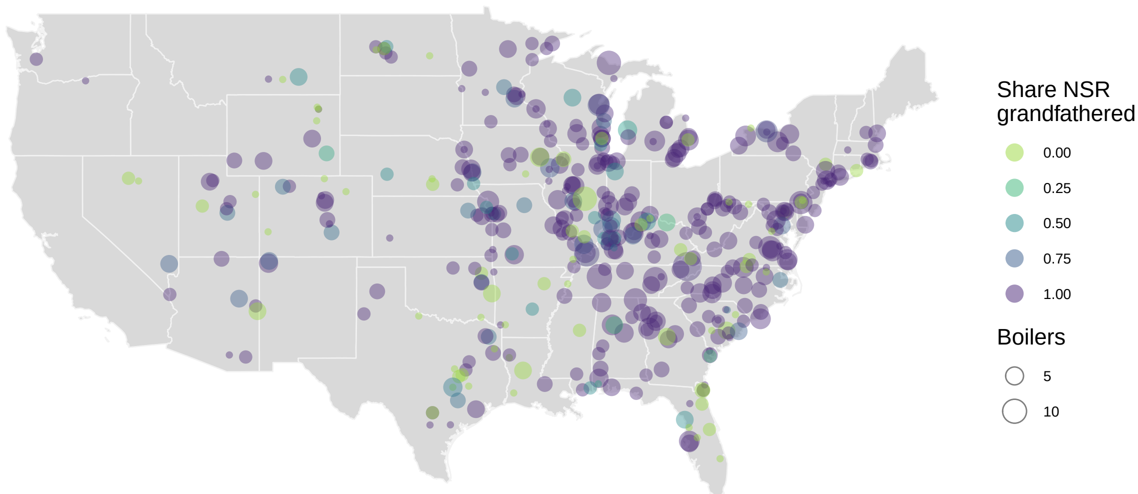
Regarding other federal regulations, we mark boilers as grandfathered from NSPS if they commenced operations prior to 1973—to leave a buffer after the regulatory cutoff date—and self-reported as exempt in EIA-767. For the Acid Rain Program, we establish whether a boiler was subject to its first phase by checking whether it was included in Table 1, Subpart B of the Clean Air Act Amendments 1990 regulations. For the second phase of the program, we assume all boilers with capacity greater than 25 MW are program participants. We source permit prices from spot auction data published by the EPA. Finally, information on county attainment status stems from the EPA Green Book and, for years before 1991, from work by Randy A. Becker as made available by the EPA.

[26] The EPA gathers relevant permit information in the "RACT/BACT/LAER Clearinghouse" which had been used in earlier studies for the identification of grandfathered boilers. However, the Clearinghouse data suffers from a number of drawbacks. It is a voluntary dataset across many regulatory programs. Thus, it does not incorporate all NSR permits and includes many which are unrelated to NSR entirely. Furthermore, the dataset lacks unique identifiers making it challenging to extract relevant permits. The EIA-767, on the other hand, releases data on applicable regulations and NSR permits that could be used to establish grandfathering status. Unfortunately, the data is inconsistent and, frequently, implausible.

[27] See 44 Fed. Reg. 33,580 (June 11, 1979). 40 CFR 60.40Da.

[28] We assume that all boilers, apart from those classified as commercial or industrial in the EIA-860 form, generate electricity for utility sales.

Figure 2: Coal-fired boilers by initial NSR grandfathering status



Notes: Initial grandfathering status refers to the original assignment of NSR grandfathering status. Bubbles show individual power plants, while their size represents the number of constituent coal-fired boilers. The color indicates the share of boilers within each power plant which are NSR grandfathered. Due to data limitations, we exclude California, Maine, Ohio and Pennsylvania.

5.2 State regulations

We build a state-level regulatory dataset through a comparison of: EPA summary files from the 1970's on sulfur dioxide regulations for coal-fired power plants; archived state administrative codes from the 2000's; and, current state administrative codes.[29] If the three sources were consistent, we assume the same set of standards applied throughout our sample period. If there were differences, we undertook an investigation to pinpoint when and how the standards changed.[30]

The investigation was dependent on the particular sources available for each state. For example, we consulted: two EPA reports compiling all state sulfur performance standards, one from 1975 and one from 1976; State Implementation Plan revision histories available through the Federal Register; old versions of state administrative codes available online;

[29] The EPA summary files reviewing sub-national sulfur dioxide regulations were published in March 1976 and September 1977.

[30] We exclude California and Ohio due to the complexity of their regulations, as well as Maine and Pennsylvania since the geographic boundaries of their air quality control regions (AQCR) are not congruent with county lines. Both cases render a clean assignment of regulatory regime to power plant a time-intensive and impractical exercise. In fact, clean assignment may not be possible in some cases. A handful of other individual observations from other states were removed for similar reasons.

and, in some cases, EPA documents describing the effective dates of different provisions in the State Implementation Plans. The stringency of the local regulations frequently depends on plant characteristics, such as capacity, location, vintage, etc. We, thus, account for boiler characteristics when matching them with the local regulations. These standards were often emissions standards based on pounds of sulfur dioxide per MMBtu. Other times, they were fuel composition requirements.[31] Occasionally, these regulations were limits on sulfur parts per million, and in others, the standards were tied to stack height. Consequently, it was not always possible to parse the standards into equivalent values.[32] Figure 6 in Appendix C presents the mean local regulation by state as defined by our research.

5.3 Boiler characteristics

We construct a panel of coal-fired boilers between 1985 and 2017 using data from the EIA, specifically annual forms EIA-767, EIA-860 and their predecessors. EIA-767 contains boiler-level data from 1985 to 2005 for steam-electric plants with nameplate capacity greater than 10 MW. EIA-860 provides data for electric power plants with nameplate capacity greater than 1 MW. It contains boiler and scrubber data commencing in 2007. Thus, we rely on EIA-767 from 1985 to 2005 and EIA-860 from 2007 onward. Once combined, the panel consists of 35,297 boiler-year observations representing 1,238 unique boilers across 429 power plants. The main variables include boiler age, capacity and scrubber installation.

Moreover, we develop a survival indicator based on the status of the boiler reported in EIA-767. We code boilers as 'not surviving' either when their status changes to 'retired' and remains so in the following years, or when they drop from the form entirely. Retired boilers are then dropped from our sample. Between 1985 and 2017, we observe 542 boiler retirements. Figure 7 in the Appendix C displays their geographic distribution.

We also extract information from EIA-923 and its predecessor EIA-423 about the average sulfur content of purchased coal. Based on the same datasets, we construct an instrumental variable capturing the sulfur content of coal available to individual plants. To that end, we prepare a weighted average of the median sulfur content of coal from all counties using their inverse distances to the plant as weights. The EIA-923 and 423 provide information on power plant coal deliveries, including the source county and sulfur content by weight, while plant geographic locations are sourced from EIA-860. For any missing locations, we replace them using coordinates from the facility attributes within the EPA Air Markets Program Data. Figure 8a presents median sulfur content by state based on EIA-923 data,

[31] For example, "input coal must not contain more than 3 percent sulfur, by weight."

[32] A full appendix detailing our processes for the sulfur dioxide standards within each state is available on request.

and Figure 8b in the Appendix C displays the constructed sulfur IV metric for each plant in our sample.

5.4 Boiler operations

We collect boiler operations data from the Continuous Emissions Monitoring System (CEMS) published by the EPA. The data are a unit-by-hour panel containing hours under load, generation and emissions for fossil-fired plants greater than 25 MW across the US and commencing in 1995. To be able to study the emissions intensity of boilers, we normalize the boiler's total annual emissions by its capacity and the number of hours under load. In effect, our emissions measure is defined as pounds of SO_2 emitted per MW of capacity per hour operated.

Usage of CEMS data presents a couple of challenges. First, EPA and EIA data lack a shared identifier. In order to match across data sources, we rely on the EPA's Power Sector Data Crosswalk, which associates EPA units with EIA boilers.However, the crosswalk does not allow for a unique match of all boilers in our data to CEMS records.[33]

Second, CEMS reports gross generation, which includes plant auxiliary loads. For our purposes, we require net generation, or equivalently, the amount of energy transmitted to the grid. To determine net generation, we scale the CEMS data by a net-to-gross generation ratio. The EIA-923 and predecessor forms, EIA-906 and EIA-920, summarize monthly data for units above 10 MW, providing a plant-by-fuel-by-month panel of net generation. Data for utility plants are available from 1970, while non-utility plants are available from 1999. We calculate the ratio by aggregating CEMS gross generation and EIA net generation to the plant-by-month level. Then, taking the quotient of net-to-gross generation results in a plant-specific ratio which can be applied across all CEMS generation data.

5.5 Electricity market data

To supplement the boiler and regulatory data mentioned above, we collect annual electricity market data, including demand, aggregate capacity and fuel prices. Annual electricity demand at the state level is sourced from the EIA State Energy Data System, while we procure utility-level demand from EIA-861. For the latter, we use the "Sales to Ultimate Customers" table which is available from 1990 onward and represents a balanced panel by

[33] The EPA Power Sector Data Crosswalk is a contemporary mapping. It lacks matches for units which have since retired. Additionally, some matching difficulties relate to the fact that the purpose of CEMS is to monitor emissions and determine compliance with various emissions standards. Thus, each unit is associated with a 'smokestack,' which does not consistently translate to boilers.

utility. We use the demand data to compute year-over-year demand growth rates by state and utility.

