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Are Emission Performance Standards Effective in Pollution Control? Evidence from the EU's Large Combustion Plant Directive

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Are Emission Performance Standards Effective in Pollution Control? Evidence from the EU's Large Combustion Plant Directive

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Abstract

This paper explores the extent to which the Large Combustion Plant (LCP) Directive succeeded in mitigating local air pollutants from thermal electricity generating plants in the European Union. Using yearly data on plant-level operations from the EEA, we investigate whether emissions limits on stack concentrations were effective in cleaning emissions from existing combustion plants and a catalyst for improved environmental performance of new installations. We take advantage of the discontinuities in regulation status to show that the emission performance standards led to sizeable declines in SO_2, NOx, and particle dust concentrations at the stack level from older combustion plants. We also find suggestive evidence of anticipation effects from newer plants in response to tighter emission standards.

JEL Codes: Q53, Q58, K32

Keywords: Air pollution, Emission standards, Large combustion plant, EU

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1 Introduction

Fossil-fuel combustion for power generation is the largest source of global greenhouse gas emissions (GHG) and also a significant common source of local air pollutants. In the European Union (EU), the energy production and distribution sector is one of the major emitters of toxic pollutants such as sulfur dioxide (SO_2) and nitrogen oxides (NOx), which are known to damage ecosystems and detrimental to human health (EEA Report No 13/2017 on air quality). The European Commission adopted a number of command-and-control (CAC) instruments[1] to regulate emissions from thermal power plants, including the Large Combustion Plant (LCP) Directive which was intended to control emission intensities of SO_2, NOx, and particulate matter. The EU community also established its first cap-and-trade program, a multinational emissions trading scheme (EU ETS) to control carbon dioxide (CO_2) emissions, along with country-level caps on CO_2 emissions from all thermal combustion plants generating electricity larger than 20 MWth.

The body of research devoted to investigating the short-run effects of the EU ETS is growing and recent quasi-experimental work has used firm-level data to identify the causal impact of the EU carbon market on CO_2 emissions. Based on these micro-level studies, there is evidence that the EU ETS caused CO_2 emissions from industrial firms to fall between 10 and 26 percent as a result of the EU ETS regulation during Phase II, 2008-2012 (Martin et al. 2016). Currently, there is no such compelling evidence of the effect of EU ETS on emissions from the electricity sector. Studies using sector-level data estimate close to 3 percent reduction in emissions across all regulated sectors (Martin et al. 2016).

Although we do have some robust evidence on the effect of EU ETS on the abatement of GHG emissions, we know considerably less about the policy impact of overlapping command-and-control policies in the EU context which have been used for decades in controlling local pollutants from common sources of GHG emissions, e.g. fossil-fuel power plants. Quantifying the causal effects of conventional regulation such as the LCP directive is essential to accurately evaluating the benefits of such environmental instruments and (re-)designing them to meet the increasingly challenging climate policy goals in the future. For example, the Industrial Emissions Directive (IED 2010/75/EU) succeeds and tightens the provisions in the LCP directive

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[1] CAC instruments are a direct form of regulation in which the regulator specifies a target or a standard that a firm, plant, or locality must achieve – or face non-compliance penalties.

and the corresponding emission performance standards (EPS) were applicable to all existing combustion plants starting only in 2016.

This paper offers the first policy impact assessment of the Large Combustion Plants directive on flue emissions rates from thermal combustion plants in the European Union[2]. The LCP directive set mandatory minimum EPS for SO_2, NOx, and particle dust, which applied to all combustion plants with a rated thermal input of 50 MWth or more. We examine the following research questions in this paper: 1) How effective were the EPS under the LCP Directive in cleaning up emissions from the existing stock of EU combustion plants? 2) To what extent were more stringent EPS, applied to newer plants, effective in reducing emissions intensity of regulated local air pollutants? The key challenges in answering these questions are separating the effects of the LCP Directive from the 2008 economic crisis, the EU ETS, the National Emission Ceilings (NEC) Directive, the policy interaction with the Integrated Pollution Prevention and Control (IPPC) Directive, along with time-varying confounding factors leading to selection bias in estimating treatment effects.

A number of regulation-specific factors makes the LCP Directive an ideal policy to study the effectiveness of emission performance standards on the full population of combustion plants in the EU. First, the directive had three distinct regulation arms (Articles 4-1, 4-2, and 4-3) that were in effect starting January 2008 - regulation was differentiated across plants based on the operation licensing dates and this allowed us to construct plausible counterfactuals. Specifically, the directive took the form of a typical CAC regulation in which the prescribed emission limits are for more stringent for newer plants than for existing plants. Combustion plants that were brought into operation between July 1987 and than November 2003 were subject to lenient emission standards laid down in Article 4-1. Meanwhile newer plants that started to operate post November 2003 were subject to tighter emission limits values (ELVs) under Article 4-2. This variation in performance standards across plants facilitates a quasi-experimental research design that mitigates selection bias. We treat plants subject to the provisions under Article 4-1 as baseline, against which we compare emissions intensity of plants under Article 4(2) to

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[2] This paper does not assess the compliance rate of individual plants or Member States covered under the LCP regulation. However, it does provide an evaluation of whether the policy instrument succeeded in pollution control by the oldest thermal power operators and whether stricter emission standards were a significant catalyst for improved environmental performance. For a useful report on the subject of compliance, see Wynn and Coghe (2017). They assess emission concentrations from the dirtiest coal-fired power plants in Europe and discuss the implications that the new round of emission limits under the EU's Industrial Emission Directive have on their operation decisions.

answer whether newer plants are significantly cleaner than existing plants due to the policy. In the core empirical model, we find that tighter standards prompted newer plants to reduce NOx emission concentrations by about 9% after the policy deadline. No such changes were statistically significant for SO_2 and dust.

Second, the LCP directive differs from the usual vintage-differentiated regulation in the United States (see Stavins, 2006) because it does not exempt older plants from any form of regulatory intervention. All plants licensed before July 1987 were required under the provisions of Article 4-3 to either 1) take appropriate measures to achieve annual emissions concentrations established under Article 4-1, 2) be included under a national emission reduction plan (NERP), or 3) opt-out from emission limits values to instead limit operation hours to 20,000 and be required to shut down by the end of 2015. We treat opt-out plants as the control group and investigate the environmental performance of older plants that chose to comply with new environmental standards (ELV treatment). We find that average NOx, SO_2 and particle dust emission concentrations were 34%, 15%, and 24% lower respectively after the policy deadline.

Third, we also take into account the fact there is a time gap between when the directive was issued and the effective date of compliance, possibly giving rise to anticipation effects of the regulation. Since plant operators had perfect foresight of the EPS required under the LCP directive, that was in effect starting 2008, it is plausible that pre-trends in emissions concentrations could be indicative of the fact that operators made early retrofits in anticipation. Another strong reason for this is also the policy interaction between the LCPD and the IPPC directive - which required permits (necessitating compliance with emission performance standards) to operate new combustion plants or make changes to existing installations from 1999. Using a technique based on Malani and Reif (2015), we report quasi-myopic treatment estimates of the LCP directive. We find evidence that the anticipation of the LCPD and/or the IPPC caused emission concentrations of SO_2 and particle dust to respond to future treatment when estimating the effect of stringent standards on newer installations. Such ex-ante treatment effects were not detectable for older combustion plants regulated under Article 4-3.

To my knowledge, Meyer and Pac (2017) are the only ones to empirically explore the consequences of the LCPD regulation in the European Union. They focus on correlation rather than causation, however. Their results suggest that higher coal or lignite fuel input at power-generating plants was associated with a lower probability of opting out of the emission-rate standards applied to all combustion plants operating before 1987.[3] We go beyond the analysis found in Meyer and Pac (2017) and compare emissions concentrations of installations that opted-out to those that chose to comply with performance standards.

In the next section, we briefly review the empirical literature concerning air quality control using emission-rate standards. The remainder of the paper is organized as follows: Section 3 provides a detailed description of the Large Combustion Plant Directive and other overlapping policies that were in force during the same regulation period. Section 4 describes the data from the EEA, while Section 5 presents the identification strategy employed in the research design. Sections 6 and 7 explains our findings and provides falsification tests respectively. Finally section 8 discusses the results and concludes.

2 Related Literature

In the last two decades, there has been a notable increase in research evaluating policy for environmental protection. The design of empirical studies emphasizes causal inference by comparing group of regulated (treated) firms with a comparable (control) group of firms that were not subject to the treatment. As a result, we now have an improved perspective on the causal effects of environmental policy instruments that addresses industrial pollution. The literature evaluating the effectiveness of emission performance standards has been extensive.

