CO_2 Spillover Effects from the Environmental Regulation of Power Plants

Preliminary Draft: Comments Welcome

Stephen P. Holland
University of North Carolina at Greensboro [*][†]

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Abstract

Pollutant spillover from environmental regulations have important implications for policy design, modeling, and benefit-cost analysis. This project empirically tests for pollutant spillover effects on CO_2 emissions of power plants from regulations targeting NO_X emissions under the Clean Air Act Amendments. The fixed effects estimator uses changes in attainment status over time as a proxy for an increase in the cost of NO_X emissions. Identification is aided by testable predictions from theory and the fact that CO_2 emissions were not regulated during the sample period. Consistent with the predictions, I find, for California, that nonattainment reduced NO_X emissions by approximately 40% with approximately half of the reduction attributable to substitution effects and half to output effects. Moreover, I find that nonattainment is associated with a spillover effect on CO_2 emissions (a 20% reduction), which is primarily attributable to output effects. For this spillover, which indicates gross complementarity, the regressions cannot separate the effects of the nonattainment designation from other regulations.

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[†] Send correspondence to: Stephen P. Holland, Dept. of Economics, University of North Carolina, Greensboro, NC 27402-6165, sphollan@uncg.edu.

1 Introduction

The ability of environmental regulations to achieve a desired level of environmental quality at least cost depends on understanding how the regulations affect firm behavior. Unfortunately, the effects of environmental regulations may extend well beyond the targeted firms and pollutants and may have unintended consequences.[1] This paper analyzes *pollutant spillovers*, *i.e.,* the effects of environmental regulations on emissions of nontarget pollutants.[2,3] In particular, I empirically test for pollutant spillover effects on power plant CO_2 emissions from regulations targeting NO_X emissions under the Clean Air Act Amendments (CAAAs).

Pollutant spillovers have important implications for policy design, modeling, and benefit-cost analysis. First, the CAAAs, which are the primary regulatory framework for addressing air pollution in the U.S., focus on ambient concentrations for each of six criteria pollutants. Significant pollutant spillovers may argue for a multi-pollutant regulatory approach rather than the criteria pollutant approach of the CAAAs. Second, federal resistance to regulating greenhouse gas emissions has forced states to adopt innovative regulatory approaches to avoid violating federal guidelines and prohibitions.[4] Understanding pollutant spillovers can be essential for assessing these innovative approaches.[5] Third, most policy analyses focus only on a single pollutant or a small set of pollutants usually holding emissions *rates* constant.[6] These assumptions may be invalid if pollutant spillovers are significant and have significant effects on emissions rates. Finally, positive pollutant spillovers increase the benefits of environmental regulations whereas negative spillovers reduce those benefits. Ignoring pollutant spillovers may bias benefit-cost analysis.[7]

Despite the importance of pollutant spillovers, they have received little empirical analysis. Greenstone (2003) studies pollutant spillovers across media and finds little evidence that the

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[1] For an analysis of the effects of the CAAAs on firm exits see Henderson (1996); on plant births and scale see Becker and Henderson (2000); and on jobs, capital stock, and output see Greenstone (2002).

[2] Greenstone (2003) calls this effect "regulation-induced substitution."

[3] Innovation spillovers and geographic spillovers (sometimes called "leakage") have been analyzed elsewhere.

[4] Twelve states joined local governments and environmental organizations in Massachusetts v. EPA Supreme Court No. 05-1120 to clarify the EPA's obligation to regulate greenhouse gas emissions under the Clean Air Act.

[5] In 2007, California sued the EPA to obtain a waiver allowing the state to implement emissions standards reducing greenhouse gas emissions from automobiles under California AB 1493 (the Pavley Bill). At issue in granting the waiver is whether or not AB 1493 would reduce damages from *ozone*. See CA v. EPA (2007) and Douglas (2007).

[6] For example, see Burtraw *et al.* (2003) or Holland & Mansur (2006).

[7] Burtraw *et al.* (2003) find substantial ancillary benefits of greenhouse gas regulations on emissions of other pollutants using a detailed electricity model.

CAAAs increase releases into waterways and the ground. My analysis extends his investigation in three ways. First, unlike his analysis, the data used here have enough variation to estimate a fixed-effects model, thus controlling more completely for individual source heterogeneity. Second, Greenstone analyzes spillovers to other pollutants that are themselves regulated and may not adequately control for an increase in overall regulatory stringency. In contrast, this paper studies spillovers to CO_2 emissions, which were not regulated (and were not anticipated to be regulated) during the sample period. Finally, this investigation has data on output and thus can parse the spillovers into output and substitution effects.

Pollutant spillovers arise because a firm can change its production process in response to environmental regulations. These changes could either increase or decrease emissions of nontarget pollutants. For example, if a regulation leads a dual-fuel power plant to use more natural gas and less oil, the regulation could reduce emissions not only of the targeted pollutant, but of other pollutants as well. Similarly, if the regulation causes the firm to reduce output, emissions of all pollutants might decrease. Conversely, if a regulation causes a power plant to install equipment which controls emissions of a single pollutant, the plant may require additional electricity internally, thus increasing emissions of other pollutants.[8] Similarly, a firm may respond by using more of a low-emissions fuel source, *e.g.,* low-sulfur coal, or by reoptimizing the combustion procedures leading to lower emissions of the targeted pollutant but higher emissions of other pollutants, *e.g.,* CO_2.[9] My estimates suggest a gross complementarity between NO_X and CO_2 emissions attributable primarily to output effects.

Beyond this analysis of pollutant spillovers, the paper makes three additional contributions. First, the effectiveness of the CAAAs regulations has been analyzed by Henderson (1996) who argued that the CAAAs regulations reduced ambient ozone concentrations. On the other hand, Greenstone (2004) found that the CAAAs regulations played a minor role in the dramatic reduction of SO_2 concentrations from 1969-1997, and Goklany (1999) argues that the Clean Air Act failed to reduce air pollution concentrations beyond extant trends. I present evidence that the CAAAs indeed reduced power plant emissions of NO_X in California. A reduction in emissions

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[8] Most power plants have flexibility in utilizing installed pollution control equipment.

[9] See Bushnell and Wolfram (2007) on the ability of power plant operators to reoptimize combustion procedures.

is necessary for the CAAAs to reduce ambient concentrations of a targeted pollutant. Second, there is debate about *how* the CAAAs reduced pollution. Henderson (1996) provides evidence that the CAAAs induced polluting firms to exit; Becker and Henderson (2000) maintain that the CAAAs reduced plant births and shifted industrial structure toward less regulated single-plant firms; and Greenstone (2002) shows that nonattainment counties lost jobs, capital stock and output in pollution-intensive industries. Since power plant output can be accurately measured, I am able to parse the effect of the CAAAs regulations into output and substitution effects. I find that approximately half of the reduction in NO_X emissions can be attributed to output reductions and half to input substitution. Third, the CAAAs regulations have been used as an instrumental variable in studies of whether pollution is capitalized into housing values (Chay and Greenstone 2005), and of whether pollution reduced adult or elderly mortality (Chay *et al.* 2003). My research supports use of the CAAAs regulations as an instrumental variable by showing that the CAAAs indeed reduce emissions.