For aggregate capacity data, we utilize the "Existing Nameplate and Net Summer Capacity by Energy Source, Producer Type and State" table based on annual data reported in form EIA-860. The data is a panel of nameplate capacity by state, fuel source and producer type from 1990 onward. We aggregate over all producer types to generate a panel of state capacity. We use the result to compute a measure of competitive pressure from other generators.

For input fuel prices, we again turn to EIA-923 and its predecessor EIA-423. These forms provide monthly fuel receipts and cost data for fossil-fired plants with a nameplate capacity of at least 50 MW. The data are available from 1972 onward, where the cost data includes the fuel price and haulage. Using the data, we then perform the following three aggregations: plant-year coal prices weighted by mass; state-year coal prices weighted by mass; and, state-year gas prices weighted by volume. We then calculate another competitive pressure metric: the ratio of procurement and delivery costs of gas to those of coal. For those plants where we have specific fuel receipts, the ratio is plant specific; otherwise, we rely on a state based measure. In states where the prices of gas or coal are not available, we use the country-level average for the given year.

6 Results

In this section, we present our results. We begin by comparing grandfathered and non-grandfathered boilers across a number of characteristics. This is followed by our main regression results for utilization, survival and emissions. Finally, we discuss heterogeneity in our results across years and hours.

6.1 Comparing grandfathered and non-grandfathered boilers

First, we want to understand how boilers that initially enjoyed NSR grandfathering status differ from ones exposed to NSR regulation. We find measurable differences in baseline observables between grandfathered and non-grandfathered boilers as shown in Table 5 in Appendix B. Non-grandfathered boilers are younger, larger, and regulated more stringently. They tend to be located closer to the Northeast and are not as frequently operated by investor-owned utilities. Naturally, both their in-service and retirement years are later. For outcome variables, our naive comparison of mean utilization and retirement share produces differences counter to expectation, such that grandfathered plants are used less and are more likely to have retired. Regarding sulfur dioxide emissions, our naive comparison agrees with expectations and shows that grandfathered plants are more emissions intensive. Given that the two groups clearly differ, our empirical approach incorporates many of the variables in Table 5 as controls.

6.2 Examining the effects of grandfathering

Table 1 presents results from the estimation of equation (11), where outcome variables differ across panels and controls differ across columns. Columns (1) through (5) include boilers that are run by investor-owned utilities (IOU) as well as commercial and industrial boilers. These groups define boilers for which we can clearly identify the applicable NSR regime. Column (6) uses the whole sample. Column (7) is restricted to IOUs only. Table 2 provides the first-stage regression results for Columns (5) through (7) which instrument the coal sulfur content.

A central result is that the direct effect of NSR grandfathering increases boiler utilization, survival and emission rates in the sample at large. For emissions, the indirect effects of grandfathering drive additional increases. These results are stable to the inclusion of additional controls. For the smallest utility-owned, commercial, and industrial boilers exempted from NSPS and located in attainment regions without local sulfur dioxide regulations, NSR grandfathering encourages additional utilization exceeding 2,500 hours or over 100 days per year. Under similar restrictions, NSR grandfathering increases survival by around 3.5 percentage points, and is associated with direct and indirect increases in emissions of around 4.5 lbs of SO_2 per MW of capacity per hour. When other types of boilers, such as those owned by state and municipal actors, are included, the effects are less pronounced. For example, with utilization, the effects almost halve. This could be due to the objectives governing the operation of these units or due to the difficulty of assigning them the proper grandfathering status.

Exposure to either NSPS or state regulations has almost no direct effects on units that are already subject to NSR, as captured by $MMBTU$ variable. However, it substantially weakens the grandfathering effects. This is intuitive as NSPS and state programs restrict boiler emissions, albeit less stringently than NSR. Boilers located in non-attainment regions also exhibit reduced effects of NSR grandfathering. We speculate that this could be driven by many effects. First, states could be undertaking additional regulatory or administrative steps to control their sulfur dioxide emissions beyond the sulfur regulations measured through our $MMBTU$ variable. These regulations likely target the most polluting boilers, such that grandfathered boilers would be most impacted. Second, in non-attainment coun-

Table 1: Main regression results

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	OLS	*OLS*	*OLS*	*OLS*	*IV*	*IV*	*IV*
	IOU+	*IOU+*	*IOU+*	*IOU+*	*IOU+*	*All*	*IOU*
Panel A: Utilization							
GF	832.50***	2445.11***	2568.51***	2533.83***	2531.18***	1357.56***	2606.32***
	(13.36)	(9.62)	(9.81)	(9.10)	(9.62)	(7.32)	(7.06)
size	1288.69***	3102.65***	3166.51***	3314.39***	3019.03***	2054.01***	2930.57***
	(9.74)	(8.76)	(8.64)	(8.38)	(7.60)	(8.15)	(5.50)
GF × size		−1933.86***	−2070.97***	−2298.18***	−1935.51***	−658.19**	−1908.99***
		(−5.74)	(−5.95)	(−6.18)	(−5.63)	(−2.63)	(−3.87)
NAAQS		1066.37***	1088.42***	1185.16***	1080.34***	1006.74***	1138.10***
		(6.82)	(6.22)	(6.51)	(5.32)	(5.32)	(5.21)
GF × NAAQS		−1811.97***	−1879.89***	−1543.99***	−1900.87***	−1805.99***	−2051.80***
		(−9.38)	(−8.82)	(−7.25)	(−7.65)	(−8.52)	(−8.36)
MMBTU		37.56	38.54	27.49	44.66	159.35***	51.17
		(0.77)	(0.79)	(0.58)	(0.84)	(3.37)	(0.94)
GF × MMBTU		−380.89***	−386.14***	−285.16***	−385.66***	−465.71***	−400.97***
		(−6.81)	(−6.89)	(−6.34)	(−6.63)	(−9.52)	(−5.88)
Year FE	*X*	*X*	*X*	*X*	*X*	*X*	*X*
State FE	*X*	*X*	*X*	*X*	*X*	*X*	*X*
Utility FE	*X*	*X*	*X*	*X*	*X*	*X*	
Market Controls			*X*	*X*	*X*	*X*	*X*
Sulfur Controls				*X*	*X*	*X*	*X*
Observations	10,782	10,782	10,436	9,762	10,436	16,291	9,927
R^2	0.289	0.303	0.300	0.294	0.300	0.295	0.288
Panel B: Survival							
GF	0.86**	2.88**	3.31***	2.63**	3.24**	2.24**	4.25**
	(3.02)	(3.17)	(3.32)	(2.78)	(3.28)	(3.20)	(3.19)
size	0.63	2.70*	3.21*	2.79*	2.76*	1.55	3.88*
	(1.16)	(2.30)	(2.50)	(2.17)	(2.00)	(1.93)	(1.96)
GF × size		−2.29	−2.38	−1.97	−2.01	0.01	−3.19
		(−1.96)	(−1.86)	(−1.59)	(−1.47)	(0.01)	(−1.82)
NAAQS		2.87**	3.94***	2.99**	3.96***	3.71***	4.22***
		(2.98)	(3.31)	(2.88)	(3.70)	(3.94)	(3.29)
GF × NAAQS		−4.03***	−4.85**	−5.14***	−4.94***	−5.00***	−5.23***
		(−3.50)	(−3.24)	(−3.57)	(−3.42)	(−4.34)	(−3.42)
MMBTU		0.14	0.22	−0.31*	0.24	0.10	0.39
		(0.56)	(0.76)	(−2.15)	(0.86)	(0.56)	(1.47)
GF × MMBTU		−0.52**	−0.66**	−0.25	−0.66**	−0.73**	−0.81**
		(−2.91)	(−2.99)	(−1.66)	(−3.09)	(−2.62)	(−3.20)
Year FE	*X*	*X*	*X*	*X*	*X*	*X*	*X*
State FE	*X*	*X*	*X*	*X*	*X*	*X*	*X*
Utility FE	*X*	*X*	*X*	*X*	*X*	*X*	
Market Controls			*X*	*X*	*X*	*X*	*X*
Sulfur Controls				*X*	*X*	*X*	*X*
Observations	15,257	15,257	12,626	11,738	12,626	19,125	11,694
R^2	0.101	0.102	0.107	0.103	0.107	0.099	0.109

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	OLS	*OLS*	*OLS*	*OLS*	*IV*	*IV*	*IV*
	IOU+	*IOU+*	*IOU+*	*IOU+*	*IOU+*	*All*	*IOU*
Panel C: Emissions							
GF	0.55***	4.60***	4.60***	4.73***	3.90***	3.43***	4.13***
	(4.19)	(12.31)	(12.31)	(12.54)	(8.84)	(11.27)	(9.86)
size	−2.00***	2.57***	2.57***	2.82***	0.52	−0.47	0.68
	(−9.19)	(6.53)	(6.53)	(7.27)	(0.76)	(−1.29)	(1.09)
GF × size		−4.66***	−4.66***	−4.87***	−2.78***	−2.60***	−3.08***
		(−10.73)	(−10.73)	(−11.35)	(−4.17)	(−6.10)	(−5.10)
NAAQS		2.39***	2.39***	1.51***	2.13***	1.73***	2.17***
		(5.17)	(5.17)	(4.60)	(4.60)	(4.79)	(4.68)
GF × NAAQS		−3.18***	−3.18***	−1.55**	−2.79***	−1.32**	−2.75***
		(−5.70)	(−5.70)	(−3.26)	(−5.68)	(−2.79)	(−4.79)
MMBTU		−0.18	−0.18	−0.14	−0.06	−0.44***	−0.06
		(−1.09)	(−1.09)	(−0.82)	(−0.36)	(−5.66)	(−0.35)
GF × MMBTU		−0.98***	−0.98***	−1.00***	−0.95***	−0.85***	−0.94***
		(−5.89)	(−5.89)	(−5.92)	(−5.62)	(−10.08)	(−5.21)
Year FE	*X*	*X*	*X*	*X*	*X*	*X*	*X*
State FE	*X*	*X*	*X*	*X*	*X*	*X*	*X*
Utility FE	*X*	*X*	*X*	*X*	*X*	*X*	
Market Controls							
Sulfur Controls				*X*	*X*	*X*	*X*
Observations	10,227	10,227	10,227	9,706	10,227	16,181	10,049
R^2	0.419	0.431	0.431	0.438	0.440	0.407	0.442