A large majority of these studies use the spatial variation in the implementation of the US Clean Air Act (CAA) to evaluate the effect of air quality regulation under the CAA framework. As a result, many regulation categories of the Clean Air Act have come under empirical evaluation. Greenstone (2004) shows that by the end of 1970s most of the US counties were in compliance with the National Ambient Air Quality Standards (NAAQS) for SO_2 concentrations. But the author finds that whether a county came under SO_2 regulation (nonattainment status) under the Clean Air Act did not play a major role in the improvement of ambient

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[3] Considering that many of these combustion plants had multi-fuel input, I redo their analysis using plant-level input shares of fuel type (solid fuels, natural gas, liquid fuels, other gases, biomass) as predictor variables instead of absolute fuel inputs in petajoules. I find that relative to natural gas combustion, a higher share of coal, lignite, or liquid fuel was associated with an increased likelihood of being opted out of emission limits values - which is opposite of the result found in Meyer and Pac (2017). This may imply that some operators of coal and lignite plants found that returns to eventual shutdown by the end of 2015 were higher than investing in costly retrofits to comply with the emission limits values in the LCPD.

air quality for sulfur dioxide. While Chay and Greenstone (2003) demonstrate that total suspended particles (TSPs) pollution fell dramatically in the early 1970s and that these large changes in ambient TSPs concentrations were regulation induced. Henderson (1996) documents that nonattainment counties successfully reduced ozone concentrations relative to attainment counties. Nevertheless, the regulation may have had unintended and costly consequences due the non-uniform implementation of the environmental regulation across the US. Becker and Henderson (2000) and Henderson (1996) find evidence of a reduction in the number of polluting plants in regulated counties and a shift over time of industrial plants to unregulated counties. That is, the industries affected by the regulation slowly relocated their activities to areas that were less polluted (attainment counties) and therefore evaded regulation requirements to install the cleanest available technology.

Harrison et al. (2015) investigate the effectiveness of the Indian Supreme Court Action Plans (SCAP) and price incentives via fuel taxes to reduce coal use and promote SO_2 pollution abatement technology. Using a comprehensive industrial plant-level dataset, they find that higher coal prices led to a significant reduction in coal use as an input into production across plants. However, they further find that the SCAP were only successful in targeting large highly polluting installations. Greenstone and Hanna (2014) use city-level data to evaluate the impact of the SCAP and the Mandated Catalytic Converters. They provide evidence that air pollution regulation resulted in observable improvements in air quality. A recent paper looks at the extent to which Chinese power plants react to tighter SO_2 emission-rate standards and find that the response to the regulation was swift, with average SO_2 stack concentrations (in mg per Nm^3) falling by 13.9%.

Wätzold (2004) assesses the success of the highly ambitious SO_2 emissions limits (for both new and existing large combustion plants) of the Ordinance on Large Combustion Plants in 1983 (GFA-VO) in Germany[4]. Along with the regulatory provisions of the GFA-VO, the government of North Rhein Westfalen (NRW, the largest German state) was able to negotiate a voluntary agreement with the electricity suppliers in NRW to limit SO_2 and NOx emissions from new and existing plants. Wätzold documents that these policy initiatives led to the installation of flue-gas desulfurization (FGD) technology in the entire fleet of combustion plants regulated in

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[4] The GFA-VO and a comparable program in Netherlands (Dutch Bees WLV 1987) are considered to be model initiatives for the LCP directive.

Germany. That, is the policy was successful in the quick and uniform diffusion of state-of-the-art abatement technology.

For the purposes of policy design, if the emission-rate or technology standards for regulated pollutants only apply to new rather than existing polluting sources, there is a concern that such a policy-exemption rule, often referred to as "grandfathering", could encourage the operation of plants that are older and dirtier over the longer run. One such policy is the New Source Performance Standards (NSPS) introduced under the 1970 Clean Air Act in the US. The NSPS featured emission-based standards for only new sources and mandated up to a 90% reduction in SO2 emissions from earlier pre-regulated levels. Empirical studies validate that the mandated investment in scrubbers increased operation costs of new plants, which led the operators to utilize older unregulated plants at higher capacity (Stavins, 2006) and delayed re-investment in existing plants to avoid triggering the Clean Air Act requirements (Bushnell and Wolfram 2012). Although the LCP directive did not require stringent desulfurization or denitrification from the (older) existing polluting plants, it did nevertheless impose either lenient standards on the stack concentrations or limited operations. We will investigate the effectiveness of this specific design feature of the LCP directive in the analysis.

3 Policy Context

The LCP directive was first adopted by the European Council in 1988[5], subsequently amended in 1994[6], and then revised on the 23th October of 2001[7]. While the structure of regulation has more or less remained the same since initial implementation, the performance standards are stricter with each revision. The directive specifies upper limits for the emission intensity of SO2, NOx and particulate matter (dust) that each regulated combustion plant could emit each year. Until January 2005, installations had to comply with the 1988 directive, while the 2001 Large Combustion Plant Directive kicked into effect starting January 2008 and its validity ended on 31st December 2015.

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[5] Directive on limitation of emissions of certain pollutants in to the air from large combustion plants, 88/609/EEC, Official Journal L336, 7.12.1988.

[6] Amending Directive 88/609/EEC on the limitation of emissions of certain pollutants into the air from large combustion plants, 94/66/EC, Official Journal L337, 24.12.1994.

[7] Directive on limitation of emissions of certain pollutants in to the air from large combustion plants, 94/66/EC, Official Journal L309, 27.11.2001.

Figure 1: Licensing Date and Plant Status under the LCP Directive

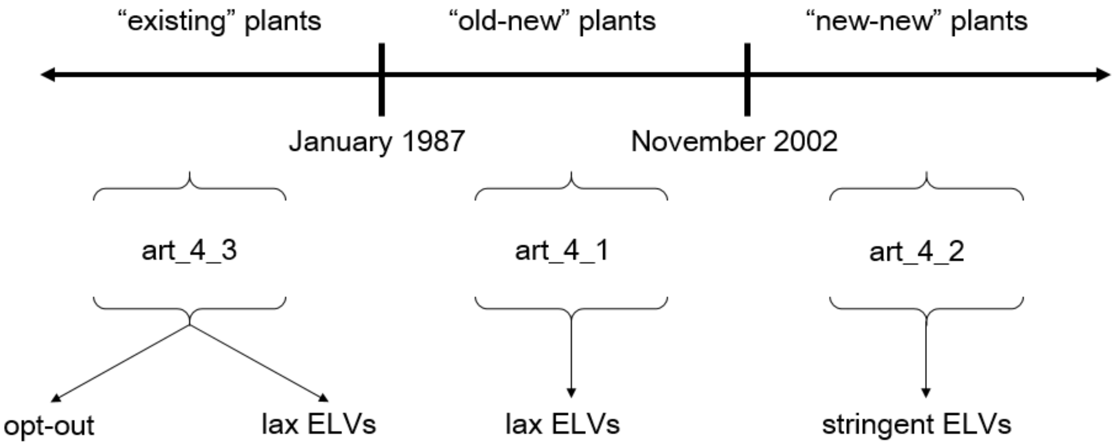

Figure 1 is a pictorial description of regulatory provisions under the LCP directive. A plant that could prove that the construction licence was granted before 27.11.2002 and that the plant went into operation before 27.11.2003 is referred to as an "old-new" plant and was subject to provisions under article 4(1) of the directive. Plants that came into operation after 27.11.2003 are referred to as "new-new" plants, subject to provisions under article 4(2) of the directive, and exposed to significantly more stringent regulations than the "old-new" plants or "existing" plants. Significant emission reductions were required from "existing plants" that were licensed before 1 July 1987 via either the national emission reduction plan or meeting the emission limit values set for "old-new" plants under article 4(1). Existing power stations (older than 1987) could "opt-in" and be subject to lenient emission standards or "opt-out" and instead reduce their operation hours and eventually shutdown.[8] In the analysis that follows, we seek to quantify the impact of emission rules on polluting behavior at the plant level.

Tables 1 to 3 summarize the emission limit values for SO_2, NOx, and particle dust that were set to be achieved by January of 2008. The emission limit values of the controlled pollutants varied in intensity depending on whether the plant was subject to article 4(1) or article 4(2) of the directive. As evident from the tables, new combustion plants regulated under article 4(2) have significantly tighter emission limit values (stricter compliance standards) than do existing plants under article 4(1). Moreover, these performance standards vary by the type of fuel input

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[8] Note that there were comparable national programs (e.g. GFA-VO 1983 in Germany, and Dutch Bees WLV 1987 in Netherlands) in place, before the EU level LCP directive. We do not expect these older policies to bias our results as we have no reason to believe that they affect article 4-1 and article 4-1 plants differentially post-2007.

(solid, liquid, or gaseous) and size of the plant as measured thermal megawatt (MWth) of the plant.

During the same regulation period, the European Parliament set national emission ceilings (NEC) for absolute emissions (in kilotonnes) for sulphur dioxide, nitrogen oxides, volatile organic compounds and ammonia for each of 15 EU member states[9]. These targets were to be achieved between 1990 and 2010. Furthermore, these emissions targets were not sector-specific: that is, they could have been achieved cumulatively by reductions in the transport, agriculture, waste, commercial, energy production, and industrial sectors.

While we focus our analysis of the LCP directive only on the energy production and distribution sector and look at emissions intensity rather than absolute emissions, the reader may have residual concern that the NEC targets could bias the estimates for the LCP directive. This may be true only if we have reason to believe that the NEC targets affected plants regulated article 4(1) differentially from plants that were regulated to article 4(2). Similarly, NEC targets are only a concern if opt-out plants reacted differently from plants that chose to comply with ELVs. Figure 2 shows that absolute emissions from the energy production and distribution sector fell at a much higher rate in 2008 and 2009. It is important therefore to focus the analysis on emissions intensity rather than absolute emissions to correctly estimate the impact of the LCP directive. To allay still any residual concerns, we will impose country-specific fixed effects in emissions intensity to capture possible confounding effects of the NEC regulation targets and year-specific to pick up time-specific unobservables.