Pollutant spillovers depend on the substitutability of the targeted and nontarget pollutants in the production process. Section 2 makes this relationship clear by modeling production where emissions are inputs. The framework also allows the spillovers to be decomposed into substitution and output effects with a Slutsky-type equation. Although this modeling is a direct application of standard microeconomic theory, the formal framework clarifies the analysis and provides testable predictions, which aid in model identification.

The econometric framework is described in Section 3. Since prices are not observed for pollution inputs, I use changes in 1-hour ozone attainment status under the CAAAs as a proxy for a change in the price of NO_X emissions. The fixed effects estimator exploits variation in the attainment status at the generating unit over time to estimate the effect. The primary analysis focuses on California, which had multiple changes in attainment status over the study period.

Section 4 describes the data on attainment status and power plant emissions along with the controls. The attainment status of counties within each state is analyzed to locate a region with suitable variation for the study. The main analysis focuses on NO_X and CO_2 emissions from power plants in California between 1997 and 2004.

Section 5 presents the results of the estimation. Consistent with the testable predictions, I find that nonattainment designation reduced $\mathrm{NO_X}$ emissions by 40% with half of the reduction attributable to the substitution effects and half to output effects. Furthermore, I find that nonattainment is associated with a spillover effect on $\mathrm{CO_2}$ emissions of approximately a 20% reduction in $\mathrm{CO_2}$ emissions, primarily attributable to output effects. Section 6 concludes.

2 Output and Substitution Effects

To understand the effects of environmental regulation, consider the standard model of production where emissions of pollutants are inputs.[10] Production requires a vector of capital, labor and fuel inputs as well as environmental inputs (*i.e.,* emissions), NO_x and CO_2.[11] It is well known that the solution to the profit maximization problem gives the *factor demand* functions which depend on prices of output and inputs, *e.g.,* the factor demand for $\mathrm{CO_2}$ emissions is $CO2(p, r, p_{NOx}, p_{CO2})$ where p is output price, r is the input price vector, and p_{NOx} and p_{CO2} are the prices (possibly zero) of the environmental inputs.[12] If $dCO2/dp_{NOx}$ is greater (less) than zero, then $\mathrm{CO_2}$ is a *gross substitute (complement)* for $\mathrm{NO_X}$ emissions.

Similarly, conditional on a given level of output, q, the firm's cost function can be derived along with the *conditional factor demand* functions which depend on the output level and input prices, *e.g.,* the conditional factor demand for $\mathrm{CO_2}$ emissions is $CO2^c(q, r, p_{NOx}, p_{CO2})$ where q is output. If $dCO2^c/dp_{NOx}$ is greater (less) than zero, then $\mathrm{CO_2}$ and $\mathrm{NO_X}$ are *net substitutes (complements).*

Since profit maximization implies cost minimization, the factor demands must equal the conditional factor demand where the output level is given by the supply function. Differentiating these identities for NOx and $CO2$ with respect to p_{NOx} give the following "Slutsky" relationships:

$$\frac{dNOx}{dp_{NOx}} = \frac{dNOx^c}{dq}\frac{dq}{dp_{NOx}} + \frac{dNOx^c}{dp_{NOx}} \tag{1}$$

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[10] Equivalently, pollution could be modeled as a joint output.

[11] With the standard assumptions from production theory, the environmental inputs are modeled like any other inputs.

[12] In the analysis, I use changes in attainment status under the CAAAs to proxy for a change in the price of $\mathrm{NO_X}$ emissions.

and

$$\frac{dCO2}{dp_{NOx}} = \frac{dCO2^c}{dq}\frac{dq}{dp_{NOx}} + \frac{dCO2^c}{dp_{NOx}}. \tag{2}$$

Equation 1 shows that the total change in NO_X emissions resulting from a change in the price of those emissions can be decomposed into an *output* and a *substitution* effect. The output effect, $\frac{dNOx^c}{dq}\frac{dq}{dp_{NOx}}$, is the change in emissions that results because the firm may choose to produce a different level of output (with different emissions) under the new input prices. The substitution effect describes the change in emissions which results from the changing relative prices of inputs while holding output constant. Intuitively, the substitution effect arises because the cheapest way of attaining a given output level may require more (different) capital or fuel or CO_2 emissions when the relative price of NO_X emissions increases.

Similarly, equation 2 decomposes the spillover effect (cross-price effect) into an output effect and a substitution effect. Note that the cross-price output effect is similar to the own-price output effect, except for the different marginal emissions rate.

Theory imposes some restrictions on the signs of these effects. These restrictions are:

Proposition 1 *Own price effects are non-positive for both the factor demand and the conditional factor demand, e.g.,* $\frac{dNOx}{dp_{NOx}} \leq 0$ *and* $\frac{dNOx^c}{dp_{NOx}} \leq 0$. *Output effects are always non-positive for the own prices, e.g.,* $\frac{dNOx^c}{dq}\frac{dq}{dp_{NOx}} \leq 0$. *Cross price (substitution and output) effects can be either positive or negative for both the factor demands and conditional factor demands.*

Proof: See appendix.

Proposition 1 provides three testable implications for the econometric estimation. Namely, own price effects should be non-positive for both the factor demand and the conditional factor demand, and the own output effect should be non-positive. For estimates that do not conform with these predictions, either the model suffers some specification error or attainment status is not a valid proxy for the price of NO_X emissions.

Although cross-price output effects can be positive, the proof of Proposition 1 makes clear that they can only be positive in the case of an inferior input. If all inputs are normal, then all output effects must be negative. Thus, the only way for two normal inputs to be gross substitutes (*i.e.,* for a regulation to increase emissions of a nontarget pollutant) is for them to be net substitutes and for the output effect to be sufficiently small that it does not outweigh the substitution effect.

3 Estimation Strategy

Although explicit prices of environmental inputs are rarely observed, changes in environmental regulation may change the implicit price of emissions of a pollutant. Under the Clean Air Act, regions that fail to achieve an ambient air quality standard for a certain pollutant are deemed to be in nonattainment status for that pollutant. Designation as nonattainment status triggers additional regulations, which vary according to each state's implementation plan (SIP), for returning to attainment status.[13] In this study, the change in attainment status for 1-hour ozone is a proxy for a change in the price of emissions of $\mathrm{NO_X}$, which is a primary ozone precursor.