Notes: This table presents our main regression results for our three channels, namely: utilization, survival and emissions. Specifications (1)-(4) are estimated using OLS, while specifications (5)-(7) use 2SLS and leverage sulfur content of the available coal as an instrument for sulfur content of the combusted coal. The unit of observation is boiler-year. The *IOU* columns restrict the sample to boilers belonging to IOUs; the *IOU+* column expands to include commercial, industrial and IOU boilers; while, the *All* column uses all types of available boilers. Utilization and emissions estimations use data from 1995-2018, while survival estimations use 1985-2017. Robust standard errors used, with *** p<0.001, ** p<0.01, * p<0.05 and *t*-statistics in parentheses.

ties there may be more public awareness of pollution problems. Press coverage of the local damages from sulfur emissions, politicians keeping a close eye on dirty facilities, and other forms of social pressure on polluters could reduce the advantage of grandfathering. On a related point, in non-attainment counties, facilities could voluntarily reduce their emissions, a type of regulatory avoidance, as the likelihood of their actions and emissions attracting attention is higher (Raff and Walter, 2020). In this way, boilers would voluntarily limit the advantage provided by grandfathering provisions.

The utilization and emissions effects of grandfathering also decrease with boiler capacity. For utilization this could be driven by the fact that larger boilers generally run most of the time; hence, there are only a limited number of additional hours that a boiler could run. For emissions, the explanation for the finding is less straightforward. It could relate to the fact that scrubber installation is generally more cost-efficient for larger units. This could cause larger units to more frequently adapt pollution abatement equipment for compliance with cap-and-trade programs even if they were not subject to NSR. It could also be the case that units with higher gross generation were more likely to be targeted by EPA for enforcement of modifications (Chan and Zhou, 2021). This could have caused such plants to engage in regulatory avoidance (Keohane et al., 2009).

Table 2: Main regression first-stage results

	(5)	(6)	(7)
	OLS	*OLS*	*OLS*
	IOU+	*All*	*IOU*
sulfur	2.62***	2.35***	2.83***
	(30.33)	(37.34)	(31.36)
GF	−0.39***	−0.20***	−0.42***
	(−7.68)	(−4.49)	(−7.81)
size	−1.19***	−0.70***	−1.35***
	(−17.11)	(−10.02)	(−18.78)
GF × size	1.04***	0.64***	1.10***
	(14.19)	(8.74)	(14.37)
NAAQS	−0.08	−0.07	−0.01
	(−0.74)	(−0.64)	(−0.06)
GF × NAAQS	−0.12	−0.05	−0.14
	(−1.02)	(−0.46)	(−1.14)
MMBTU	0.03***	−0.03**	0.02**
	(3.78)	(−3.25)	(3.01)
GF × MMBTU	0.04***	0.02*	0.04***
	(4.09)	(2.40)	(5.42)
Year FE	*X*	*X*	*X*
State FE	*X*	*X*	*X*
Utility FE	*X*	*X*	
Market Controls	*X*	*X*	*X*
Observations	13,365	19,750	12,503
R^2	0.596	0.481	0.590

Notes: This table presents the first-stage results for our main regressions. The three channels each produce similar results, so we report those for utilization only. The dependent variable is the SO_2 content of the combusted coal. All specifications are estimated using OLS. The unit of observation is boiler-year. The *IOU* columns restrict the sample to boilers belonging to IOUs; the *IOU+* column expands to include commercial, industrial and IOU boilers; while, the *All* column uses all types of available boilers. Robust standard errors used, with *** p<0.001, ** p<0.01, * p<0.05 and *t*-statistics in parentheses.

We also calculate the average total effect of NSR grandfathering accounting for interaction effects between grandfathering and state regulations, between grandfathering and boiler size, and the indirect effects. Relying on Column (5) in Table 1—our preferred specification—we calculate the average effect of grandfathering in our sample. We find that grandfathering is associated with approximately 787 additional hours of operations annually, 2.05 pounds of additional SO_2 emissions per MW of capacity per hour run. Grandfathered boilers have a 1.5 percentage point lower (i.e., 84 percent smaller) probability of retirement in a given year compared to the sample average. Note that these effects are high, especially given that we are looking at the pool of all boilers that initially enjoyed grandfathering status and which many of them lost over time.[34]

The remaining covariates, including age and size effects, are coherent with economic intuition. We observe substantial heterogeneity in the effects across years and states as captured by fixed effects.

Table 3: Net-to-gross generation ratio regressions

	(1)	(2)
Constant	0.921***	0.897***
	(2,171.75)	(902.03)
Grandfathering	−0.006***	0.003***
	(−13.24)	(4.27)
Age		*X*
Size		*X*
Observations	69,309	69,309
R^2	0.003	0.050
Adjusted R^2	0.003	0.050

Notes: This table reports results from two weighted least squares regressions based on Equation (9). The dependent variable is net-to-gross generation ratio, while the weights are based on monthly durations. Column (1) essentially represents the pure weighted average, while Column (2) presents one conditional on age and size. They rely on CEMS and EIA-861 data from 2008 to 2017. Significance is represented as *** for $p<0.001$, ** for $p<0.01$, and * for $p<0.05$; while, t-statistics are in parentheses.

Given the strong utilization advantage associated with grandfathering, we perform the net-to-gross generation analysis as presented in Equation (9). Table 3 presents the results using data restricted to the 2008-2017 period due to the limited availability of generation information. Column (1) lacks covariates and, thus, its intercept represents the pure weighted average generation ratio for non-grandfathered plants, 92.1 percent. Here, the coefficient on our grandfathering indicator is negative implying that grandfathered plants are less efficient in exporting electricity to the grid. However, the grandfathered boilers are inherently older and tend to be smaller on average. When controlling for these two characteristics, the sign on grandfathering reverses as can be seen in column (2). This correlation implies that grandfathered boilers tend to be more efficient in delivering electricity to the grid. It also supports the assumption that they are less costly to operate. However, this effect does not seem to be the main driver of the differences in utilization given its small size:

[34] Between 1999 and 2015, due to modifications, 275 boilers became the subject of investigations connected to their NSR status, which resulted in settlements and loss of grandfathering status (Chan and Zhou, 2021).

the results suggest that the net-to-gross generation ratio is 0.2 percentage points higher for grandfathered units.

6.3 Examining heterogeneity in the effects of grandfathering

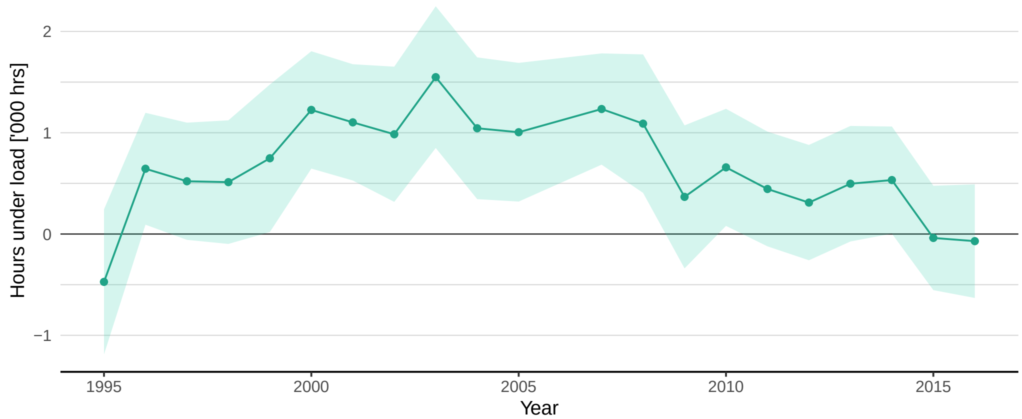
The above analyses assume constant effects of grandfathering across time. However, it is possible that over years, with a changing regulatory landscape and market conditions, the advantage of grandfathering may also change. Such heterogeneous effects are important when assessing whether the need for corrective policies remains.

To understand the changes in effects across years, we modify Column (X) from Table 1 by combining the grandfathering indicator and year fixed effects into a series of interaction terms. Figure 3 presents the results. For utilization and survival, results are similar in that they are positive, relatively stable and significant up until around 2010 when many substantial changes in electricity markets occurred, such as announcement of new environmental rules and drop in natural gas prices. For utilization prior to 2010, NSR grandfathering tends to add around 1,000 hours per year. After 2010, the effect is not statistically significant. Grandfathering increases the chance of survival assuming the boiler is present in the previous year by around 0.17 percentage points. Though the effect remains significant, its results are far less stable after 2010. For emissions, the effect decreases over time, reflecting the fact that many of the boilers that were initially grandfathered either underwent substantial modification and became subject to NSR, or decided to install scrubbers voluntarily, for instance to reduce their compliance costs with the Acid Rain Program.