4 Data

The data on combustion activities comes from the European Environment Agency (EEA), which started an inventory of reported emissions from large combustion plants starting in 2004[10]. The database covers all plants with a rated thermal input of at least 50 MWth operating in the European Union, covering 27 countries in 2004 and reaching 29 countries by 2015. For each plant, the database reports detailed information on their operations including capacity,

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[9] Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, and the U.K.

[10] Since the data is retrieved from one common source, EEA, we expect that the data is comparable across countries.

energy input, fuel input by type, emissions of local pollutants, date of operation start, and regulation status under the LCPD, including whether the plant opted-out. In addition, the inventory also collects plant identifiers (e.g. name, parent company, location, address) and also classifies the industrial sector in which the plant operates. There are six industry classifications provided: Electricity Supply Industry, Combined Heat and Power, District Heating, Iron and Steel, Refineries, and Other (Paper, Sugar, Chemicals, etc). However, there are many plants that remain unidentified in terms of industry throughout the panel.[11]

The status of the plant under the LCP directive is central to the assessment of whether a combustion plant is in compliance with the regulation. However, Germany and Sweden do not report the regulation status of their combustion plants to the EEA. To circumvent this lack of information, we impute the regulation status using the start date of operation. Still, the information on the start date of operation is unavailable for all plants in the sample, and therefore we are unable to use all available data for Germany and Sweden in our estimations. Table 4 shows the breakdown of the number of plants by regulation status in each EU country, including where unknown.

Moreover, there were no plants that opted-out of emission-rate standards from Austria, Czech Republic, Germany, Denmark, Hungary, Croatia, Kosovo, Ireland, Lithuania, Latvia, Netherlands, and Sweden. Due to lack of control plants, we exclude these countries from the estimation sample when exploring the impact of emission standards on units regulated under Article 4-3. Table 4 shows the breakdown of plants by regulation status for each country[12].

4.1 Calculation of Emissions Intensity

For the dependent variable, we combine information on raw fuel usage (in petajoules) with tonnes emissions to construct our outcome variable of interest, emissions intensity. The LCP regulation expresses the emission limit values in milligrams per cubic meter (mg per Nm^3). Since the EEA only provides absolute emissions of NOx, SO_2, and dust as reported by the plants, we convert tonnes emissions into flow rates (mg per Nm^3). To do this we need estimates of the flue rates associated with specific fuel types. We start with using flue rates assumptions

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[11] I used reported information online from the the European Pollutant Release and Transfer Register (E-PRTR) to improve the precision and coverage of the industry classification.

[12] I am in contact with the EEA to get more information on the date plant operations began in order to learn about the regulation status of plants under the "Unknown" column

provided in the study by Wynn et al. (2017). We check whether our estimates are sensitive to assumptions involved in the calculation of the flue rates and this is not the case. We also conduct sensitivity analysis by defining emissions intensity as emissions divided by total fuel input - our results are strongly robust to this and quantitative conclusions remain the same.

4.2 Historic Trends in Emissions Intensity

In Figure 3 graphs the emissions intensity grouped by concentration intensity from very high to low for all large combustion plants reported in the EEA database. Emissions intensity of regulated pollutants were on a declining trend - the combustion activities are cleaner in 2015 as compared to 2004. But we can also see that emission intensities have not come down much further since 2012. The darkest grey area represents the share of total capacity (measured by summing all plant-level MWth) that emitted pollutant concentrations above the tightest standards for solid fuels in Article 4-2. The graphs show that close to a quarter of the system in 2015 was still emitting concentrations of regulated local pollutants that are likely to not comply with even tighter standards in the future (under the IED).

The emission concentrations follow similar trends for NOx, SO_2, and dust, including the noticeable drop post-2007, same as the policy deadline for the LCP directive. Based on such observations of trends, it is hard to know the cause of the correlated declines in these three air pollutants.

4.3 Pre-treatment Statistics

Table 5 shows pre-treatment differences in means for the key variables between those plants that opted-out versus those that chose to comply with emission limits under Article 4-3. The table suggests that on average opt-out plants were much larger in size (as measured by MWth) and used more solid fuels (excluding biomass) and liquid fuels as a share of the total energy input. On the other hand, plants that chose to comply with the emission limit values were on average using more gaseous fuels and biomass as a share of total energy input. We will control for the size of the plant and construct the dependent variable (emission intensity) using information on specific-fuel input and their associated flue rates. Fuel-switching is one of the mechanisms using which plants seek to comply with emission-performance standards. For this reason, we will avoid controlling for time-varying plant-level fuel controls such as fuel type shares to avoid post-treatment bias.

Table 6 presents pre-treatment differences in means for the key variables between plants regulated under Article 4-1 Article 4-2. The variables shown appear to be similar in distribution. Overall, pre-treatment balance on these variables is relatively stable across years as well (not shown here). Nevertheless, in order to interpret the estimates as casual impacts of LCPD, it is necessary to have common trends in emission concentrations.

5 Empirical Strategy

In an ideal research setting we would have that the policy treatment was randomly assigned to plants such that regulatory status was independent of all possible factors affecting plant-level emissions - this is not the case. Moreover, we do not have emissions data on plants that were not regulated under the directive, i.e. all combustion plants with a rated thermal input less than 50MWth. To construct plausible counter-factuals, we look in the implementation details of the regulation within the set of plants under regulation.

We take advantage of the variation across the three vintage-differentiated regulatory arms of the directive to assess the impact of emission performance standards using a difference-in-differences (DiD) framework. 1) To investigate the effect of EPS on older plants (regulated under Article 4-3), we treat plants that opted-out as the control group and plants that chose to meet the emission-rates as the treatment group. 2) The identification of the impact of tighter standards on newer plants comes from the change in emission intensity of Article 4-2 units, starting in 2008, the last date to comply, compared with changes for Article 4-1 units. We require that any unobserved factors specific to plants under different regulation status that affect emissions intensity are constant over time. This is certainly true for plant-vintage, which is captured crucially by the plant-fixed effects.

The base specification is a DiD equation, which uses the reported emissions before the policy deadline (2004 to 2007) for pre-treatment data. Main estimation equation is the following:

$$y_{pt} = \alpha_p + \eta_t + \beta_0 \, D_{pt} + \theta_{ct} + \boldsymbol{\gamma} \cdot \mathbf{X}_{pt} + \phi_{it} + \boldsymbol{\lambda}_{rc} \cdot (\delta_{rc} \times t) + \epsilon_{pt} \tag{1}$$

where we expect the regulation to be in effect during the period from 2008 to 2015. y_{pt} is the log of emissions intensity at plant p in year t. β_0 captures the regulatory effect on emission concentrations at the stack level. All time-invariant confounders that capture plant-level features such as plant vintage and fuel technology are captured by the plant-level fixed effects α_p, and η_t absorbs year-specific shocks that are common across plants. θ_{ct} and ϕ_{it} are country-year and industry-year fixed effects respectively. $\mathbf{X}_{pt}$ includes time-varying controls such as plant capacity (GWth) and indicators for whether the plant has a gas engine or a diesel engine.

Finally, to account for the considerable heterogeneity (unevenness) in the implementation of the LCPD policy across countries, we also use regulation-specific linear trends ($\delta_{rc} \times t$) that are allowed to vary by country. This is in addition to the country-specific fixed effects to allow for time-varying differences in the policy environment across countries. Note that we do not control for fuel-type shares in our preferred estimation equation because it would lead to post-treatment estimation bias. This is because fuel-switching (e.g. substituting natural gas for other fossil-fuels, particularly coal) is an important option for thermal operators to meet the requirements of the LCP directive.

5.1 Identifying Assumptions

Here we will address the main identifying assumptions. Due to the fixed effects, the identification in the core empirical model comes from within-plant variation. For difference-in-differences specifications, we require that the Stable Unit Treatment Value Assumption (SUTVA) is met: that the treatment status of a regulated unit p does not impact the outcome of units other than p. Although it is in the operator's interest to minimize costs of operation, SUTVA could be violated if the parent company that owns multiple units chooses to retrofit all plants irrespective of regulation status. The potential biases due to such regulation spillovers can be signed. Namely, we provide lower-bounds of the true effect of EPS under the LCP directive.

We also require common trends: that the emissions intensity outcomes of treated plants would have followed similar trends to those of the control plants in absence of treatment. It is not possible to test this directly, but we provide tests to diagnose this. Figure 4 demonstrates a favorable picture for pre-treatment trends in outcomes for Article 4-3 plants that opted out versus those that chose emission limit values. Note that here we exclude plants from countries that did not have any opt-out plants.

From Figure 5, we see that the requirement of parallel trends does not hold because trends in emissions intensity of article 4(1) plants differ from that of article 4(2) plants during the pre-treatment period (i.e. before 2008), most notably for NOx. To the extent that the long-term trends are correlated with fixed-observable characteristics of the plants, we can control for any biases in the unconditional DID estimate by adjusting for differences in observable covariates. We will also capture time-varying unobservables and use regulation-specific trends to strengthen the conditional DiD identification assumption. Generally, threats to identification exist only if emission concentrations from plants in the treatment and controls groups are affected differentially and we are unable to control for it. Take for example the EU ETS, after conditioning on the size of the plant (GWth), we do not have a strong reason to believe that the trading market would confound our estimates of the impact of the LCPD.