The estimation strategy uses a fixed effects estimator to estimate the effect of a change in attainment status on the emissions of $\mathrm{NO_X}$ and $\mathrm{CO_2}$.[14] The basic estimating equation is:

$$\ln(\mathrm{Emiss}_{it}) = \beta \mathrm{Nonattain}_{it} + \gamma X_{it} + f_i + g_i t + \nu_{jt} + \epsilon_{it} \tag{3}$$

where Emiss_{it} is emissions from generating unit i at time t; $\mathrm{Nonattain}_{it}$ is a dummy variable indicating that unit i is in nonattainment status for 1-hour ozone at time t; X_{it} is a vector of controls for other regulations; f_i is a unit-specific fixed effect; $g_i t$ is a unit-specific linear trend; ν_{jt} is a market-year-month fixed effect for market j; and ϵ_{it} is the error term. To correct for possible serial correlation, the error term, ϵ_{it}, is clustered at the generating unit.

The parameter of interest is β, which indicates the response of emissions to a change in attainment status.[15] Since the nonattainment dummy is a proxy for an increase in the price of $\mathrm{NO_X}$ emissions, the estimated coefficient captures the own price effect when $\mathrm{NO_X}$ emissions are the dependent variable. With $\mathrm{CO_2}$ emissions as the dependent variable, the estimated coefficient captures the pollutant spillover. A positive (negative) coefficient indicates that $\mathrm{NO_X}$ and $\mathrm{CO_2}$ are gross substitutes (complements).

Most of the potentially confounding variation is controlled for by the fixed effects. The unit-specific fixed effects capture any differences in emissions across units due to fuel-mix, generation technology, generator capacity, installed emissions control equipment, or any other time-invariant

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[13] For detailed descriptions of the regulatory effects of nonattainment designation under the CAAAs, see Henderson (1996), Becker and Henderson (2000), Greenstone (2002) & (2004), or Chay and Greenstone (2005).

[14] Results are also presented for $\mathrm{SO_2}$.

[15] The percentage change in emissions from nonattainment designation is given by $e^{\beta} - 1$.

characteristics of the generating units. The unit-specific linear trends capture any trends at the unit level, *e.g.,* phasing out of old units. The market-year-month fixed effects are a vector of indicators for each month of each year for each market, *e.g.,* one indicator is for January 1999 for the northern California market (NP15) and another indicator is for January 1999 for the southern market. The market-year-month fixed effects capture all variation over time such as seasonal effects and changes in relative fuel prices, in labor costs, in capital costs, and in regulations affecting all generators as well as differences across the markets. This flexible set of fixed effects captures most of the potentially confounding effects.

The controls, X_{it}, capture changes is other regulations such as changes in attainment status for other pollutants, *e.g.,* carbon monoxide, nitrogen dioxide, and particulate matter, as well as other regulations under the Acid Rain Program.[16]

Given this extensive set of nonparametric controls, model identification is based on variation in the attainment status of generating units over time in the sample. With no variation in attainment status, the nonattainment indicator would be perfectly collinear with the unit fixed effects. With changes in attainment status at one point in time, the estimator would be similar to the well-known difference-in-differences estimator. Intuitively, the generating units with unchanged attainment status would serve as controls for the generators with changed attainment status (the treated group).[17] With a one-time change in attainment status, the estimated effect would be biased if there were unobserved differential trends in emissions that were correlated with the change in attainment status. This threat to identification is addressed in two ways. First, the main study analyzes California, which had multiple changes into and out of attainment status over the sample period. These multiple changes diminish the potential for bias from unobserved trends. Second, the model incorporates unit-specific linear trends to control for any unit-specific trends, which would not be captured by the market-year-month fixed effects.

The regulatory changes that accompany nonattainment designation vary and are subject to local discretion. The estimated spillover effect could therefore be biased if regulatory authorities

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[16] When the dependent variable is daily emissions, a flexible function of daily average temperature controls for changes in demand for electricity within the month. The temperature controls are not included when the dependent variable is average monthly emissions since it would be perfectly collinear with the market-year-month effects.

[17] Some of the controls are always in attainment status whereas some are always in nonattainment status.

used the additional statutory authority to attempt to reduce emissions of other pollutants. In this case, changes in attainment status would indicate variations in the prices of both NO_X emissions and other pollutants, and the estimated effect would combine the direct and spillover effects. This potential confounding is limited by analyzing spillover effects on CO_2 emissions. There is still disagreement over whether CO_2 is a harmful pollutant and CO_2 is neither listed nor regulated by the EPA as a criteria pollutant. Although a consensus is developing that CO_2 emissions are a contributor to global climate change, during the sample period it was hotly debated whether CO_2 had harmful effects. Therefore, regulators had little incentive to try to reduce CO_2 emissions. This lack of regulatory attention to CO_2 emissions suggests that the nonattainment indicator is not a proxy for an increase in the price of CO_2 emissions and that the spillover effect is properly identified.[18]

Identification is supported by the testable predictions from theory. In particular, Proposition 1 shows that the own price effect should be non-positive for factor demands. A negative own price effect, estimated by β in [3] with NO_X emissions as the dependent variable, is consistent with the theoretical predictions and provides evidence that the change in nonattainment status is a proxy for an increased price of NO_X emissions.[19]

Additional testable predictions provide further evidence that the model is properly identified. Specifically, Proposition 1 shows that the conditional own price effect should be non-positive. The conditional factor demand, which is the input demand for a given level of output, can be estimated by conditioning on output. In particular, by estimating the equation:

$$\ln(\text{Emiss}_{it}) = \beta^c \text{Nonattain}_{it} + \beta^{MWh} \ln(\text{MWh}_{it}) + \gamma X_{it} + f_i + g_i t + \nu_{jt} + \epsilon_{it} \tag{4}$$

with NO_X emissions as the dependent variable, the coefficient β^c estimates the conditional own price effect if MWh_{it} properly conditions for output. Thus an estimated β^c less than or equal to zero is consistent with the requirement in Proposition 1 that the conditional own price effect be non-positive.

Proposition 1 also shows that the output effect should be non-positive for own prices, *i.e.,*

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[18] This argument does not hold for SO_2 emissions.

[19] Theory makes no prediction about the sign of the spillover effect, estimated with CO_2 emissions as the dependent variable.

$\frac{dNOx^c}{dq}\frac{dq}{dp_{NOx}}$ should be non-positive. This provides another testable implication: the own price effect should be stronger than the conditional own price effect, i.e., $\beta - \beta^c \leq 0$.

I also present results from regressing output on the same set of controls.[20] This result estimates all four derivatives in [1] separately. In particular, [1] is $\beta = \beta^{MWh}\beta' + \beta^c$. This identity holds since the sample and all conditioning variables are identical.

A similar procedure can be used to separate the spillover effect on CO_2 emissions into output and substitution effects. In particular, by estimating [3] and [4] with CO_2 emissions as the dependent variable, all four derivatives in [2] can also be estimated. This does not provide further testable implications of the theory since cross price effects can be either negative or positive. However, separating the spillover effects into output and substitution effects is important for understanding the policy and modeling implications of spillovers.