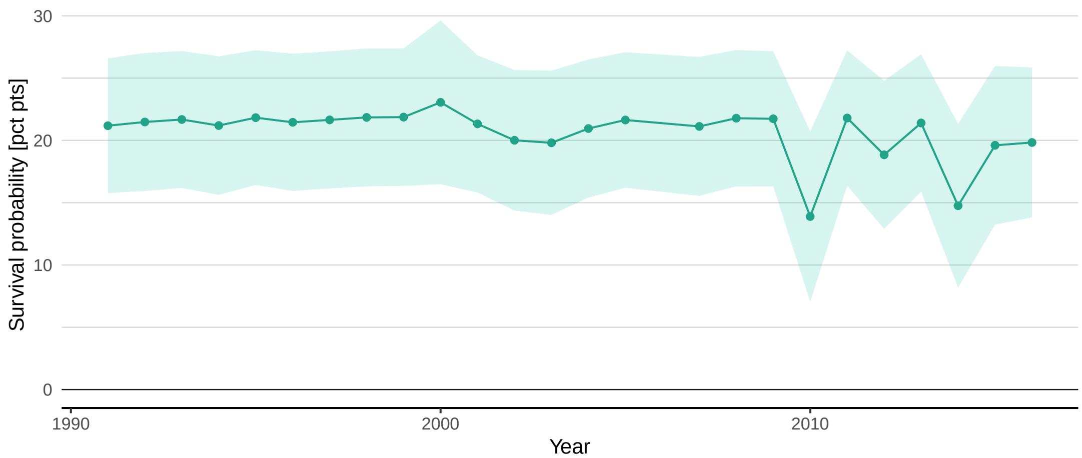
The distribution of utilization effects over the course of a day matters as well. Different types of energy production resources tend to be marginal in different hours. So, depending on when the additional utilization happens, grandfathered boilers could push out different resource types. As a consequence, the utilization channel can have different marginal emission impacts and, thus, different welfare implications depending on the average daily distribution.

To understand the hourly effects of grandfathering, we use CEMS data and run 24 separate regressions of Equation (11) for each hour of the day. Figure 4 presents the resulting estimates for the effects of grandfathering on utilization, where the effect is stable and significant across all hours of the day. For every hour, NSR grandfathering is associated with an increase in utilization of approximately 0.27 hours, which is equivalent to around 16 minutes per hour.

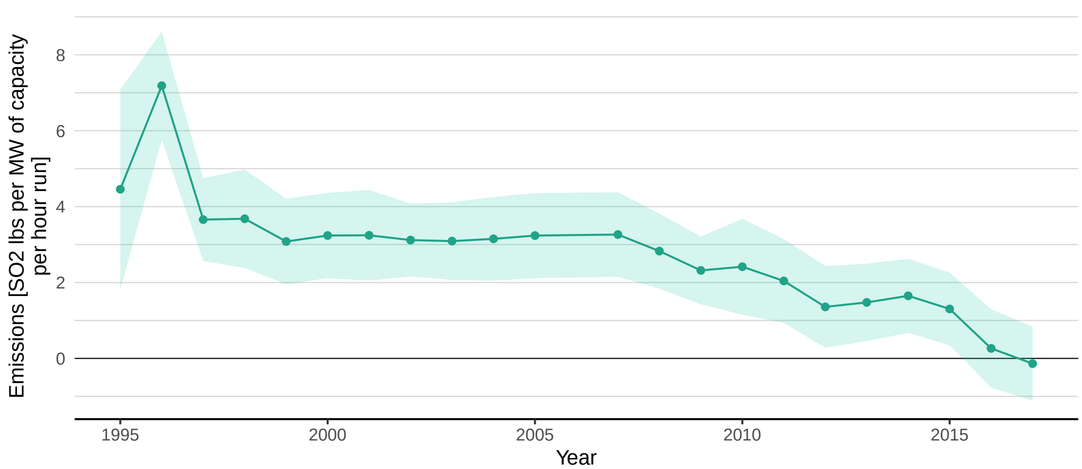
Figure 3: Yearly effects of NSR grandfathering.



(a) Hourly utilization. Coefficients derived from a regression using CEMS data and performed by including grandfathering-year interactions in Column (5) from Table 1.

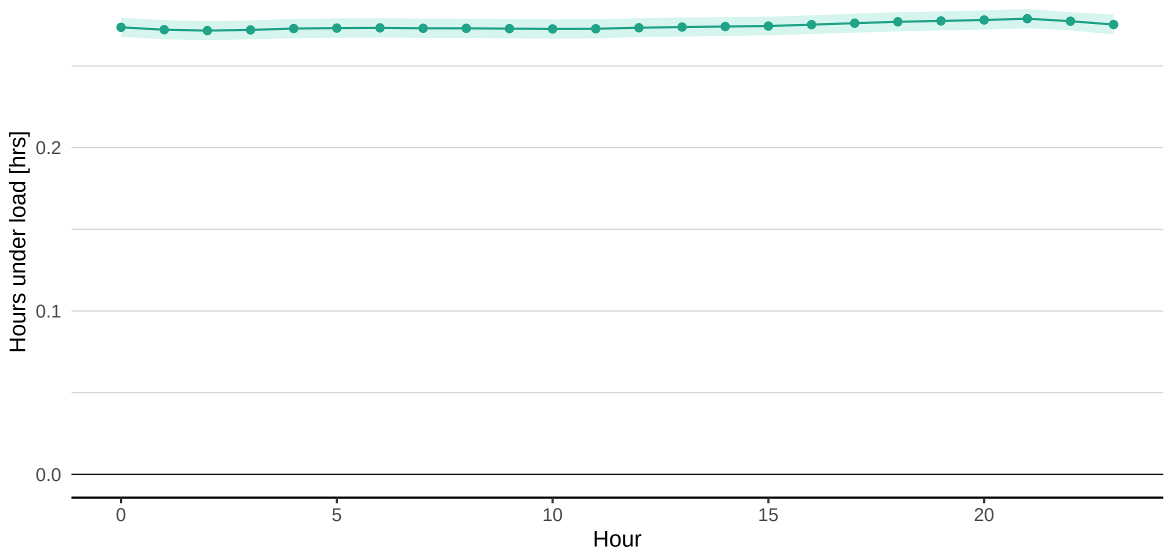


(b) Survival. Coefficients derived from a regression performed by including grandfathering-year interactions in Column (5) from Table 1.



(c) Sulfur emissions rate. Coefficients derived from a regression based on CEMS data and performed by including grandfathering-year interactions in Column (5) from Table 1.

Figure 4: Hourly effects of NSR grandfathering on utilization.



Notes: Coefficients derived from a set of regression equivalent to Column (5) from Table 1, where the sample is limited to that for the specific hour.

6.4 Robustness checks

We perform a number of robustness checks related to our definition of grandfathering status.

First, we assess whether our results hold when restricting our sample around the cutoff. A potential problem with our approach is that, with boilers built in different decades, unobserved improvements in boiler technology could confound the inference and bias our results. Regressions restricted to boilers constructed just before and just after the introduction of NSR could provide cleaner results. That is, a sample restricted around the NSR status discontinuity increases the likelihood that the support across the two groups—grandfathered and non-grandfathered boilers—is better aligned. However, a narrower sample necessarily implies that a larger proportion of boilers may be incorrectly assigned grandfathered status.[35] Thus, we restrict the sample to boilers with in-service years between 1972 and 1994. We anticipate that this time range restricts variation in boiler technologies while also limiting the share of boilers with misassigned grandfathering status. This leaves us with 125 grandfathered and 291 non-grandfathered boilers, out of which 54 and 152 are operated by IOUs, respectively.

[35] See Section 5.1 for further details.

Second, we assess a more "conservative" definition of NSR grandfathering status. Despite our best efforts to determine which boilers were grandfathered, there exists the possibility that status was misassigned in some cases. We can, thus, test the robustness of our main results by adopting a "conservative" assignment of NSR grandfathering status, i.e. by assuming that all boilers with in-service years after the passage of the relevant NSR rules were subject to these rules, notwithstanding when their construction commenced. The cut-off year for grandfathering is thus 1979 for boilers generating electricity for utility sales with capacity above 73 MW, 1987 for commercial and industrial boilers above 29 MW, and 1990 for commercial and industrial boilers with capacity between 2.9 and 29 MW. Such an approach guarantees that all non-grandfathered boilers are correctly classified, though it is susceptible to false negatives. So, some boilers that were grandfathered are unintentionally marked as non-grandfathered, since, in reality, a boiler only needs to have commenced construction prior to the cutoff date to attain grandfathered status.

The resulting estimates, shown in Tables 6 through 9 in Appendix D, are consistent with our main findings but of smaller magnitude. For both robustness checks, this may be due to the heightened significance of noise within our grandfathering status indicator.

6.5 Aggregate environmental damages from grandfathering provisions

Finally, using our regression results, we estimate the damages from NSR grandfathering by comparing business-as-usual to the counterfactual where grandfathering exemptions are not provided within NSR. To understand the magnitude of the damages, we perform a back-of-the-envelope calculation of the emissions that would have be avoided in the absence of such exemptions. We focus on utility, commercial, and industrial (IOU+) boilers, as we have the highest confidence in their assignment to grandfathering status. We limit the calculation to the 1998-2017 period as earlier emissions data is lacking for many boilers. We focus on SO_2 emissions only and ignore other pollutants, e.g., CO_2 emissions that would be cut by boiler replacement. In effect, we estimate a subset of the damages.