6 Emissions Control Under Article 4-3

6.1 Main Results

We estimate the effect of emission-rate standards under Article 4-3 in Tables 7 - 9. The identification only uses plants from countries that had at any opt-out plants. These are 16 EU countries, with a total of 223 plants opting out of Article 4-3.

The tables shows six different specifications for quantifying the impact of ELVs on emission-intensity at the plant level. Column (1) is the simplest model, including only the interaction term of interest (Post 2007)*(ELVs), time and plant fixed effects, and operation controls such as plant capacity (GWth) and indicators for whether the plant includes a gas turbine, boiler, or is part of a refinery. In order to control for time-varying unobservables, we include country-by-year fixed effects in Columns (2) and (2) respectively. Columns (5) shows estimates equation (1), which is our preferred specification, and controls regulation-specific linear trends that are allowed to differ by country. In Table 7, we see a negative change in NOx emission concentrations but the estimate is insignificant. In Tables 8 and 9, we find that emission-rate standards prompted plants under Article 4-3 to reduce SO_2 emission concentrations by close to 34% and dust concentrations by 24% relative to opt-out firms.

To allay concerns that the differences in the distribution of covariates concerning fuel usage are driving the results, we add fuel controls in Column 6. The difference in the estimates from Columns 5 and 6 provide some indication of the importance of fuel-switching for older plants due to the emission-rates standards. I also run the preferred specifications on absolute emission levels and find similar results at those for emission concentrations, just discussed.

6.2 Balancing Tests

We showed in Table 5 that there were differences in the distribution of key covariates between treatment and control groups prior to the policy deadline. To assure the reader that these differences were stable over time and that the changes in emissions intensity are not associated with changes in the distribution of covariates, we estimate covariate balance regression. To test for compositional changes, we simply replace the outcome variable with the covariate of concern in our preferred model (in Column 5). We fit the model on total energy input in petajoules, the share fuel input that was solid, liquid, natural gas, and biomass. We are unable to reject the null hypotheses that there are no compositional changes post-treatment[13].

6.3 Falsification Tests

Here we repeat the analyses in Tables 7 to 9 using different hypothetical policy timings of the LCP directive. Specifically, I try both 2006 and 2007 dates as a falsification test since these dates did not coincide with any changes in regulation. We stick to the preferred specification in equation (1)[14]. As expected, estimated effects on emission concentrations of all three pollutants are close to zero and statistically insignificant. See Table 10 for the results. This gives us assurance that the effects observed are prompted by the emission performance standards under Article 4-3, rather than something else unobserved.

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[13] Regression tables for these specifications are available upon request

[14] The inclusion of fuel controls do not change the result.

7 Impact of Article 4-2 Versus Article 4-1

7.1 Main Results

Now we turn to estimating the effect of tighter emission limits under Article 4-2 versus Article 4-1. The identification uses all plants for which we have data. Tables 11 to 13 display the same specifications as in Tables 7 to 9. Focusing on our preferred model, Column (5) in Table 11 suggests that NOx emissions concentrations fell by 9% as a result of tighter emission-rate standards under Article 4-2, although this estimate is not statistically significant. Tables 12 to 13 provide some evidence that Article 4-2 did not lead to reductions in plant-level stack concentrations of SO_2 and dust post-compliance deadline.

Given that we are comparing plants regulated under lenient versus tighter standards, an absence of treatment effect could be interpreted as the following: 1) There may have been uniform compliance strategy. That is, regardless of regulation status of Article 4-1 or 4-2, combustion plants subject to regulation switched to comparable technology specific to the fuel type and operations. In this case, tighter emissions standards would not make a significant impact on emission reductions.

2) New plants that start to operate after November 2002 anticipate the regulation, which means that the policy was effective well before 2008. In what follows, we carry out separate estimates under the assumption that the LCP provisions were anticipated by new plants.

7.2 Anticipation Effects

In this section, we explore the possibility that the emission performance standards were anticipated by regulated units and the quasi-myopic model is based on Malani and Reif (2015).

Anticipation is reasonable if 1) plant operators are forward-looking and have access to information on future compliance requirements, 2) there are costs for plant operators to delay retrofitting plants to reduce non-carbon pollution, 3) policy interaction with the IPPC requires that new units use best available technology for environmental standards. Moreover, we consider it difficult to rule out anticipation as one of the explanations for the significant declines in emission intensity of NOx by treated plants before the LCPD deadline, as shown in Figure 5.

The quasi-myopic model accounts for anticipation using leading indicators for the compliance deadline. We estimate the following equation with maximum 3 leading indicators, adding one more leading indicator in each subsequent specification:

$$y_{pt} = \alpha_p + \eta_t + \beta_0^{quasi}\, D_{pt} + \sum_{j=1}^{3} \beta_j^{quasi}\, D_{p,t+j} + \boldsymbol{\gamma} \cdot \mathbf{X}_{pt} + \theta_{ct} + \phi_{it} + \boldsymbol{\lambda}_{rc} \cdot (\delta_{rc} \times t) + \epsilon_{pt} \qquad (2)$$

where β_j^{quasi} captures the ex-ante treatment effect in period j before policy deadline and β_0^{quasi} captures the ex post effect. This model assumes that anticipation over a time horizon greater than 3 years do not matter. If this assumption does not hold, our estimates are inconsistent. Since we are limited to 3 years due to data limitations and have reason to believe that the time horizon is indeed longer than 3 years, we take these results as suggestive evidence of anticipation.

Tables 14 report estimates for equation (2), quasi-myopic model that accounts for anticipation. Column (1) in Table 14 shows the ex-post treatment effect under the assumption of no anticipation (myopic model). Estimated ex post and ex ante treatment effects on NOx concentrations for the quasi-myopic plant operator are all statistically insignificant in Columns (2) to (4). Table 15 shows that all coefficient estimates for ex-ante treatment effects on SO_2 concentrations were statistically different from zero with large anticipation effects found in period $t-2$ and $t-3$. Similarly in period $t-3$, ex-ante quasi-myopic treatment estimates for dust concentration are over 50% and statistically significant (see Table 16).

We also estimate the same quasi-myopic model to diagnose whether anticipation played any role for old plants complying with the emission limit values under Article 4-3 and the estimates generally yield insignificant ex-ante effects. This evidence is consistent with the fact that the IPPC was not a requirement for units that started operating pre-1987 and therefore older plants had no incentive to comply pre-deadline.

Table 17 reports estimates of the ex-post treatment effect from the quasi-myopic model for NOx concentrations. Columns (2) to (4) show that adding an additional leading indicator for the regulation increases the ex-post treatment effect found from the myopic model in Column (1) - and these estimates are statistically significant. This is indication that estimates from the myopic model are prone to bias.[15]

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[15] I do not report ex-post effects from the quasi-myopic model looking at changes in SO_2 and dust concen-

7.3 Placebo Outcomes

In this section, we do more falsification tests using alternative placebo outcomes that are not supposed to be affected by the treatment. To be precise, the outcomes of units regulated under Articles 4-2 versus 4-1 should not should not be affected differentially. We use fuel input shares and total energy input as the dependent variables and do not find any statistically significant effects.

8 Further Robustness Checks

Here we address the possibility that results discussed in the previous section are due to another factor that we may have not considered.

8.1 Alternative Treatment and Control Groups

It is important to show that the results are robust to alternative treatment and control groups. The reader might be worried that it is simply that newer plants are cleaner than the older ones - that a remaining confounding factor might be newer technology. We expect that plant vintage or time-invariant fuel-technology should be captured by the plant-fixed effects and trend variables already. Nevertheless, we rerun the estimations using Article 4-1 as the treatment regulation, and for the control group we use Article 4-3 plants that chose to comply with article 4-1 standards. Then the difference between these two groups should not be the regulation but rather improvements in technology. Once we control for plant-fixed effects, we do not expect to find (post-compliance deadline) that on plants under Article 4-1 provisions are significantly cleaner than those that opt-in under Article 4-3.

Table 18 demonstrates that there are no significant differences in emission intensities of local pollutants between the treatment and control groups.

These results provide further evidence that we are correctly attributing the effects we find to emission performance standards under the LCP directive. Indeed our preferred specification is capturing the effect of tighter emission standards under Article 4-2.

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trations because the ex-post treatment estimates are similar to those from the myopic model. The tables from quasi-myopic model are available upon request.

9 Conclusion

Effective pollution control in the complex regulatory context of the European Union is an important decision and the Large Combustion Plant Directive was a major EU environmental regulation. This paper offers the first policy impact assessment of the LCP directive and uses micro data for the full population of regulated large combustion plants to estimate causal changes in emissions intensity at the plant-level. We demonstrate that older units (operating before 1987) complying with new emission performance standards were significantly cleaner (as measured by SO_2 and dust emission concentrations) than those that opted-out of the directive. Furthermore, tighter ELVs under Article 4-2 prompted new plants (operating after 2002) to reduce NOx concentrations by the compliance deadline. It remains unclear whether tighter standards applied to new plants had an economically meaningful impact on other measures of emission concentrations, however. The results are robust to a range of specifications and falsification tests, so that we can be confident that we are accurately attributing the findings to variations in emission limits values under the Large Combustion Plant directive. This paper also considers the possibility that newer plants (that start to operated post-2002) were not as myopic in complying with the performance standards as we would assume. We have strong priors to believe this because of the policy interaction between the LCPD and the IPPC directive, which required new units and those undergoing "substantial changes" to meet technology standards starting 30 October 1999. Overall, evidence from this empirical study in this paper suggests that the LCP directive was an effective instrument in pollution abatement at the stack-level.