4 Data

This analysis requires data on emissions, generation, attainment status, and other regulations. Availability of the emissions data limit the sample to the years 1997-2004.

Table 1 lists all the counties and parts of counties in the U.S. which changed attainment status for the 1-hour ozone standard between 1997 and 2004 and the number of power plants within each county. Several points are notable. First, only thirteen states had any changes in attainment status during this period. Thus the model could only possibly be estimated for these thirteen states.[21] Second, most of the changes in attainment status tend to happen simultaneously within a state. For example, Virginia had eighteen counties with changes in attainments status. However, all of these changes occurred simultaneously in 1998. On the other hand, California had changes in attainment status which occurred at three separate times. Third, designation from attainment to nonattainment was much rarer than the reverse. In fact, only California had any counties which came into nonattainment status during this period. Finally, many counties, which had changes in attainment status, did not have any reporting fossil-fuel fired power plants.

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[20] Specifically, the regression is: $\ln(\text{MWh}_{it}) = \beta'\text{Nonattain}_{it} + \gamma X_{it} + f_i + g_i t + \nu_{jt} + \epsilon_{it}$.

[21] The 8-hour ozone standard was promulgated and a number of counties were declared to be not meeting this standard in 2004. Controlling for this change is important. For example, the two counties in Alabama, which were declared to be in attainment of the 1-hour ozone standard in 2004, were simultaneously declared to be in violation of the new 8-hour standard in 2004.

Emissions data come from the hourly U.S. EPA continuous emissions monitoring systems (CEMS) for power plants. The data are very accurate, include all fossil-fuel fired generators meeting certain requirements, and have been used in a number of studies.[22] The primary level of analysis is at the generating unit level as defined by the EPA.[23] The hourly data are aggregated to the month for three reasons.[24] First, a number of units report emissions in hours for which they report no output. Aggregation accurately captures emissions and output while incorporating any start-up emissions from generating units. Second, if regulations caused a unit to be run on fewer hours, disaggregated data would not capture this reduction since the estimating equations only analyze proportional changes. Aggregation captures the zero production hours for the proportional estimating equation. Finally, the data is highly serially correlated. Aggregation reduces the problem of serial correlation.

Since California had the most variation in attainment status, the primary analysis focuses on California.[25] Of the twelve counties in California with changes in attainment status, only three counties have relevant power plants: Contra Costa, San Francisco, and San Diego.[26] Table 2 shows the power plants and number of units in these three counties reporting in the CEMS data before and after a change in attainment status.[27] The effective dates of the redesignations (Aug. 10, 1998 and July 28, 2003) are from the Federal Register.[28] The redesignation months of August 1998 and July 2003 are dropped from the sample for all units. After dropping non-reports and data inconsistencies, the model identification is based on changes in attainment status at 29 of 178 generating units.[29]

Table 2 also reports the average year online of the generators at each power plant.[30] The

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[22] For example, see Puller (2007), Holland and Mansur (forthcoming).

[23] A unit may consist of one or more smokestacks, boilers and/or generators.

[24] Results for daily aggregation are also presented as a robustness check.

[25] Future work will extend the analysis to other states/regions.

[26] Six counties had no power plants during the sample. Santa Clara County had no power plants when its designation changed in 1999. The Kern and Solano County redesignations were for partial counties. Kern County had three power plants coming online after 2001 and Solano County had four power plants coming online after 2002, but these plants were not in redesignated areas.

[27] San Diego was declared to be in nonattainment of the new 8-hour ozone standard in 2004. The estimation controls for this redesignation.

[28] See 63 FR 37258-37280 and 68 FR 37976-37978.

[29] Five units report zero emissions and generation throughout the sample. The five reporting units at Hunters Point are aggregated since four units report zero generation but positive emissions.

[30] Since generators and units are not necessarily the same, the age of each unit cannot be known. The average age (year online) of the generators at plant thus is a proxy for the age of the units.

average year online across the 178 units in the sample is 1982. The fourteen units which are always in attainment are somewhat older: average year online is 1978; whereas the 139 units which were never in attainment were somewhat newer: average year online is 1984. The units which switch attainment status also tend to be somewhat older on average. The relevant units in Contra Costa and San Francisco counties, which were designated as not in attainment in 1999, are quite a bit older: average year online is 1961. The units in San Diego, which was designated to be in attainment in 2004, are slightly older than average: average year online is 1978. The unit fixed effects control for these differences in the age of the units.[31]

Table 3 presents summary statistics of the data aggregated to the month and to the day. The first three rows are for the primary dependent variables: NO_X , CO_2, and SO_2 emissions. The monthly means are approximately 20 times the daily means, implying that units are generating 20 days per month on average. SO_2 emissions are particularly noisy (the coefficient of variation is about 15). Most generating units in California are gas-fired and thus have negligible SO_2 emissions, so the large coefficient of variation is driven by a few units with exceptionally high SO_2 emissions. The proxy for the price of NO_X emissions, nonattainment of the 1-hour ozone CAAAs standard, is positive for 86% of the monthly sample and 84% of the daily sample. This slight difference arises because the exclusion of months or days with zeroes for the dependent variables puts a different weight on each hour. About 30% of the observations are from the northern California electricity market (North Path 15). The market-year-month fixed effects control for differences across the two markets. Approximately 45% of the observations are of units which were also in nonattainment of the CAAAs' carbon monoxide (CO) standard. The regressions control for these other programs. There is no unit-level variation in PM nonattainment, so this control is dropped from the regression, *i.e.,* is perfectly collinear with the unit fixed effects. None of the units is affected by the NO_X budget program (NBP) or the Ozone Transport Commission (OTC). None of the units is affected by the Acid Rain Program provisions affecting NO_X , although a four units at three plants did choose early election into the NO_X program.[32] All of the units were Phase 2 units

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[31] The unit fixed effects cannot control for different trends at different age units. The unit-specific linear trends address this issue. In addition, the sample is split to estimate the model separately for units with different average plant age.

[32] The three power plants were AES Alamitos, Etiwanda Generating Station, and Riverside Canal Power Company.

under the Acid Rain Program affecting SO_2 (Title IV of the CAAAs). Since these regulations affected all units beginning in 2000, this control is dropped from the regressions, *i.e.,* is perfectly collinear with the market-year-month fixed effects.

Figures 1-3 show average monthly NO_X emissions, CO_2 emissions, and generation over the sample years for four groups of units in California: two *control* groups (those units either always or never in attainment) and two *treatment* groups (those units declared in nonattainment in 1999 and those units redesignated as attainment in 2004).[33] Figure 1 shows that average monthly NO_X emissions from units generally fell over the sample. The monthly averages are mostly above the sample mean of 24,000 lbs. since the largest group (those units always in nonattainment) contains 139 of the 178 units. Average emissions from the units always in nonattainment only declined slightly over the sample, however average emissions of the 14 units always in attainment declined dramatically between 2000 and 2003. The NO_X emissions from the 11 units that were redesignated in nonattainment in 1999 also show a steep decline in emissions after 2000. Note that these units initially had higher emissions than the controls which were always in attainment, but then in 1999 and after had lower emissions. This suggests that the redesignation may have lowered emissions at these units. However, the units which were redesignated as in attainment in 2004 do not show a noticeable uptick in 2004 as might be expected in response to relaxed regulations.