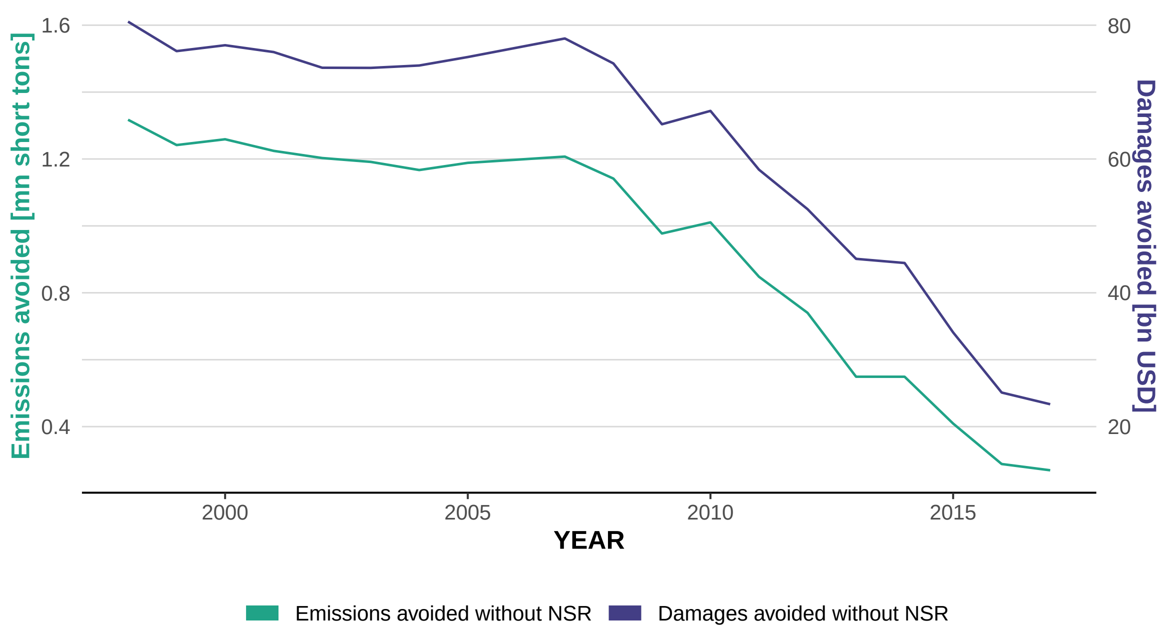
We calculate grandfathering-driven increases in SO_2 emissions by combining the estimates from Column (5) of Table 1 with the county-year-level sample averages for N_O, hr_O, EI_O, and EI_N in accordance with Equation (4).[36] The resulting estimates represent annual additional emissions that occurred in each county, which can be aggregated to obtain total emission effects. For the approximately 500 IOU+ boilers with grandfathering status, we

[36] For counties with only grandfathered boilers, we use state-level EI_N value. When that is not available, we adopt to the federal EI_N average.

calculate that in 1998, their SO_2 emissions would have been lower by around 1.5 million tons–i.e., by about a third of their emissions–had they not been assigned the grandfathering exemption. Over time, as the state and other federal regulations increase in stringency, the amount of avoided emissions without grandfathering drops significantly to around 0.5 million tons in 2017 as shown in Figure 5.

Ideally, to obtain the associated damages, we would use time- and location-varying measure of the average damages given that the emissions we calculate represent a significant portion of the total US SO_2 emissions. Lacking such estimates, we, instead, use county-level marginal damages from SO_2 emissions from 2011 as calculated by Holland et al. (2016).[37] Our results suggest damages of around $65 billion in 1998 falling over time to slightly above $10 billion in 2017, as reported in 2000 USD.

Figure 5: Total SO_x emissions and damage effects from NSR



Notes: The Figure shows results of the back-of-the-envelope calculations based on Equation (4) and Column (5) of Table 1. Estimates for ca. 500 IOU+ boilers identified as having enjoyed grandfathering status after the introduction of NSR.

[37] We note that using marginal effects will tend to overestimate total damages as they are not equivalent to average values. We also note that our calculation only estimates impacts from SO_2 emissions, excluding potential health and environmental damages from other pollutants (e.g., NO_x and particulate matter).

7 Conclusions

The Clean Air Act is the centerpiece for air pollution control within the US. Nevertheless, some of its aspects remain relatively little understood. This holds true, among others, for NSR and its associated grandfathering provisions. Despite their importance for the operations of regulated units and for sulfur emissions, only a small set of papers addresses them empirically.

We offer new insight into the impacts of NSR grandfathering provisions on the operation of coal boilers with respect to their utilization and retirement decisions. We also show how NSR grandfathering allowed incumbent boilers to maintain high sulfur dioxide emissions, even decades after the implementation of NSR. We combine various sources of data on boilers, coal, electricity markets, and federal sulfur dioxide regulations between 1985 and 2018. We also create a dataset of state-level sulfur dioxide regulations. Our econometric analysis, aided by the differences of NSR's applicability across boilers of various size and type, documents how the cost wedge introduced by grandfathered boilers biased the outcomes in the sector. We find that, on average, grandfathering status was associated with 787 additional hours under load annually and a 1.5 percentage point increase in the probability of surviving an additional year. This suggests that the vintage differentiation in NSR pushed generation towards less efficient incumbent boilers. The effects were particularly pronounced for smaller boilers in attainment counties and for the early years of our sample, i.e., in the 1990s. We also show the importance of state regulations in limiting the perverse effects of NSR grandfathering.

A motivating factor behind this work was the sustained usage of VDR provisions, especially in an environmental context. For policymakers, our analysis represents a cautionary tale regarding grandfathering provisions without well-designed sunset clauses, especially when the regulated asset is long-lived.

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A Data overview

Table 4: Variables summary

Variable	Description	Source
$hours_{it}$	Dependent variable representing the number of hours boiler i operated in a year t	EPA CEMS
$survive_{it}$	Dependent binary variable equal to one if boiler i continued operation in year $t+1$	EIA-767; EIA-860
$emissions_{it}$	Dependent variable representing sulfur dioxide emissions per hour for boiler i in year t	EPA CEMS
GF_i	Indicator variable equal one if boiler i was covered by the grandfathering provision when NSR was enacted	EIA-767; Own research
$NAAQS_{jt}$	Indicator variable equal to one if county j is a non-attainment region for sulfur dioxide under NAAQS	EPA Green Book
$MMBTU_{it}$	Variable representing the more stringent of the local sulfur regulation and New Source Performance Standard, if applicable, for boiler i in year t expressed as an inverse	Own research
$price_{it}$	Effective permit price faced by boiler i in year t for a short ton of sulfur dioxide emissions	Federal Register; EPA
$SO2cont_{it}$	The average sulfur content of coal used by boiler i during year t	EIA-923 & EIA-423
$sulfur_{it}$	IV based on the average sulfur content of coal available to boiler i during year t	EIA-923 & EIA-423; EIA-860 & EPA
age_{it}	Boiler i age in years	EIA-860
$size_i$	Boiler i capacity in GW	EIA-767; EIA-860; EPA
$growth^s_{jt}$	Percentage growth in state j electricity demand in year t	EIA State Energy Data System
$growth^u_{it}$	Percentage growth in utility electricity demand faced by boiler i in year t	EIA-861
$GasCap_{jt}$	Competitive pressure from natural gas units measured as their total capacity in state j during year i	EIA-860
$VRECap_{jt}$	Competitive pressure from variable renewable energy, including wind and solar, measured as their total capacity in state j during year i	EIA-860
$GasPress_{it}$	Competitive pressure from gas units measured as the ratio of procurement and delivery costs of gas to coal for boiler i in year t	EIA-923 & EIA-423
α_j	State fixed effects	EIA-767; EIA-860

Variable	Description	Source(s)
μ_m	Owner type fixed effects, including utility, independent power producer, state, coop, etc.	EIA-860
η_t	Year fixed effects	