[Refer to Wynn (2017) paper and talk about the recommendation in the policy report vis-a-vis top polluting non-compliant fossil-fuel power plants still operating in the EU.]

Whether the LCP directive created a perverse incentive for older power stations to continue highly polluting operations remains an empirical question. A uniform policy with respect to plant vintage is more likely to encourage investment by incumbents towards cleaner equipment earlier in the regulation period. The "grandfathering" convention was partially present in the LCP directive, because it allowed a large share of older installations to continue operations without requiring stringent emission-rate standards. Although politically more feasible, this had the potential to worsens pollution over the longer-run by encouraging the operation of power stations that are older and dirtier. We find that those that chose to opt-out of the directive and eventually shutdown by the end of 2015 were more likely to be coal and lignite power plants. Future research should investigate whether the LCP directive gave rise to the "old-plant" effect, deferring plant shutdowns or replacements that would otherwise be crucial for environment protection.

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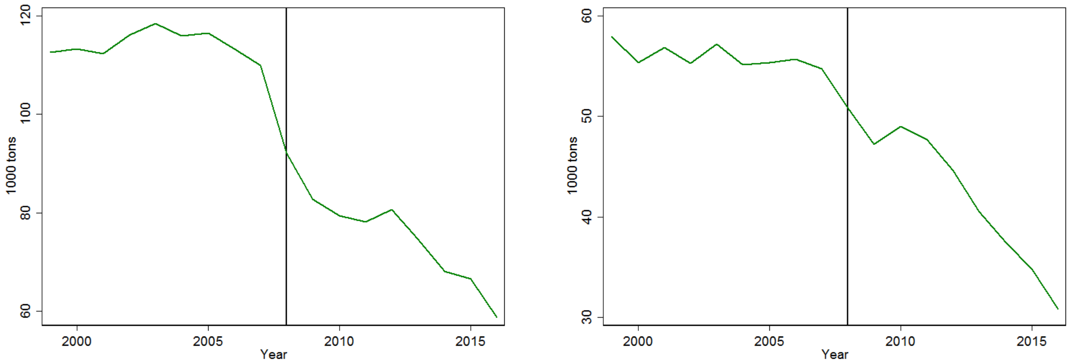
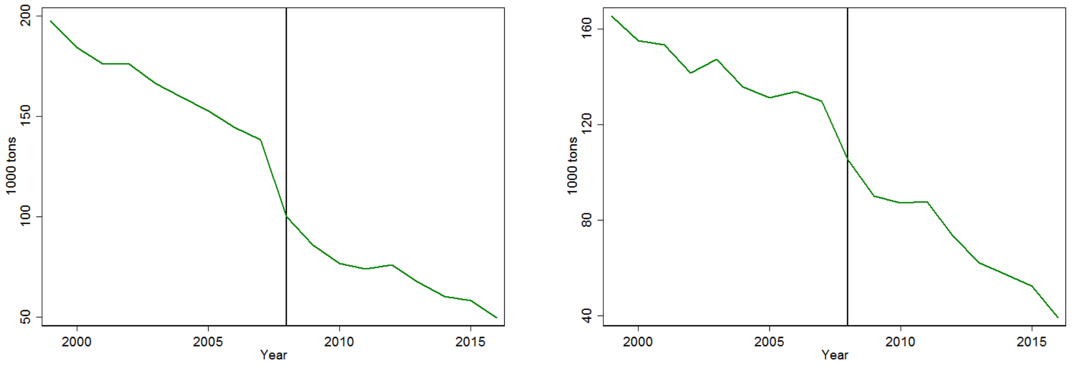
Figure 2: Trends in Absolute Emissions by EU Region



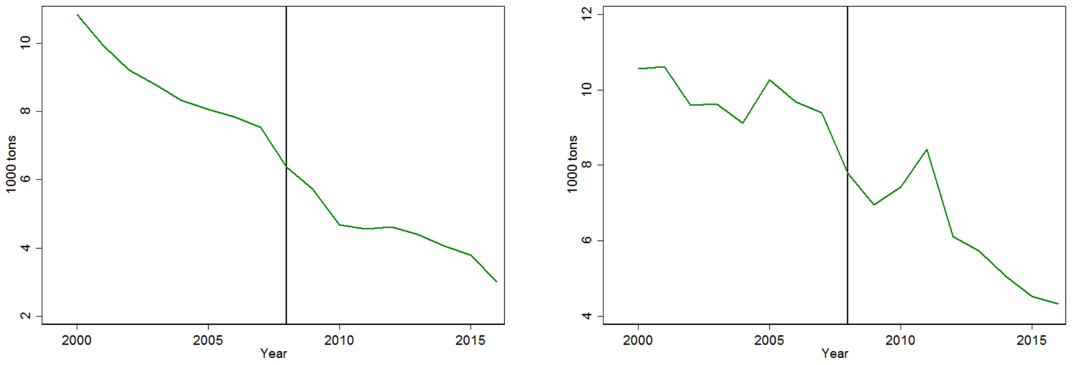
(a) NOx emissions in Western EU

(b) NOx emissions in Eastern EU



(c) SO2 emissions in Western EU

(d) SO2 emissions in Eastern EU



(e) PM10 emissions in Western EU

(f) PM10 emissions in Eastern EU

Note: Data come from the air emission inventories (EEA, Eurostat), which provides annual data on air pollutants by source sector. The figures plot the trends in absolute emissions from the energy production and distribution sector. Eastern EU region consists of Romania, Czech Republic, Hungary, Lithuania, Poland, Slovakia, Slovenia, Bulgaria, Cyprus, Estonia, Malta, Latvia. Western EU region consists of the remaining 16 EU countries. The vertical black line is to mark year 2008.

Figure 3: How Dirty are EU's Thermal Combustion Plants?

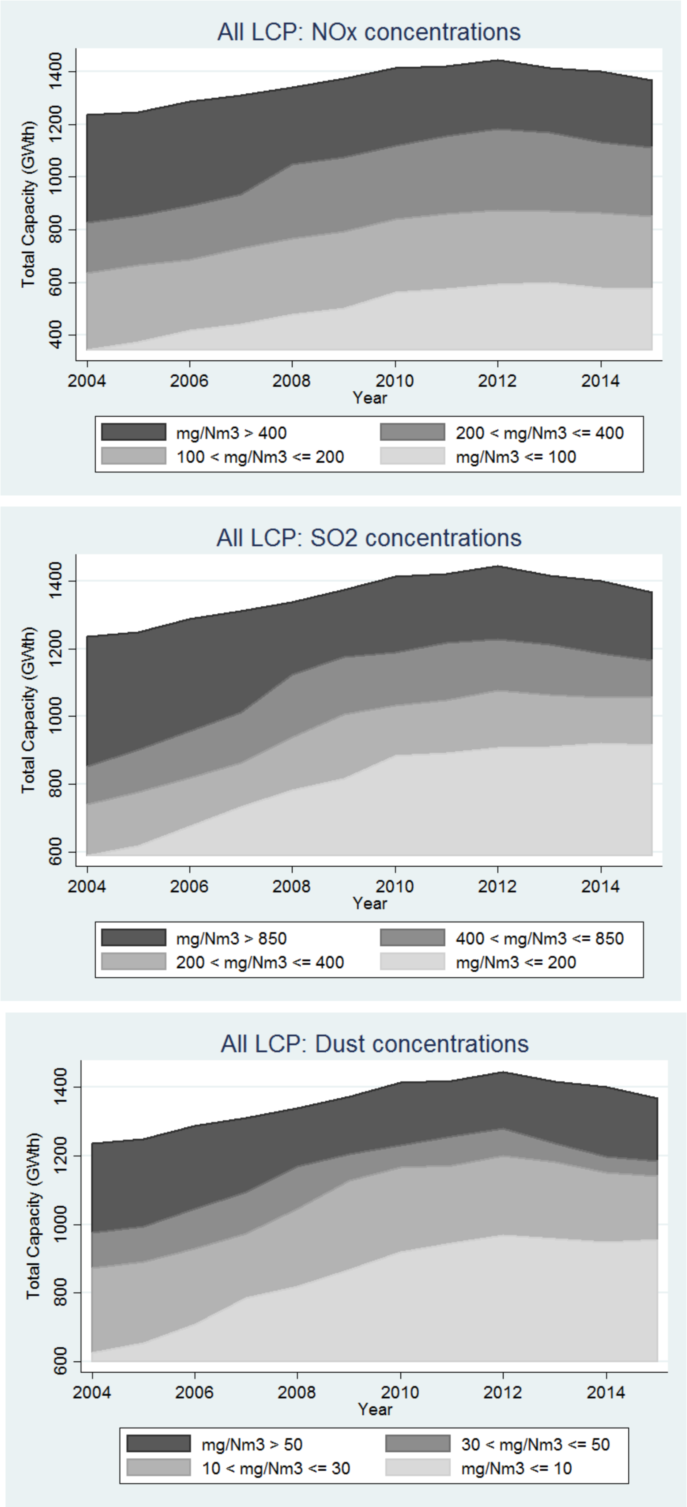


Table 1: Emission Limit Values for SO_2 by Regulation Status under LCPD

	Size of the Plant (MWth)					
	50 - 100		100 - 300		> 300	
Under article	**4(1)**	**4(2)**	**4(1)**	**4(2)**	**4(1)**	**4(2)**
Solid Fuels	2000	850	2000 to 400 (linear decline)	200	400	200
Liquid Fuels	1700	850	1700 to 400 (linear decline)	400 to 200 (linear decline)	400	200
Biomass	n.a.	200	n.a.	200	n.a.	200
Gaseous Fuels in general	35	35	35	35	35	35
Liquefied Gas	5	5	5	5	5	5
Low calorific gas from coke oven	800	400	800	400	800	400
Low calorific gas from blast furnace	800	200	800	200	800	200

Note: The emission limit values are expressed in milligrams per normal cubic meter (mg/Nm^3).