Similar patterns are evident in the average monthly CO_2 emissions and generation shown in Figures 2 & 3. In particular, a decline is seen in CO_2 emissions and generation from 2001-2003 for some groups. There does not seem to be as strong a decline over time as shown for the NO_X emissions. Comparing the CO_2 emissions at units always in attainment with those designated nonattainment in 1999, we again see lower emissions and generation after 1998 at the units which were designated nonattainment. The pattern is not as clear, since these units then have higher emissions after 2001. The regressions will estimate whether emissions were higher or lower controlling for other confounds.

The indicators are only positive between 1997 and 1999.

[33] The two control groups had 14 units and 139 units. The two treatment groups had 11 units and 14 units.

5 Estimation Results

The main results from estimating equations [3], [4], and the output equation for California are presented in Table 4. The preferred specification (in Panel A) controls for other regulatory programs, while the specification in Panel B omits these controls. Throughout, the unit fixed effects, unit-specific linear trends, and market-year-month fixed effects are highly significant but are not reported.

Each column in the tables reports the results from one of seven regressions. Column (1) reports the results from estimating equation [3] where ln(NO_X) is the dependent variable. This equation estimates the NO_X factor demand since it does not control for output. Similarly, columns (3) and (5) capture the factor demands for CO_2 and SO_2. Columns (2), (4), and (6) estimate the conditional factor demands since they control for output, *i.e.,* ln(MWh). Column (7) reports estimates from regressing output on the same set of controls.

The three testable implications, which relate to the own "price" effects, are shown in columns (1) and (2). In Panel A, the estimated 38% reduction in NO_X emissions from nonattainment designation is significant at the 5% level. When controlling for output, the estimated 20% reduction is significant at the 10% level. Both own-price effects are non-positive. Finally, the estimated own price effect is larger for the factor demand than for the conditional factor demand, *i.e.,* the output effect is negative.[34] Thus, the regression results are consistent with the theoretical predictions. Moreover these results show that approximately half of the 38% reduction in NO_X emissions can be attributed to substitution effects with the remainder being attributable to output effects.

The pollutant spillover effects are reported in columns (3)-(6). For CO_2, the point estimate indicates that nonattainment designation reduced CO_2 emissions by 22%, suggesting gross complementarity. Controlling for output, the point estimate indicates quite small net substitutability ($\sim$ 2%) with a 95% confidence interval from -0.06 to 0.12. This quite limited net effect suggests that almost all of the (statistically insignificant) reduction in CO_2 emissions can be attributed to

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[34] Since the output effect is estimated from two separate regressions, this is not a formal statistical test, but rather a comparison of the point estimates. The 95% confidence interval for each point estimate includes the other estimate, *e.g.,* the 95% confidence interval around -0.473 includes -0.219.

output effects.

Similarly, the results for SO_2, columns (5) and (6), also suggest a rather substantial (but statistically insignificant) gross complementarity with NO_X but negligible net effects. As detailed above, SO_2 emissions are quite small for all but a few units in California so the SO_2 results are less reliable. In addition, SO_2 emissions are themselves regulated and thus the estimates can be confounded by an increase in general regulatory stringency.

The point estimates for output (column seven in Panel A) suggest that nonattainment designation reduced output by 27%. Although this point estimate suggests quite a large effect, it is not statistically significant.

The output controls imply emissions elasticities for the three pollutants of 0.8, 0.9, and 0.9 with respect to output. These estimates are statistically significant and statistically less than one implying that the emissions rates (emissions per MWh) are declining in output. However, the limited net effects suggest that the emissions rates do not vary substantially with changes in prices of other environmental inputs, *i.e.,* pollutant spillovers do not change emissions rates.

The controls for other regulations are mostly not significant individually. Only three of 28 estimated coefficients are statistically different from zero. Moreover, the four estimated coefficients are only jointly significant in the regression in column (6). Despite this lack of statistical significance, it is important to control for the potential confounding from other regulations.

The controls for other regulations are omitted for the regression results in Panel B. The estimated coefficients of interest are larger when not controlling for the other regulatory programs and statistical significance increases. In particular, the pollutant spillovers for CO_2 and SO_2, which were previously insignificant, are now significant as is the change in output. Although these other regulations are only weakly correlated with the 1-hour ozone designation, the regressions cannot disentangle the effects sufficiently to attribute the observed reduction in CO_2 and SO_2 emissions to the change in 1-hour ozone attainment status.

Tables 5-8 present the robustness of the results to different specifications. Table 5 splits the sample into two time periods: before and after 2001. Identification of the result in Panel A is based on the 1999 redesignation of the San Francisco Bay Area to nonattainment status, while identification in Panel B is based on the redesignation to attainment of San Diego in 2004. Following the 1999 redesignation to nonattainment, the Bay Area Air Quality Management District was required to submit a State Implementation Plan (SIP) for how it would regain attainment status. The plan did not require new power plant controls (BA AQMD 2001). Thus, it is perhaps not surprising that the results in Panel A do not satisfy the testable predictions from theory. The results in Panel B, however, do satisfy the testable predictions and are quite similar in sign and magnitude to the main results in Table 4. When San Diego was designated as attainment in July 2003, the state was required to file a maintenance plan to prevent backsliding, however, other requirements associated with nonattainment designation for 1-hour ozone were relaxed.[35]

Table 6 splits the sample into old plants (those with average generator age before 1980) and new plants (those with average generator age after 1995). Note that no plants had an average generator age between 1980 and 1995 reflecting the lack of new construction of large power plants in California over this time frame. Table 6 shows that the results in Table 4 come primarily from the changes at older plants and the results in Panel A are quite similar in sign and magnitude to the results in Table 4. In particular, the gross CO_2 spillovers are significant at the 5% level as is the effect on output. The results in Panel B are not consistent with the testable predictions.

Table 7 presents analysis based on different levels of aggregation. Panel A presents results based on aggregating the data to the plant level. This reduces the number of observations by more than half and thus increases the standard errors. In addition, this analysis does not control for changes at the plant level, such as additions or retiring of units, which may be correlated with attainment designation. The preferred specifications directly control for these changes with the unit fixed effects and additionally control for differential trends within a plant with the unit-specific linear trends.

Panel B of Table 7 presents the results based on aggregating the hourly data to the day instead of the month. The signs and magnitudes of the results are quite similar to the preferred results in Table 4. Additionally, the standard errors are more precise leading to statistical significance of the gross spillover effects for both CO_2 and SO_2 as well as a significant effect on output.