B Comparing grandfathered and non-grandfathered boilers

Table 5: Average characteristics of boilers by NSR grandfathering status

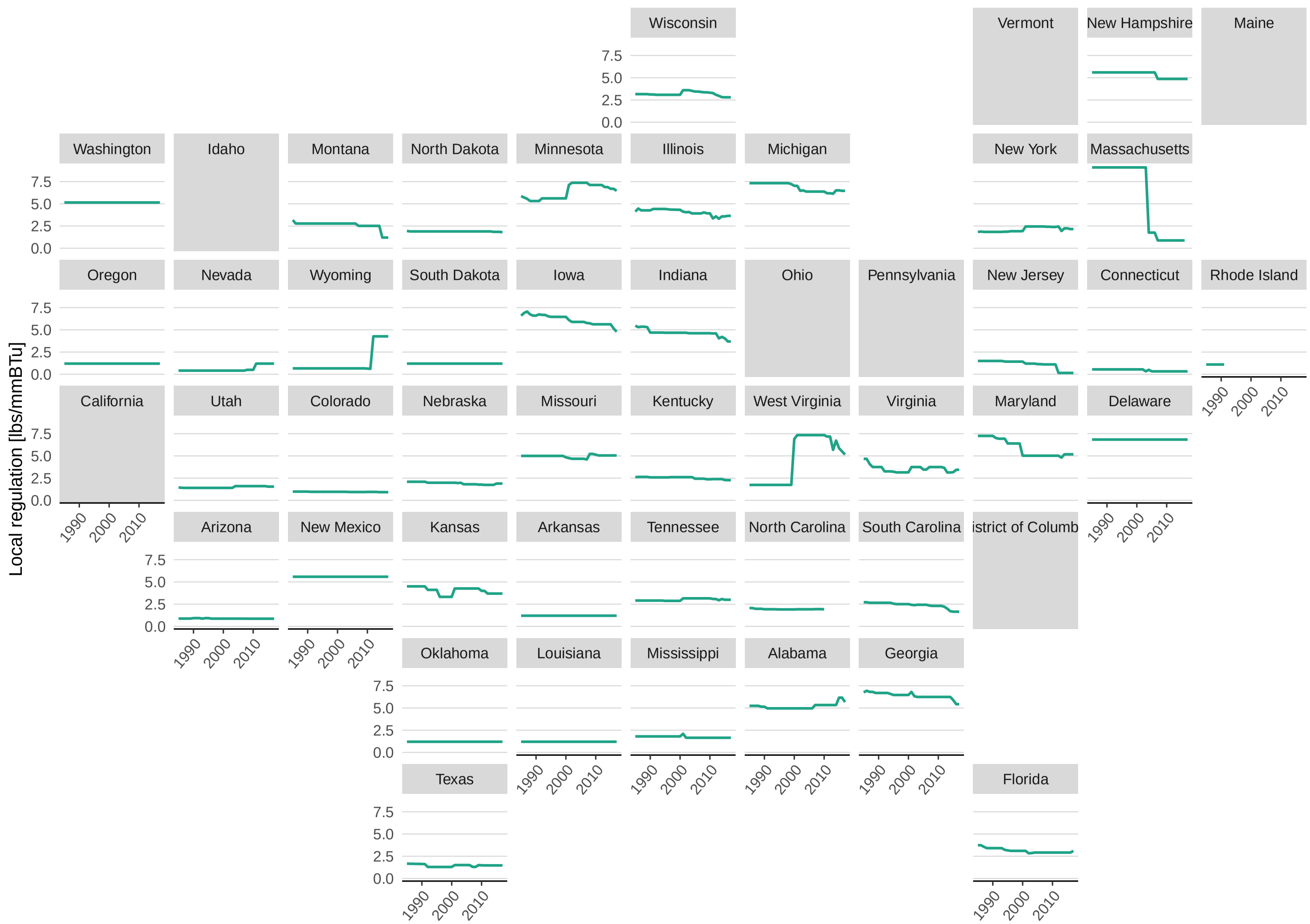
Variable	Grandfathered	Non-Grandfathered	Difference
Nonattainment	0.07	0.01	0.05***
	(0.18)	(0.07)	[7.24]
Acid Rain Program	0.95	1.00	−0.05***
	(0.22)	(0.00)	[−7.62]
Applicable Non-NSR Emission Standard [lbs/mmBTu]	5.31	4.54	0.78**
	(3.07)	(3.17)	[3.14]
Latitude	38.67	37.51	1.15**
	(4.02)	(4.75)	[3.16]
Longitude	−87.21	−90.90	3.69***
	(8.87)	(9.82)	[4.85]
Capacity	251.31	497.17	−245.86***
	(243.45)	(247.36)	[−12.62]
Age	36.78	12.05	24.73***
	(11.07)	(5.99)	[44.71]
Inservice Year	1,962.66	1,993.05	−30.39***
	(12.18)	(10.96)	[−34.66]
Retirement Year	2,010.99	2,013.52	−2.52**
	(8.03)	(4.09)	[−2.92]
Retire	0.51	0.14	0.37***
	(0.54)	(0.35)	[12.36]
Duration† [hr/yr]	6,071.61	7,104.42	−1,032.81***
	(1,936.48)	(1,410.65)	[−8.02]
Generation† [GWh/yr]	1,602.98	3,366.25	−1,763.27***
	(1,571.93)	(1,637.21)	[−11.52]
SO2 Emissions† [lbs/mmBTu]	1.03	0.35	0.68***
	(0.76)	(0.25)	[19.87]
Weighted Average Mine Sulfur	1.66	1.63	0.03

Variable	Grandfathered	Non-Grandfathered	Difference
Content [% weight]	(0.19)	(0.22)	[1.92]
Share of Co-operatives	0.06	0.10	−0.04
	(0.23)	(0.30)	[−1.79]
Share of Commercial	0.01	0.02	−0.00
	(0.11)	(0.13)	[−0.27]
Share of Federal	0.04	0.08	−0.04
	(0.20)	(0.27)	[−1.77]
Share of Investor-Owned	0.56	0.41	0.15***
	(0.50)	(0.49)	[3.74]
Share of Industrial	0.01	0.03	−0.01
	(0.12)	(0.16)	[−0.99]
Share of Municipal	0.06	0.09	−0.03
	(0.24)	(0.29)	[−1.35]
Share of Political	0.07	0.10	−0.03
	(0.25)	(0.30)	[−1.48]
Share of IPPs	0.12	0.13	−0.01
	(0.32)	(0.34)	[−0.54]
Share of State	0.07	0.05	0.02
	(0.26)	(0.21)	[1.39]
Number of Boilers	1,030	192	

Notes: This table displays average characteristics by NSR grandfathering status. Standard deviations are in parentheses, with t-statistics of the difference between 'grandfathered' and 'non-grandfathered' boilers in brackets where *** p<0.001; ** p<0.01; * p<0.05. All variables utilize the full extent of our dataset, except for those from CEMS which are from 1997 onwards and are identified with a †. Each row is a separate calculation, and is not conditional on the other variables reported here. Co-operatives, commercial, federal, investor-owned, industrial, IPPs (independent power producers), municipal, political, and state refer to boiler ownership.

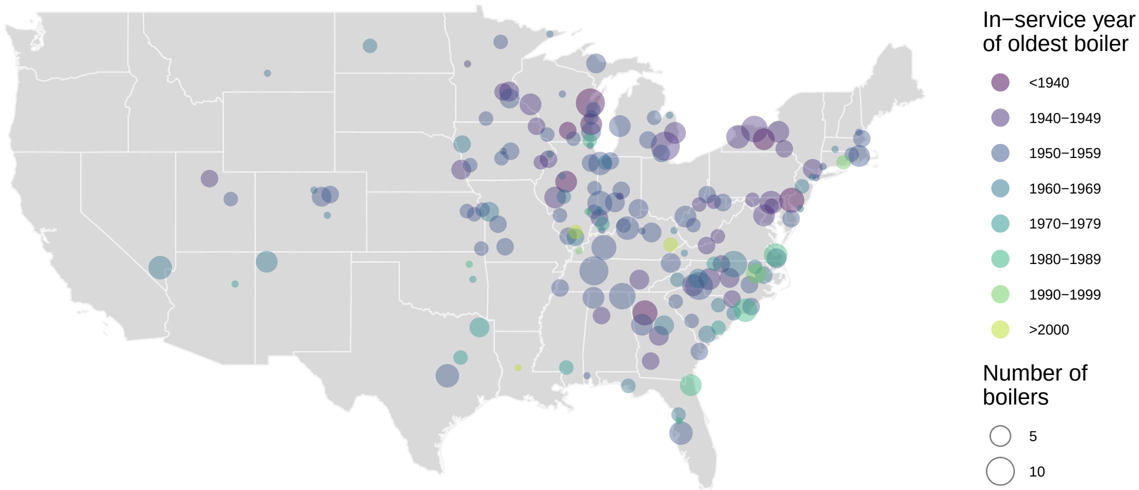
C Additional figures

Figure 6: Mean local regulations by state and year



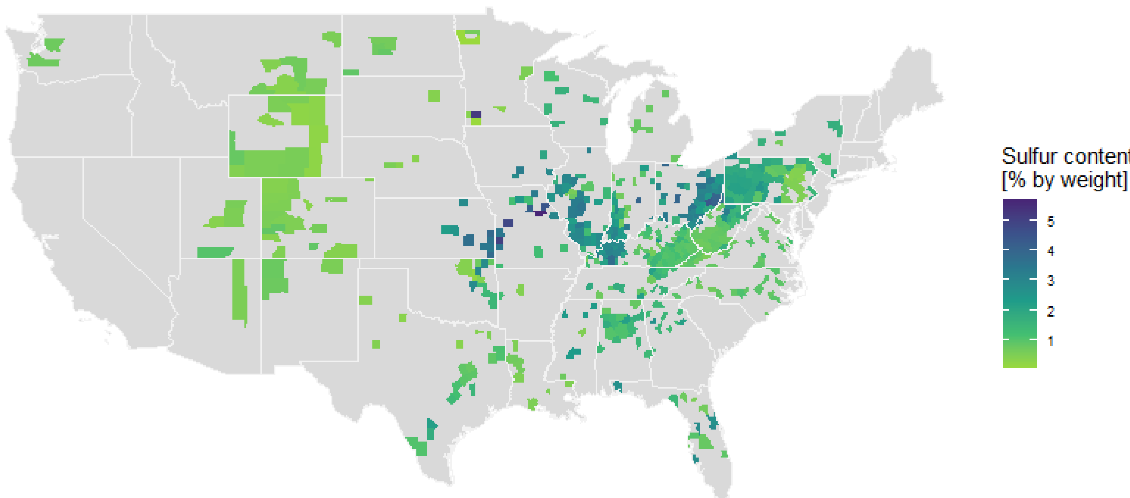
Notes: The line shows local emissions requirements averaged over active boilers in a given year. Absence of pollution limits for individual boilers was coded as a standard of 9 lbs/mmBTU. Grey boxes indicate states for which we either were unable to compile the information on local regulations or states that had no active coal boilers.