Table 2: Emission Limit Values for NOx by Regulation Status under LCPD

Under article 4(1)	Size of the Plant (MWth)	
	50 - 500	> 500
Solid Fuels	600	500
Liquid Fuels	450	400
Gaseous Fuels in general	300	200

Under article 4(2)	Size of the Plant (MWth)		
	50 - 100	100 - 300	> 300
Solid Fuels	400	300	200
Liquid Fuels	400	200	200
Natural gas	150	150	100
Other gas	200	200	200
Biomass	400	300	200

Note: The emission limit values are expressed in milligrams per normal cubic meter (mg/Nm^3).

Table 3: Emission Limit Values for Particle Dust by Regulation Status under LCPD

Under article 4(1)	Size of the Plant (MWth)	
	< 500	≥ 500
Solid Fuels	100	50
Liquid Fuels	50	50
Gaseous Fuels		
general rule	5	
blast furnace gas	10	
gases produced by steel industry	50	

Under article 4(2)	Size of the Plant (MWth)	
	50 to 100	> 100
Solid Fuels	50	30
Liquid Fuels	50	30
Gaseous Fuels		
general rule	5	
blast furnace gas	10	
gases produced by steel industry	30	

Note: The emission limit values are expressed in milligrams per normal cubic meter (mg/Nm^3).

Table 4: Regulation Status by Country

	4-3 Opt out	4-3 ELVs	4-1 ELVs	4-2 ELVs	Unknown	Total
Austria	0	68	45	16	28	157
Belgium	3	72	38	30	4	147
Bulgaria	2	24	1	4	3	34
Cyprus	6	6	10	3	0	25
Czech Republic	0	94	26	2	7	129
Germany	0	311	177	85	224	797
Denmark	0	45	64	20	23	152
Spain	26	88	24	141	6	285
Finland	19	100	36	79	9	243
France	28	168	52	54	53	355
Greece	4	39	11	26	0	80
Croatia	0	18	0	2	0	20
Hungary	0	34	7	20	9	70
Ireland	0	21	6	8	3	38
Italy	17	186	163	149	81	596
Lithuania	0	28	3	3	13	47
Luxembourg	0	0	1	0	0	1
Latvia	0	24	1	12	6	43
Malta	4	0	6	1	0	11
Netherlands	0	116	75	41	36	268
Poland	35	52	12	12	26	137
Portugal	6	14	6	22	2	50
Romania	41	119	11	14	8	193
Sweden	0	78	19	27	110	234
Slovenia	4	11	1	3	0	19
Slovakia	11	39	27	14	0	91
United Kingdom	17	238	155	57	27	494
Kosovo	0	5	0	0	0	5
Total	223	1998	977	845	678	4721

Note: The table shows the number of plants regulated under each regulation arm of the LCPD.

Table 5: Summary Statistics of Key Plant Features

	Regulation Status							
	Article 4(3) - Opt out				**Article 4(3) - ELVs**			
	Mean	SD	Min	Max	Mean	SD	Min	Max
Size (MWth)	739.91	1173.24	50	7889	450.32	913.26	0	12600
Energy Input (pt)	7.28	14.81	0	122.71	6.44	17.22	0	280.97
Solid Fuel %	41.92	47.08	0	100	24.32	40.78	0	100
Liquid Fuel %	33.19	44.51	0	100	22.48	35.19	0	100
Natural Gas %	21.11	37.48	0	100	36.94	44.92	0	100
Other Gases %	3.29	15.63	0	100	13.62	29.06	0	100
Biomass %	0.49	2.84	0	30.56	2.65	13.50	0	99.86

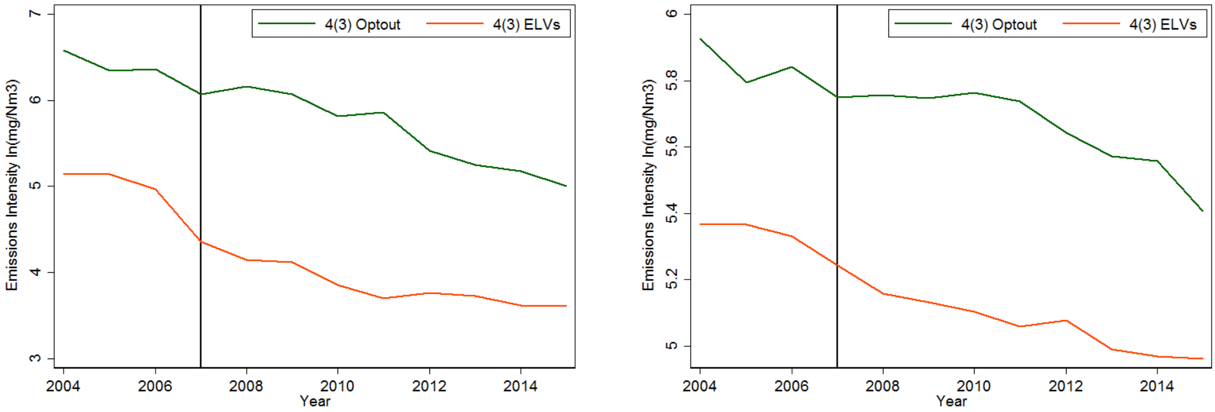
Note: The table reports average values from pre-treatment years (2004 - 2007).

Table 6: Summary Statistics of Key Plant Features

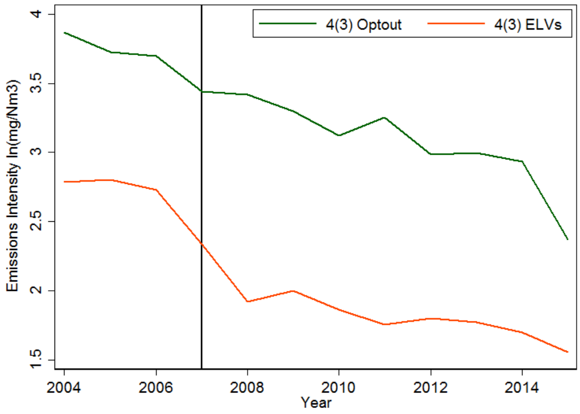
	Regulation Status							
	Article 4(1) - Control				**Article 4(2) - Treated**			
	Mean	SD	Min	Max	Mean	SD	Min	Max
Size (MWth)	322.32	464.87	0	5500	364.96	366.22	0	2400
Energy Input (pt)	5.19	8.62	0	92.69	4.69	6.26	0	38.99
Solid Fuel %	10.13	28.62	0	100	7.25	22.98	0	100
Liquid Fuel %	10.10	27.85	0	100	13.98	32.57	0	100
Natural Gas %	63.66	46.30	0	100	66.15	46.03	0	100
Other Gases %	11.87	30.69	0	100	5.53	21.53	0	100
Biomass %	4.24	18.20	0	100	7.10	22.31	0	100

Note: The table reports average values from pre-treatment years (2004 - 2007).

Figure 4: Diagnosis of Parallel Trends (Article 4-3)



(a) NOx emissions by Regulation Status (b) SO2 emissions by Regulation Status



(c) Dust emissions by Regulation Status

Table 7: Estimated Effect of ELVs Under Article 4(3) Regulation

	Dependent variable: ln (NOx)					
	(1)	(2)	(3)	(4)	(5)	(6)
(Post 2007)*(ELVs)	-0.102**	-0.060	-0.070	-0.093	-0.092	-0.063
	(0.043)	(0.047)	(0.047)	(0.060)	(0.061)	(0.055)
Operation Controls	Yes	Yes	Yes	Yes	Yes	Yes
Fuel Controls	No	No	No	No	No	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Plant FE	Yes	Yes	Yes	Yes	Yes	Yes
Country-by-Year FE	No	Yes	Yes	Yes	Yes	Yes
Industry-by-Year FE	No	No	Yes	Yes	Yes	Yes
Regulation-Specific Trend	No	No	No	Yes	No	No
Regulation-Country Specific Trend	No	No	No	No	Yes	Yes
N	12,277	12,277	12,277	12,277	12,277	12,277
R^2 (within-plant)	0.7631	0.7727	0.7784	0.7785	0.7794	0.8204

Notes: The dependent variable is the log of emissions intensity (mg/nM^3). We use the date of starting operation to impute the regulation status of DE and SE combustion plants. Combustion plants that were licensed post-January 1987 are not included in the analysis. We also exclude plants that were using a gas or diesel engine. Operation controls include size of the plant in GWth, dummy indicators for whether the plant includes a gas turbine or boiler. Fuel controls include the fuel input share of solid, biomass, liquid, other gases, and natural gas (%). Standard errors in parentheses are clustered at the plant level and robust to heteroskedasticity. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 8: Estimated Effect of ELVs Under Article 4(3) Regulation