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[35] San Diego was designated as in nonattainment of the 8-hour ozone standard in 2004. The main regressions control for this designation.

These regressions additionally control for a quadratic function of temperature, which is statistically significant.

Table 8 omits the unit-specific linear trends from the specification. The signs of the estimates are generally consistent with those in the preferred specification; however, the magnitudes of the own price effects are somewhat smaller. This specification also shows a marginally significant reduction in CO_2 emissions and a significant reduction in output from nonattainment designation.

6 Conclusion

Pollutant spillovers are important for policy design, modeling and benefit-cost analysis. This paper contributes to the understanding of pollutant spillovers by analyzing the effects of nonattainment designation under the 1-hour ozone standard of the CAAAs (a proxy for the price of NO_X emissions) on power plant emissions of CO_2. For California, I find that nonattainment reduced NO_X emissions by approximately 40% with approximately half of the reduction attributable to substitution effects and half to output effects. Moreover, I find that nonattainment is associated with approximately a 20% reduction in CO_2 emissions. This spillover, which indicates gross complementarity, is not statistically significant when controlling for other regulations, but is significant at the 10% level when excluding these controls. Thus the analysis finds that nonattainment is associated with CO_2 spillovers, but cannot separate the effects of the nonattainment designation from other regulations. This CO_2 spillover can be attributed primarily to output effects with estimated substitution effects very near zero.

This evidence of spillovers suggests that it is important for policy analysis to incorporate spillovers. Since the spillovers arise primarily from output rather than substitution effects, the analysis can focus on output effects, *i.e.,* pollutant spillovers do not change emissions rates. However, I do find evidence that emissions rates may not be constant in output since the log-log specifications reject a unitary elasticity.

This evidence from California supports the finding that the CAAAs had a causal effect on reducing emissions. Moreover, the reduction did not arise merely by reducing output, but also from substitution to other inputs. This evidence does not support Goklany's argument since my analysis adequately controls for trends. Finally, this analysis supports the use of attainment status as an instrumental variable by clarifying one mechanism by which attainment status affects ambient concentrations: namely through reduced emissions.

The results are subject to a number of caveats. First, the results are presented only for California. Future work will extend the analysis to other regions with sufficient variation in attainment status to identify the model. Second, the results hold only for the electricity industry. Although this industry is a large source of the economy's emissions, other industries should be studied as well. Finally, the results analyze primarily one pollutant: CO_2 emissions. Analysis of other pollutants is potentially confounded by changes in general regulatory stringency, since most other pollutants are themselves regulated. Nonetheless, other empirical strategies can perhaps overcome this difficulty.

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Appendix

Proof of Proposition 1:

Since the profit function is convex, its Hessian matrix is positive definite, so its main diagonal elements must be positive. Since the factor demands are the additive inverses of the first derivatives of the profit functions, the positive definite Hessian implies that the own-price effects are negative. Similarly, since the conditional factor demands are the derivatives of the concave cost function, the own-price substitution effects must be negative.

To show that the own-price output effect must be negative, decompose the output effect into:

$$\frac{dNOx^c}{dq}\frac{dq}{dp_{NOx}} = \frac{dNOx^c}{dq}\frac{dq(P = MC)}{dMC}\frac{dMC}{dp_{NOx}}$$

where MC is the marginal cost. Since quantity decreases when marginal cost increases, $\frac{dq(P=MC)}{dMC}$ is negative. For an inferior input, an increase in the input price can decrease marginal cost. But since

$$\frac{dNOx^c}{dq} = \frac{d^2c}{dq dp_{NOx}} = \frac{dMC}{dp_{NOx}}$$

the first and last factors must have the same sign even if the input is inferior. Thus the own-price output effect is negative.[36]

Since the cross-price effects are the off-diagonal elements of the matrix they can be either negative or positive. Moreover, if one of the inputs is an inferior input, then the cross-price output effect can be positive. ■

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[36] This argument follows Nicholson's well-known text.

Table 1: Counties with changes in attainment status for the 1-hour ozone standard from 1997-2004.

State	Changes in attainment status: County (# plants)
Alabama	2004 (A): Jefferson (1), Shelby (1)
California	1999 (NA): Alameda, Contra Costa (2), Marin, Napa, San Francisco (2), San Mateo, Santa Clara, W. Solano, Sonoma 2001(NA): E. Kern 2004(A): E. Kern, San Diego (8), Santa Barbara
Colorado	2002(A): Adams (1), Arapahoe, Boulder (2), Broomfield, Denver (3), Douglas, Jefferson
Illinois	2003(A): Madison (2), Monroe, St. Clair
Indiana	1998(A): Vanderburgh 2002(A): Clark, Floyd (1)
Kentucky	2002(A): Bullit, Jefferson (2), Oldham 2003(A): Boone (1), Campbell, Kenton
Louisiana	2002(A): Lafourche Par
Michigan	2001(A): Allegan (1), Bay (2), Genesee, Midland, Muskegon (1), Saginaw
Missouri	2003(A): Franklin (1), Jefferson (1), St Charles (1), St Louis, St Louis Co. (1)
Pennsylvania	2002(A): Allegheny (2), Armstrong (2), Beaver (1), Butler, Fayette (1), Washington (2), Westmoreland
Utah	1998(A): Davis, Salt Lake (1)
Virginia	1998(A): Charles City, Chesapeake (1), Chesterfield (1), Colonial Heights, Hampton, Hanover, Henrico (1), Hopewell, James City, Newport News, Norfolk, Poquoson, Portsmouth, Richmond, Suffolk, Virginia Beach, Williamsburg, York (1)
Wisconsin	2003(A): Door, Manitowoc (1)

Notes: The year indicates the year of the new attainment status. (A) indicates the county was designated as attaining the standard, and (NA) indicates that the county was designated as not attaining the standard. Source: http://www.epa.gov/air/oaqps/greenbk/anay.html.

Number of power plants in the county is from EGRID 2000. More recent plants added to California from EPA-CEMS.

Table 2: Power plants in California counties with changes in attainment status for the 1-hour ozone standard from 1997-2004.

County	Re-designation	Power Plants (# units, mean year online)
Contra Costa	Nonattainment Aug. 10, 1998	Contra Costa Power Plant (2, 1964) Pittsburg Power Plant (7, 1958)
San Francisco	Nonattainment Aug. 10, 1998	Hunters Point (1, 1958) Potrero Power Plant (1, 1973)
San Diego	Attainment July 28, 2003	Cabrillo Power I (Encina) (5, 1965) Duke Energy South Bay (4, 1966) Cal Peak Power - Border (1, 2002) Cal Peak Power - El Cajon (1, 2002) Cal Peak Power - Enterprise (1, 2002) Escondido Power Plant (2, 2001) Chula Vista Power Plant (2, 2002) Larkspur Energy Facility (2, 2001)

Notes: Mean year online, from EGRID, averages the starting years of the generators within the power plant. The five units at Hunters Point are combined since only one reports positive output.