Figure 7: Counties with boiler retirements in years 1985-2017.

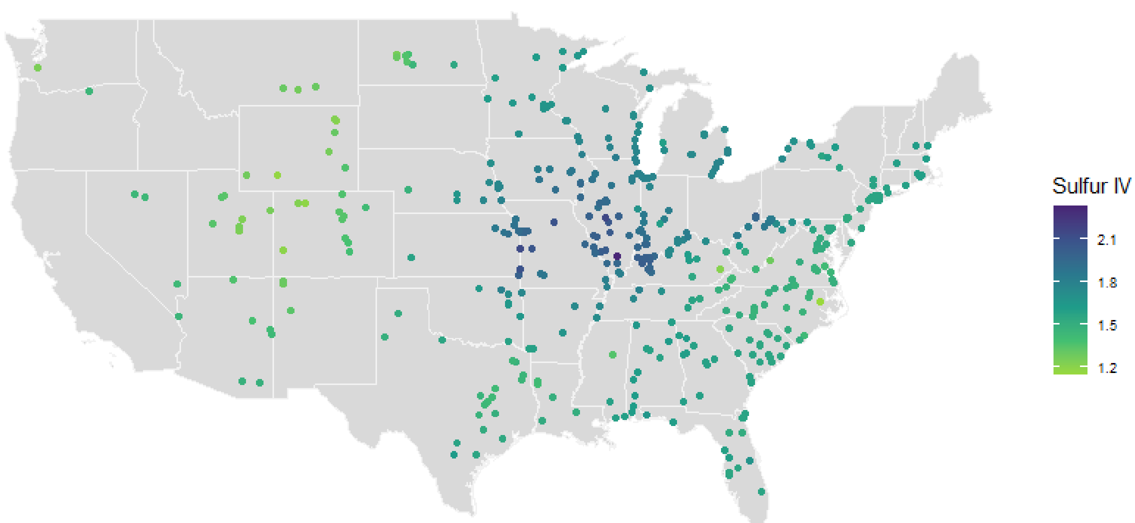


Notes: Bubbles show individual counties, while their size represents the number of constituent coal-fired boiler retirements. The color indicates the in-service year of the oldest retired boiler within the county. Due to data limitations, we exclude California, Maine, Ohio and Pennsylvania.

Figure 8: Associating available coal to all coal-fired power plants



(a) Median sulfur content of coal by county.



(b) Weighted average of median sulfur content of available coal by inverse distance for all coal-fired power plants.

D Robustness checks

This appendix presents results for the robustness checks presented in Section 6.4.

Restricting the boiler vintages.

First, we perform a robustness check of our main results in Table 1 by restricting the sample to boilers taken into service in years 1970-1994. Table 6 reports the main regression results, while the first three columns in Table 7 presents the results of the corresponding first stage regressions.

Table 6: Restricted sample regression results

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	OLS	*OLS*	*OLS*	*OLS*	*IV*	*IV*	*IV*
	IOU+	*IOU+*	*IOU+*	*IOU+*	*IOU+*	*All*	*IOU*
Panel A: Utilization							
GF	−44.87	869.80***	850.23***	962.78***	1118.41***	343.01*	610.17*
	(−0.66)	(3.60)	(3.43)	(3.91)	(4.35)	(2.22)	(2.44)
size	978.46***	1997.84***	1938.61***	1756.55***	2736.56***	1839.27***	1957.77***
	(7.28)	(6.11)	(5.78)	(4.94)	(7.38)	(8.15)	(5.64)
GF × size		−1252.42***	−1227.07***	−1264.40***	−1754.90***	−709.49**	−1050.94**
		(−3.91)	(−3.75)	(−3.77)	(−5.09)	(−3.23)	(−3.16)
NAAQS		331.30*	296.55	433.96**	294.80	822.43***	290.53
		(2.35)	(1.83)	(2.78)	(1.79)	(3.63)	(1.80)
GF × NAAQS		−23.95	89.30	27.94	150.38	−548.08*	158.92
		(−0.12)	(0.42)	(0.14)	(0.68)	(−2.03)	(0.75)
MMBTU		132.27**	126.14*	99.14*	110.59*	−10.24	69.32
		(2.74)	(2.55)	(2.05)	(2.35)	(−0.24)	(1.51)
GF × MMBTU		−160.35**	−143.16**	−157.56**	−153.20**	41.45	−90.13
		(−3.23)	(−2.84)	(−3.19)	(−3.01)	(1.11)	(−1.70)
Year FE	X	X	X	X	X	X	X
State FE	X	X	X	X	X	X	X
Utility FE	X	X	X	X	X	X	
Market Controls			X	X	X	X	X
Sulfur Controls				X	X	X	X
Observations	3,577	3,577	3,420	3,292	3,420	5,739	3,228
R^2	0.309	0.319	0.307	0.287	0.310	0.396	0.273

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	OLS	*OLS*	*OLS*	*OLS*	*IV*	*IV*	*IV*
	IOU+	*IOU+*	*IOU+*	*IOU+*	*IOU+*	*All*	*IOU*
Panel C: Emissions							
GF	−0.11	0.12	0.12	0.09	0.20	−0.48*	0.31
	(−0.92)	(0.40)	(0.40)	(0.28)	(0.70)	(−2.56)	(1.17)
size	1.24***	1.27***	1.27***	1.15**	1.52**	−0.07	1.75***
	(5.39)	(3.67)	(3.67)	(3.16)	(3.06)	(−0.21)	(3.90)
GF × size		−0.00	−0.00	0.04	−0.16	0.31	−0.39
		(−0.01)	(−0.01)	(0.10)	(−0.39)	(1.01)	(−0.98)
NAAQS		0.79**	0.79**	0.26	0.83**	0.42	0.82*
		(2.84)	(2.84)	(0.97)	(2.65)	(1.31)	(2.34)
GF × NAAQS		−0.75	−0.75	−0.13	−0.68	−0.91*	−0.74
		(−1.86)	(−1.86)	(−0.33)	(−1.62)	(−2.53)	(−1.68)
MMBTU		−0.25*	−0.25*	−0.24*	−0.25*	−0.33***	−0.26*
		(−2.55)	(−2.55)	(−2.40)	(−2.33)	(−5.89)	(−2.41)
GF × MMBTU		−0.22*	−0.22*	−0.23*	−0.22*	−0.04	−0.23*
		(−2.25)	(−2.25)	(−2.27)	(−2.10)	(−0.72)	(−2.12)
Year FE	*X*	*X*	*X*	*X*	*X*	*X*	*X*
State FE	*X*	*X*	*X*	*X*	*X*	*X*	*X*
Utility FE	*X*	*X*	*X*	*X*	*X*	*X*	
Market Controls							
Sulfur Controls				*X*	*X*	*X*	*X*
Observations	3,438	3,438	3,438	3,337	3,438	5,842	3,374
R^2	0.473	0.485	0.485	0.490	0.486	0.456	0.489

Notes: This table presents robustness check results based on a sample restricted to boilers which started their service between 1972 and 1994. Specifications (1)-(4) are estimated using OLS, while specifications (5)-(7) use 2SLS and leverage sulfur content of the available coal as an instrument for sulfur content of the combusted coal. The unit of observation is boiler-year. The *IOU* columns restrict the sample to boilers belonging to IOUs; the *IOU+* column expands to include commercial, industrial and IOU boilers; while, the *All* column uses all types of available boilers. Utilization and emissions estimations both use data from 1995-2018. Estimations of survival effects are not possible given that the sample contains too few retirements. Robust standard errors used, with *** p<0.001, ** p<0.01, * p<0.05 and t-statistics in parentheses.

Grandfathering status

Next, we check the robustness of our main results presented in Table 1 by adopting a conservative definition of NSR grandfathering status, as described in Section 6.4. Table 8 presents the main results, while the corresponding first stage results are shown in the last three columns of Table 9.

Table 7: Restricted sample regression first-stage results

	(5)	(6)	(7)
	OLS	*OLS*	*OLS*
	IOU+	*All*	*All*
sulfur	2.44***	1.94***	2.74***
	(14.82)	(15.25)	(17.00)
GF	−0.66***	−0.46***	−0.50***
	(−9.55)	(−7.39)	(−7.06)
size	−1.82***	−1.11***	−1.78***
	(−20.02)	(−13.48)	(−18.46)
GF × size	1.18***	0.68***	0.99***
	(11.89)	(7.50)	(9.73)
NAAQS	−0.01	0.08	0.07
	(−0.08)	(0.73)	(0.50)
GF × NAAQS	−0.04	−0.36**	0.17
	(−0.23)	(−2.68)	(1.07)
MMBTU	0.01	−0.02*	0.03***
	(1.40)	(−2.33)	(4.59)
GF × MMBTU	0.04***	0.10***	0.01
	(3.81)	(7.80)	(1.10)
Year FE	*X*	*X*	*X*
State FE	*X*	*X*	*X*
Utility FE	*X*	*X*	
Market Controls	*X*	*X*	*X*
Observations	4,245	6,778	3,966
R^2	0.716	0.644	0.715

Notes: This table presents the first-stage results for our robustness check based on a sample restricted to boilers which started their service between 1972 and 1994. The three channels each produce similar results, so we report those for utilization only. The dependent variable is the SO_2 content of the combusted coal. All specifications are estimated using OLS. The unit of observation is boiler-year. The *IOU* columns restrict the sample to boilers belonging to IOUs; the *IOU+* column expands to include commercial, industrial and IOU boilers; while, the *All* column uses all types of available boilers. Robust standard errors used, with *** p<0.001, ** p<0.01, * p<0.05 and *t*-statistics in parentheses.