	Dependent variable: ln (SO_2)					
	(1)	(2)	(3)	(4)	(5)	(6)
(Post 2007)*(ELVs)	-0.270**	-0.162	-0.183	-0.343***	-0.335***	-0.257***
	(0.119)	(0.123)	(0.126)	(0.111)	(0.109)	(0.087)
Operation Controls	Yes	Yes	Yes	Yes	Yes	Yes
Fuel Controls	No	No	No	No	No	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Plant FE	Yes	Yes	Yes	Yes	Yes	Yes
Country-by-Year FE	No	Yes	Yes	Yes	Yes	Yes
Industry-by-Year FE	No	No	Yes	Yes	Yes	Yes
Regulation-Specific Trend	No	No	No	Yes	No	No
Regulation-Country Specific Trend	No	No	No	No	Yes	Yes
N	10,609	10,609	10,609	10,609	10,609	10,609
R^2 (within-plant)	0.8650	0.8733	0.8772	0.8773	0.8782	0.9163

Notes: The dependent variable is the log of emissions intensity (mg/nM^3). We use the date of starting operation to impute the regulation status of DE and SE combustion plants. Combustion plants that were licensed post-January 1987 are not included in the analysis. We also exclude plants that were using a gas or diesel engine. Operation controls include size of the plant in GWth, dummy indicators for whether the plant includes a gas turbine or boiler. Fuel controls include the fuel input share of solid, biomass, liquid, other gases, and natural gas (%). Standard errors in parentheses are clustered at the plant level and robust to heteroskedasticity. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 9: Estimated Effect of ELVs Under Article 4(3) Regulation

	Dependent variable: ln (Dust)					
	(1)	(2)	(3)	(4)	(5)	(6)
(Post 2007)*(ELVs)	-0.278*** (0.092)	-0.246*** (0.089)	-0.234** (0.092)	-0.297*** (0.109)	-0.236** (0.109)	-0.188** (0.093)
Operation Controls	Yes	Yes	Yes	Yes	Yes	Yes
Fuel Controls	No	No	No	No	No	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Plant FE	Yes	Yes	Yes	Yes	Yes	Yes
Country-by-Year FE	No	Yes	Yes	Yes	Yes	Yes
Industry-by-Year FE	No	No	Yes	Yes	Yes	Yes
Regulation-Specific Trend	No	No	No	Yes	No	No
Regulation-Country Specific Trend	No	No	No	No	Yes	Yes
N	10,088	10,088	10,088	10,088	10,088	10,088
R^2 (within-plant)	0.7996	0.8112	0.8175	0.8175	0.8188	0.8529

Notes: The dependent variable is the log of emissions intensity (mg/nM^3). We use the date of starting operation to impute the regulation status of DE and SE combustion plants. Combustion plants that were licensed post-January 1987 are not included in the analysis. We also exclude plants that were using a gas or diesel engine. Operation controls include size of the plant in GWth, dummy indicators for whether the plant includes a gas turbine or boiler. Fuel controls include the fuel input share of solid, biomass, liquid, other gases, and natural gas (%). Standard errors in parentheses are clustered at the plant level and robust to heteroskedasticity. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

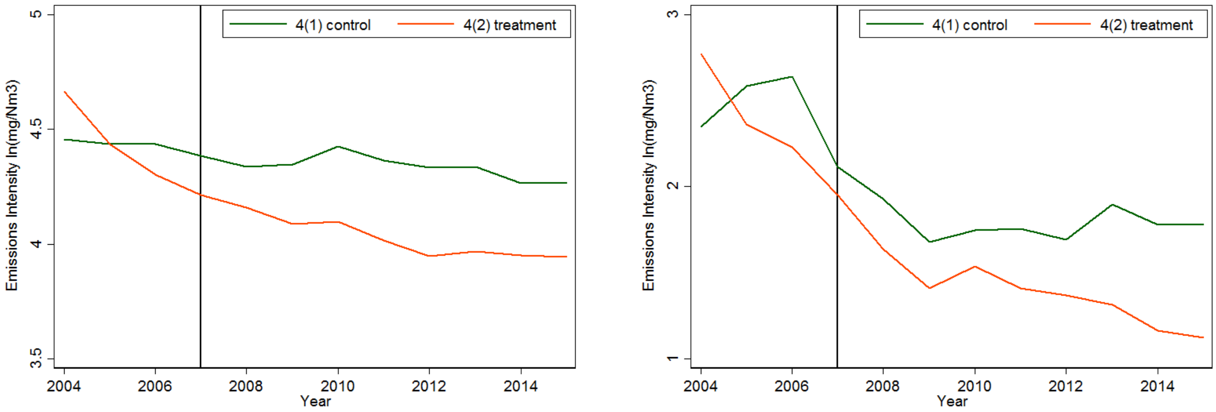
Table 10: Estimated Effect of ELVs Under Article 4(3) Regulation

Falsification Test

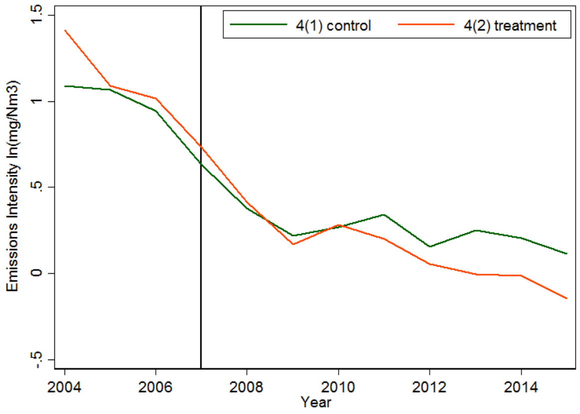
	Dependent variable: ln (mg/nM^3)					
	NOx	SO_2	Dust	NOx	SO_2	Dust
(Post 2006)*(ELVs)	-0.074 (0.064)	-0.096 (0.121)	-0.072 (0.118)			
(Post 2005)*(ELVs)				-0.011 (0.048)	-0.015 (0.111)	0.055 (0.108)
Operation Controls	Yes	Yes	Yes	Yes	Yes	Yes
Fuel Controls	No	No	No	No	No	No
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Plant FE	Yes	Yes	Yes	Yes	Yes	Yes
Country-by-Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Industry-by-Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Regulation-Country Specific Trend	Yes	Yes	Yes	Yes	Yes	Yes
N	12,277	10,609	10,088	12,277	10,609	10,088
R^2 (within-plant)	0.7793	0.8781	0.8187	0.7793	0.8780	0.8185

Notes: The dependent variable is the log of emissions intensity (mg/nM^3). We use the date of starting operation to impute the regulation status of DE and SE combustion plants. Combustion plants that were licensed post-January 1987 are not included in the analysis. We also exclude plants that were using a gas or diesel engine. Operation controls include size of the plant in GWth, dummy indicators for whether the plant includes a gas turbine or boiler. Fuel controls include the fuel input share of solid, biomass, liquid, other gases, and natural gas (%). Standard errors in parentheses are clustered at the plant level and robust to heteroskedasticity. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Figure 5: Diagnosis of Parallel Trends (Articles 4-1 & 4-2)



(a) NOx emissions by Regulation Status (b) SO2 emissions by Regulation Status



(c) Dust emissions by Regulation Status

Table 11: Estimated Effect of Article 4(2) versus Article 4(1) Regulation

Myopic Estimates

	Dependent variable: ln (NOx)					
	(1)	(2)	(3)	(4)	(5)	(6)
(Post 2007)*(Stringent)	-0.014	-0.048	-0.057	-0.089*	-0.089	-0.083*
	(0.045)	(0.050)	(0.051)	(0.051)	(0.056)	(0.048)
Operation Controls	Yes	Yes	Yes	Yes	Yes	Yes
Fuel Controls	No	No	No	No	No	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Plant FE	Yes	Yes	Yes	Yes	Yes	Yes
Country-by-Year FE	No	Yes	Yes	Yes	Yes	Yes
Industry-by-Year FE	No	No	Yes	Yes	Yes	Yes
Regulation-Specific Trend	No	No	No	Yes	No	No
Regulation-Country Specific Trend	No	No	No	No	Yes	Yes
N	14,329	14,329	14,329	14,329	14,329	14,329
R^2 (within-plant)	0.7705	0.7774	0.7785	0.7785	0.7794	0.7941

Notes: The dependent variable is the log of emissions intensity (mg/nM^3). We use the date of starting operation to impute the regulation status of DE and SE combustion plants. "Existing plants" that were licensed before January 1987 are not included in the analysis. We also exclude plants that were using a gas or diesel engine. Operation controls include size of the plant in GWth, dummy indicators for whether the plant includes a gas turbine or boiler. Fuel controls include the fuel input share of solid, biomass, liquid, other gases, and natural gas (%). Standard errors in parentheses are clustered at the plant level and robust to heteroskedasticity. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 12: Estimated Effect of Article 4(2) versus Article 4(1) Regulation