Table 3: Means and standard deviations for California by unit aggregated to the month and day.

	Monthly	Daily
NOx lbs	24,073 (58,973)	1,297 (2,614)
CO2 tons	30,111 (38,140)	1,623 (1,526)
SO2 lbs	783 (12,439)	42 (583)
Megawatt hours	49,823 (67,057)	2,689 (2,740)
1-hour Ozone nonattainment	0.860 (0.347)	0.842 (0.365)
North Path 15	0.310 (0.462)	0.346 (0.476)
CO nonattainment	0.473 (0.499)	0.442 (0.497)
NO2 nonattainment	0.083 (0.276)	0.082 (0.274)
8-hr Ozone nonattainment	0.178 (0.382)	0.154 (0.361)
PM nonattainment	0.599 (0.490)	0.573 (0.495)
ARP: NOx Early Elect	0.008 (0.089)	0.006 (0.076)
ARP: SO2 Phase 2	0.746 (0.435)	0.735 (0.441)
Average temperature (NP15)		58.761 (10.189)
Average temperature (SP15)		65.040 (9.509)
N	8,239	152,642

Table 4: Main Results. California results for NOx, CO2, and SO2 emissions and Megawatt hours.

Panel A: Including other regulatory controls.

	$\ln(NO_X)$		$\ln(CO_2)$		$\ln(SO_2)$		ln(MWh)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Nonattain	-0.473**	-0.219*	-0.254	0.028	-0.304	-0.020	-0.314
	(0.209)	(0.132)	(0.202)	(0.047)	(0.170)	(0.129)	(0.205)
ln(MWh)		0.809**		0.900**		0.896**	
		(0.016)		(0.010)		(0.012)	
CO nonattain	0.158	-0.006	0.296	0.113	0.251	0.076	0.203
	(0.211)	(0.159)	(0.183)	(0.085)	(0.153)	(0.134)	(0.164)
NO2 nonattain	0.073	0.017	0.109	0.047	0.247	0.211**	0.069
	(0.260)	(0.135)	(0.277)	(0.034)	(0.247)	(0.080)	(0.291)
8hr Oz nonattain	0.172	0.045	0.182	0.041	0.495**	0.334	0.157
	(0.185)	(0.119)	(0.182)	(0.035)	(0.247)	(0.223)	(0.218)
ARP NOx Early Elect	0.068	-0.197**	0.242	-0.053	0.319	-0.003	0.328
	(0.511)	(0.098)	(0.624)	(0.046)	(0.630)	(0.067)	(0.651)

Panel B: Omitting other regulatory controls.

	$\ln(NO_X)$		$\ln(CO_2)$		$\ln(SO_2)$		ln(MWh)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Nonattain	-0.516**	-0.221*	-0.326*	0.003	-0.371**	-0.037	-0.365*
	(0.203)	(0.131)	(0.190)	(0.030)	(0.170)	(0.132)	(0.200)
ln(MWh)		0.809**		0.900**		0.897**	
		(0.016)		(0.010)		(0.013)	

Notes: 8,239 monthly observations for 178 generating units. (8,188 observations for the SO_2 regressions.)

Dependent variable is log of emissions or log of MWh of generation.

Regressions additionally control for market-year-month fixed effects, generating unit fixed effects, and generating unit linear trends.

Controls for other regulations: (CO, NO2, and 8-hour ozone nonattainment and ARP NOx Early Election) are not jointly significant in six of the seven regressions.

** indicates significance at the 5% level and * indicates significance at the 10% level.

Table 5: Early and late. California results for NOx, CO2, and SO2 emissions and Megawatt hours.

Panel A: Before 2000: 1997 to 2000. 3,022 observations with 96 units.

	ln(NO_X)		ln(CO_2)		ln(SO_2)		ln(MWh)
Nonattain	0.250	-0.098	0.387	0.020	0.291	-0.081	0.416
	(0.277)	(0.150)	(0.239)	(0.077)	(0.245)	(0.139)	(0.252)
ln(MWh)		0.836**		0.884**		0.896**	
		(0.027)		(0.017)		(0.019)	

Panel B: After 2000: 2001 to 2004. 5,217 observations for 174 units.

	ln(NO_X)		ln(CO_2)		ln(SO_2)		ln(MWh)
Nonattain	-0.450*	-0.274*	-0.265	-0.063	-0.782**	-0.587**	-0.224
	(0.252)	(0.140)	(0.244)	(0.040)	(0.229)	(0.146)	(0.246)
ln(MWh)		0.787**		0.907**		0.900**	
		(0.021)		(0.015)		(0.017)	

Note: Regressions additionally control for other regulations, for market-year-month fixed effects, for generating unit fixed effects, and for unit-specific linear trends.

Table 6: Old and new plants. California results for NOx, CO2, and SO2 emissions and Megawatt hours.

Panel A: Old plants (starting year before 1980). 5,566 observations with 89 units.

	ln(NO_X)		ln(CO_2)		ln(SO_2)		ln(MWh)
Nonattain	-0.715**	-0.297*	-0.462**	-0.011	-0.325*	0.124	-0.511**
	(0.230)	(0.159)	(0.198)	(0.020)	(0.174)	(0.140)	(0.222)
ln(MWh)		0.817**		0.883**		0.887**	
		(0.018)		(0.012)		(0.013)	

Panel B: New plants (starting year after 1995). 2,673 observations with 89 units.

	ln(NO_X)		ln(CO_2)		ln(SO_2)		ln(MWh)
Nonattain	0.154	0.090	0.044	-0.037	-0.536	-0.615*	0.085
	(0.445)	(0.279)	(0.507)	(0.053)	(0.517)	(0.364)	(0.495)
ln(MWh)		0.754**		0.957**		0.926**	
		(0.037)		(0.022)		(0.030)	

Note: Regressions additionally control for other regulations, for market-year-month fixed effects, for generating unit fixed effects, and for unit-specific linear trends.

Table 7: Plant and daily. California results for NOx, CO2, and SO2 emissions and Megawatt hours with generating unit fixed effects and fixed effect trends.