Table 8: Conservative grandfathering regression results

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	OLS	*OLS*	*OLS*	*OLS*	*IV*	*IV*	*IV*
	IOU+	*IOU+*	*IOU+*	*IOU+*	*IOU+*	*All*	*IOU*
Panel A: Utilization							
GF^c	681.81***	587.25***	608.83***	577.70***	606.56***	207.86***	559.20***
	(12.45)	(9.05)	(9.26)	(9.03)	(8.63)	(3.75)	(7.46)
size	1391.77***	1276.60***	1224.17***	1394.10***	1191.81***	909.64***	892.00**
	(10.45)	(6.14)	(5.73)	(6.43)	(4.49)	(6.25)	(3.13)
$GF^c \times$ size		274.78*	274.22	27.13	301.64	723.25***	500.73**
		(1.97)	(1.93)	(0.20)	(1.79)	(6.24)	(2.79)
NAAQS		686.29***	684.40***	739.18***	685.04***	617.44***	884.04***
		(4.95)	(4.48)	(4.77)	(3.76)	(4.65)	(5.07)
$GF^c \times$ NAAQS		−1451.01***	−1493.75***	−1107.05***	−1504.10***	−1443.66***	−1814.54***
		(−8.05)	(−7.61)	(−5.80)	(−6.35)	(−9.01)	(−8.61)
MMBTU		−284.75***	−292.11***	−296.39***	−290.08***	−17.31	−291.78***
		(−3.61)	(−3.65)	(−3.91)	(−3.31)	(−0.40)	(−3.34)
$GF^c \times$ MMBTU		26.46	33.14	129.22	31.79	−239.05***	27.06
		(0.34)	(0.42)	(1.85)	(0.38)	(−5.61)	(0.32)
Year FE	*X*	*X*	*X*	*X*	*X*	*X*	*X*
State FE	*X*	*X*	*X*	*X*	*X*	*X*	*X*
Utility FE	*X*	*X*	*X*	*X*	*X*	*X*	
Market Controls			*X*	*X*	*X*	*X*	*X*
Sulfur Controls				*X*	*X*	*X*	*X*
Observations	10,782	10,782	10,436	9,762	10,436	16,291	9,927
R^2	0.287	0.297	0.293	0.286	0.293	0.292	0.282
Panel B: Survival							
GF^c	0.94***	1.08***	1.23***	0.98**	1.22***	0.71*	1.34***
	(3.47)	(3.39)	(3.32)	(2.71)	(3.49)	(2.54)	(3.33)
size	0.73	0.75	1.06	1.09	0.79	0.04	0.98
	(1.33)	(1.05)	(1.28)	(1.35)	(0.83)	(0.06)	(0.79)
$GF^c \times$ size		0.15	0.37	0.19	0.57	1.98***	0.39
		(0.30)	(0.64)	(0.34)	(0.80)	(3.33)	(0.52)
NAAQS		1.18	1.76	0.49	1.80	1.08	1.84
		(0.65)	(0.74)	(0.19)	(0.77)	(0.92)	(0.75)
$GF^c \times$ NAAQS		−2.30	−2.58	−2.52	−2.69	−2.29	−2.75
		(−1.20)	(−1.02)	(−0.92)	(−1.00)	(−1.61)	(−1.03)
MMBTU		−0.08	−0.06	−0.52**	−0.04	−0.11	−0.05
		(−0.29)	(−0.18)	(−3.08)	(−0.13)	(−0.65)	(−0.17)
$GF^c \times$ MMBTU		−0.19	−0.26	0.07	−0.27	−0.41	−0.23
		(−1.09)	(−1.16)	(0.42)	(−1.28)	(−1.81)	(−0.99)
Year FE	*X*	*X*	*X*	*X*	*X*	*X*	*X*
State FE	*X*	*X*	*X*	*X*	*X*	*X*	*X*
Utility FE	*X*	*X*	*X*	*X*	*X*	*X*	
Market Controls			*X*	*X*	*X*	*X*	*X*
Sulfur Controls				*X*	*X*	*X*	*X*
Observations	15,257	15,257	12,626	11,738	12,626	19,125	11,694
R^2	0.101	0.102	0.106	0.102	0.107	0.099	0.108

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	OLS	*OLS*	*OLS*	*OLS*	*IV*	*IV*	*IV*
	IOU+	*IOU+*	*IOU+*	*IOU+*	*IOU+*	*All*	*IOU*
Panel C: Emissions							
GF^c	0.78***	1.01***	1.01***	1.01***	0.91***	1.37***	0.99***
	(6.11)	(7.20)	(7.20)	(6.99)	(6.48)	(10.14)	(7.55)
size	−1.95***	−1.05***	−1.05***	−0.90**	−2.42***	−2.86***	−2.39***
	(−8.95)	(−3.81)	(−3.81)	(−3.15)	(−5.26)	(−11.00)	(−5.74)
GF^c × size		−0.40	−0.40	−0.46*	0.69	0.24	0.58
		(−1.87)	(−1.87)	(−2.18)	(1.95)	(1.03)	(1.73)
NAAQS		1.59***	1.59***	0.77**	1.81***	0.54	1.73***
		(3.75)	(3.75)	(2.93)	(4.17)	(1.44)	(3.87)
GF^c × NAAQS		−2.39***	−2.39***	−0.81	−2.49***	−0.06	−2.33***
		(−4.52)	(−4.52)	(−1.86)	(−5.18)	(−0.11)	(−4.10)
MMBTU		−0.79***	−0.79***	−0.76***	−0.61***	−0.78***	−0.62***
		(−7.22)	(−7.22)	(−6.91)	(−5.32)	(−10.40)	(−5.33)
GF^c × MMBTU		−0.21*	−0.21*	−0.21*	−0.28**	−0.35***	−0.24*
		(−2.10)	(−2.10)	(−2.04)	(−2.62)	(−4.99)	(−2.24)
Year FE	*X*	*X*	*X*	*X*	*X*	*X*	*X*
State FE	*X*	*X*	*X*	*X*	*X*	*X*	*X*
Utility FE	*X*	*X*	*X*	*X*	*X*	*X*	
Market Controls							
Sulfur Controls				*X*	*X*	*X*	*X*
Observations	10,227	10,227	10,227	9,706	10,227	16,181	10,049
R^2	0.419	0.429	0.429	0.435	0.438	0.407	0.439

Notes: This table presents robustness check results based on a "conservative" definition of grandfathering, GF^c. Specifications (1)-(4) are estimated using OLS, while specifications (5)-(7) use 2SLS and leverage sulfur content of the available coal as an instrument for sulfur content of the combusted coal. The unit of observation is boiler-year. The *IOU* columns restrict the sample to boilers belonging to IOUs; the *IOU+* column expands to include commercial, industrial and IOU boilers; while, the *All* column uses all types of available boilers. Utilization and emissions estimations use data from 1995-2018, while survival estimations use 1985-2017. Robust standard errors used, with *** p<0.001, ** p<0.01, * p<0.05 and t-statistics in parentheses.

Table 9: Conservative grandfathering regression first-stage results

	(5)	(6)	(7)
	OLS	*OLS*	*OLS*
	IOU+	*All*	*IOU*
sulfur	2.58***	2.32***	2.80***
	(29.76)	(36.76)	(31.15)
GF^c	−0.06	0.02	−0.04
	(−1.90)	(0.98)	(−1.38)
size	−0.87***	−0.49***	−0.98***
	(−16.70)	(−10.00)	(−18.48)
$GF^c \times$ size	0.65***	0.39***	0.66***
	(13.63)	(8.74)	(13.85)
NAAQS	0.02	−0.01	0.09
	(0.19)	(−0.09)	(0.83)
MMBTU	0.08***	0.00	0.08***
	(7.50)	(0.33)	(7.55)
$GF^c \times$ MMBTU	−0.03**	−0.02	−0.03**
	(−2.63)	(−1.79)	(−2.74)
Year FE	*X*	*X*	*X*
State FE	*X*	*X*	*X*
Utility FE	*X*	*X*	
Market Controls	*X*	*X*	*X*
Observations	13,365	19,750	12,503
R^2	0.594	0.480	0.589

Notes: This table presents the first-stage results for our robustness check based on a "conservative" definition of grandfathering. The three channels each produce similar results, so we report those for utilization only. The dependent variable is the SO_2 content of the combusted coal. All specifications are estimated using OLS. The unit of observation is boiler-year. The *IOU* columns restrict the sample to boilers belonging to IOUs; the *IOU+* column expands to include commercial, industrial and IOU boilers; while, the *All* column uses all types of available boilers. Robust standard errors used, with *** p<0.001, ** p<0.01, * p<0.05 and *t*-statistics in parentheses.