Myopic Estimates

	Dependent variable: ln (SO_2)					
	(1)	(2)	(3)	(4)	(5)	(6)
(Post 2007)*(Stringent)	-0.076 (0.140)	-0.129 (0.152)	-0.140 (0.153)	0.014 (0.146)	-0.031 (0.146)	0.062 (0.129)
Operation Controls	Yes	Yes	Yes	Yes	Yes	Yes
Fuel Controls	No	No	No	No	No	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Plant FE	Yes	Yes	Yes	Yes	Yes	Yes
Country-by-Year FE	No	Yes	Yes	Yes	Yes	Yes
Industry-by-Year FE	No	No	Yes	Yes	Yes	Yes
Regulation-Specific Trend	No	No	No	Yes	No	No
Regulation-Country Specific Trend	No	No	No	No	Yes	Yes
N	9,024	9,024	9,024	9,024	9,024	9,024
R^2 (within-plant)	0.8920	0.8892	0.8911	0.8911	0.8920	0.9112

Notes: The dependent variable is the log of emissions intensity (mg/nM^3). We use the date of starting operation to impute the regulation status of DE and SE combustion plants. "Existing plants" that were licensed before January 1987 are not included in the analysis. We also exclude plants that were using a gas or diesel engine. Operation controls include size of the plant in GWth, dummy indicators for whether the plant includes a gas turbine or boiler. Fuel controls include the fuel input share of solid, biomass, liquid, other gases, and natural gas (%). Standard errors in parentheses are clustered at the plant level and robust to heteroskedasticity. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 13: Estimated Effect of Article 4(2) versus Article 4(1) Regulation

Myopic Estimates

	Dependent variable: ln (Dust)					
	(1)	(2)	(3)	(4)	(5)	(6)
(Post 2007)*(Stringent)	-0.103	-0.061	-0.097	-0.059	-0.023	-0.029
	(0.143)	(0.152)	(0.152)	(0.161)	(0.164)	(0.161)
Operation Controls	Yes	Yes	Yes	Yes	Yes	Yes
Fuel Controls	No	No	No	No	No	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Plant FE	Yes	Yes	Yes	Yes	Yes	Yes
Country-by-Year FE	No	Yes	Yes	Yes	Yes	Yes
Industry-by-Year FE	No	No	Yes	Yes	Yes	Yes
Regulation-Specific Trend	No	No	No	Yes	No	No
Regulation-Country Specific Trend	No	No	No	No	Yes	Yes
N	8,547	8,547	8,547	8,547	8,547	8,547
R^2 (within-plant)	0.8266	0.8408	0.8437	0.8437	0.8450	0.8529

Notes: The dependent variable is the log of emissions intensity (mg/nM^3). We use the date of starting operation to impute the regulation status of DE and SE combustion plants. "Existing plants" that were licensed before January 1987 are not included in the analysis. We also exclude plants that were using a gas or diesel engine. Operation controls include size of the plant in GWth, dummy indicators for whether the plant includes a gas turbine or boiler. Fuel controls include the fuel input share of solid, biomass, liquid, other gases, and natural gas (%). Standard errors in parentheses are clustered at the plant level and robust to heteroskedasticity. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 14: Estimated Effect of Article 4(2) versus Article 4(1) Regulation

Quasi-Myopic Estimates

	Dependent variable: ln (NOx)			
	(1)	(2)	(3)	(4)
Ex-post effect ($\hat{\beta}_0$)	-0.089 (0.056)	-0.068 (0.053)	-0.047 (0.054)	-0.038 (0.055)
Ex-ante effect(t-1) ($\hat{\beta}_1$)		0.008 (0.061)	0.089 (0.072)	0.110 (0.073)
Ex-ante effect(t-2) ($\hat{\beta}_2$)			-0.110 (0.082)	-0.102 (0.084)
Ex-ante effect(t-3) ($\hat{\beta}_3$)				-0.027 (0.095)
Model	Myopic	QM	QM	QM
Operation Controls	Yes	Yes	Yes	Yes
Plant FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Country x Year FE	Yes	Yes	Yes	Yes
Industry x Year FE	Yes	Yes	Yes	Yes
Regulation x Country Trend	Yes	Yes	Yes	Yes
N	14,329	12,723	11,135	9,577
R^2	0.7794	0.7832	0.7873	0.7972

Notes: This table reports estimates of Equation (2). The dependent variable is the log of emissions intensity (mg/nM^3). Standard errors in parentheses are clustered at the plant level and robust to heteroskedasticity. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 15: Estimated Effect of Article 4(2) versus Article 4(1) Regulation

Quasi-myopic Estimates

	Dependent variable: ln (SO_2)			
	(1)	(2)	(3)	(4)
Ex-post effect ($\hat{\beta}_0$)	-0.031 (0.146)	0.031 (0.141)	-0.031 (0.145)	-0.102 (0.143)
Ex-ante effect(t-1) ($\hat{\beta}_1$)		-0.044 (0.177)	0.287* (0.152)	0.296* (0.152)
Ex-ante effect(t-2) ($\hat{\beta}_2$)			-0.581*** (0.221)	-0.393* (0.212)
Ex-ante effect(t-3) ($\hat{\beta}_3$)				-0.433* (0.246)
Model	Myopic	QM	QM	QM
Operation Controls	Yes	Yes	Yes	Yes
Plant FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Country x Year FE	Yes	Yes	Yes	Yes
Industry x Year FE	Yes	Yes	Yes	Yes
Regulation x Country Trend	Yes	Yes	Yes	Yes
N	9,024	7,996	6,988	6,017
R^2	0.8920	0.8948	0.8993	0.9030

Notes: This table reports estimates of Equation (2). The dependent variable is the log of emissions intensity (mg/nM^3). Standard errors in parentheses are clustered at the plant level and robust to heteroskedasticity. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 16: Estimated Effect of Article 4(2) versus Article 4(1) Regulation

Quasi-myopic Estimates

	Dependent variable: ln (Dust)			
	(1)	(2)	(3)	(4)
Ex-post effect ($\hat{\beta}_0$)	-0.023	-0.014	-0.073	-0.193
	(0.164)	(0.194)	(0.199)	(0.209)
Ex-ante effect(t-1) ($\hat{\beta}_1$)		-0.108	0.035	-0.006
		(0.219)	(0.236)	(0.237)
Ex-ante effect(t-2) ($\hat{\beta}_2$)			-0.248	-0.029
			(0.219)	(0.211)
Ex-ante effect(t-3) ($\hat{\beta}_3$)				-0.571**
				(0.263)
Model	Myopic	QM	QM	QM
Operation Controls	Yes	Yes	Yes	Yes
Plant FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Country x Year FE	Yes	Yes	Yes	Yes
Industry x Year FE	Yes	Yes	Yes	Yes
Regulation x Country Trend	Yes	Yes	Yes	Yes
N	8,547	7,525	6,531	5,564
R^2	0.8450	0.8577	0.8625	0.8717

Notes: This table reports estimates of Equation (2). The dependent variable is the log of emissions intensity (mg/nM^3). Standard errors in parentheses are clustered at the plant level and robust to heteroskedasticity. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 17: Estimated Effect of ELVs under Article 4(3) Regulation

Quasi-Myopic Estimates

	Dependent variable: ln (NOx)			
	(1)	(2)	(3)	(4)
Ex-post effect ($\hat{\beta}_0$)	-0.092 (0.061)	-0.109* (0.060)	-0.117** (0.058)	-0.150** (0.064)
Ex-ante effect(t-1) ($\hat{\beta}_1$)		0.006 (0.012)	0.009 (0.013)	0.005 (0.015)
Ex-ante effect(t-2) ($\hat{\beta}_2$)			0.010 (0.016)	0.010 (0.017)
Ex-ante effect(t-3) ($\hat{\beta}_3$)				0.005 (0.015)
Model	Myopic	QM	QM	QM
Operation Controls	Yes	Yes	Yes	Yes
Plant FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Country x Year FE	Yes	Yes	Yes	Yes
Industry x Year FE	Yes	Yes	Yes	Yes
Regulation x Country Trend	Yes	Yes	Yes	Yes
N	12,277	11,021	9,786	8,571
R^2	0.7794	0.7897	0.7943	0.7967

Notes: This table reports estimates of Equation (2). The dependent variable is the log of emissions intensity (mg/nM^3). Standard errors in parentheses are clustered at the plant level and robust to heteroskedasticity. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 18: Alternative Treatment (Article 4-1) and Control Group (Article 4-3) Robustness Check

	Dependent variable: ln (mg/nM^3)					
	NOx		SO_2		Dust	
(Post 2007)*(ELVs)	0.016 (0.041)	0.018 (0.040)	0.006 (0.091)	0.024 (0.084)	0.034 (0.087)	0.039 (0.086)
Operation Controls	Yes	Yes	Yes	Yes	Yes	Yes
Fuel Controls	No	Yes	No	Yes	No	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Plant FE	Yes	Yes	Yes	Yes	Yes	Yes
Country-by-Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Industry-by-Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Regulation-Country Specific Trend	Yes	Yes	Yes	Yes	Yes	Yes
N	23,982	23,982	17,586	17,586	16,707	16,707
R^2 (within-plant)	0.7235	0.7458	0.8863	0.9130	0.8357	0.8563

Notes: The dependent variable is the log of emissions intensity (mg/nM^3). We use the date of starting operation to impute the regulation status of DE and SE combustion plants. We exclude plants that were using a gas or diesel engine or opted out of ELVs or participated in the NERP. Operation controls include size of the plant in GWth, dummy indicators for whether the plant includes a gas turbine or boiler. Fuel controls include the fuel input share of solid, biomass, liquid, other gases, and natural gas (%). Standard errors in parentheses are clustered at the plant level and robust to heteroskedasticity. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.