Panel A: By plant. 3,552 observations for 71 generating plants.

	ln(NO_X)		ln(CO_2)		ln(SO_2)		ln(MWh)
Nonattain	-0.110	-0.159	0.155	0.098	-0.021	-0.081	0.062
	(0.419)	(0.180)	(0.366)	(0.076)	(0.303)	(0.192)	(0.353)
ln(MWh)		0.803**		0.924**		0.899**	
		(0.033)		(0.020)		(0.024)	

Panel B: Daily observations. 152,642 observations for 178 units.

	ln(NO_X)		ln(CO_2)		ln(SO_2)		ln(MWh)
Nonattain	-0.536**	-0.285**	-0.230*	0.053	-0.341**	-0.077*	-0.346**
	(0.172)	(0.136)	(0.118)	(0.063)	(0.095)	(0.043)	(0.099)
ln(MWh)		0.727**		0.818**		0.794**	
		(0.020)		(0.010)		(0.013)	

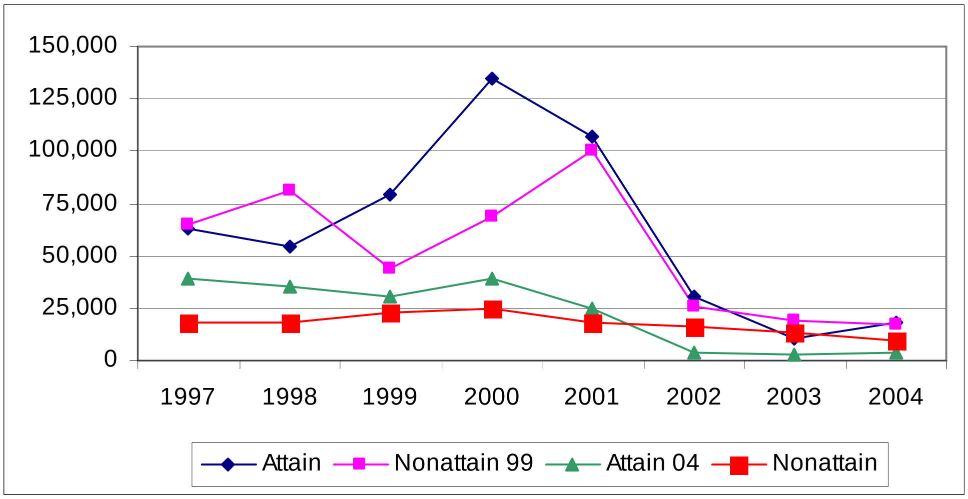
Notes: Regressions additionally control for other regulations, for market-year-month fixed effects, for generating unit fixed effects, and for unit-specific linear trends. Daily regressions additionally include a quadratic control for regional temperature.

Table 8: No trends. California results for NOx, CO2, and SO2 emissions and Megawatt hours without generating unit-specific linear trends.

	ln(NO_X)		ln(CO_2)		ln(SO_2)		ln(MWh)
Nonattain	-0.288	-0.067	-0.222*	0.022	-0.267	-0.019	-0.270**
	(0.191)	(0.166)	(0.120)	(0.034)	(0.169)	(0.128)	(0.121)
ln(MWh)		0.820**		0.906**		0.907**	
		(0.019)		(0.010)		(0.012)	

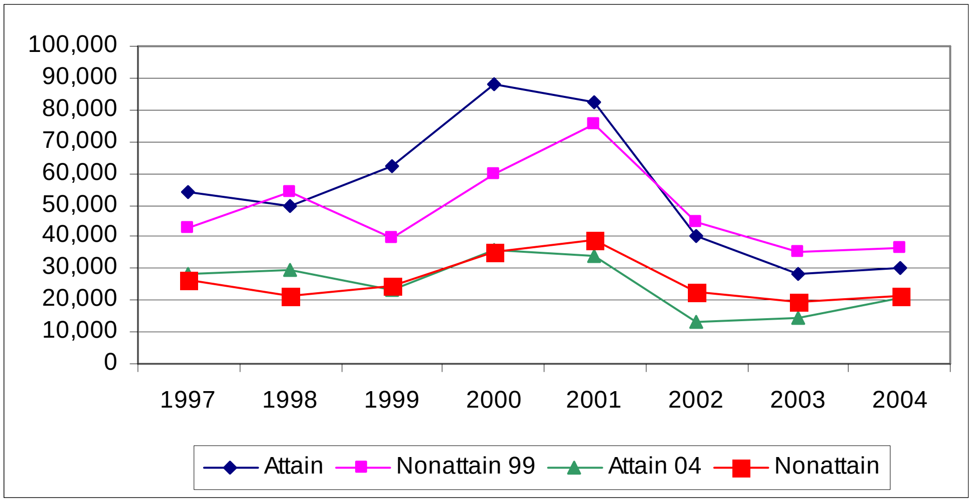
Notes: 8,239 monthly observations for 178 generating units. Regressions additionally control for other regulations, for market-year-month fixed effects, and for generating unit fixed effects.

Figure 1. Average monthly NO_x emissions at power plant units in California by attainment status.



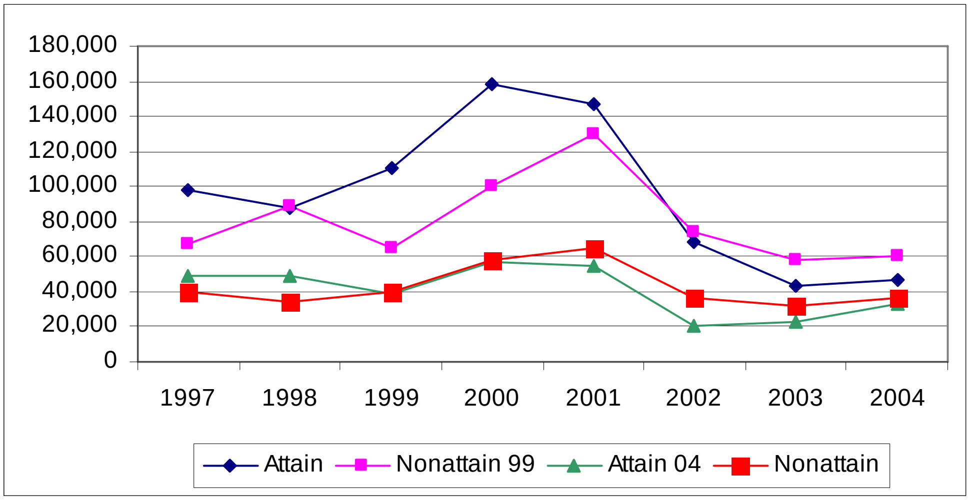
Notes: “Attain” are units which are always in attainment status; “Nonattain 99” are units which are redesignated as nonattainment in 1999; “Attain 04” are units which are redesignated as attainment in 2004; and “Nonattain” are units which are always in nonattainment status.

Figure 2: Average monthly CO_2 emissions at power plant units in California by attainment status.



Notes: “Attain” are units which are always in attainment status; “Nonattain 99” are units which are redesignated as nonattainment in 1999; “Attain 04” are units which are redesignated as attainment in 2004; and “Nonattain” are units which are always in nonattainment status.

Figure 3. Average monthly generation at power plant units in California by attainment status.



Notes: “Attain” are units which are always in attainment status; “Nonattain 99” are units which are redesignated as nonattainment in 1999; “Attain 04” are units which are redesignated as attainment in 2004; and “Nonattain” are units which are always in nonattainment status.