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

By Puja Singhal*

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Abstract

This paper explores the extent to which emissions limits on stack concentrations under the Large Combustion Plant (LCP) Directive succeeded in mitigating local air pollutants from thermal power stations in the European Union. We take advantage of the discontinuities in regulation status to show that the emission performance standards led to sizeable declines in concentrations of SO_2, NOx, and particulate matter from the oldest fleet of combustion plants. We also find that the average response from the existing old plants was stronger than that from the relatively new existing fleet. Taking into account that new plants were not myopic in complying to the standards, we estimate the treatment effect close to the regulation discontinuity date – showing that more stringent performance standards were effective. Finally, those that opted-out were not more likely to retire than similar combustion plants that chose to comply with standards - some evidence of grandfathering-induced shutdown delays.

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 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). To regulate environmental damage by thermal power plants, the European Commission adopted a number of command-and-control (CAC) instruments[1], including the Large Combustion Plant (LCP) Directive which was intended to control emission intensities of SO_2, NOx, and particulate matter (dust). The EU community also established its first cap-and-trade program in 2005, 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.

Although we do have some robust evidence on the effect of EU ETS on the abatement of CO_2 emissions (Martin et al. 2016), 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 CO_2 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 and the corresponding emission performance standards (EPS) were applicable to all existing combustion plants, effective 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 total particulate matter, which

[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. Between 1970 and 2011, over 50% of EU environmental policy instruments used were of the CAC type (regulatory, interventionist, and topdown), with emission limits and technical requirements playing the role of the top two (Schmitt and Schulze, 2011).

[2] This paper does not assess the compliance rate of individual plants or Member States covered under the LCP regulation. 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.

applied to all combustion plants with a rated thermal input of 50 MW 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 oldest 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? 3) Did the opt-out policy actually encourage the old, large, and dirty combustion units to eventually close operations?

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. Notwithstanding, a number of regulation-specific factors makes the LCP Directive an ideal policy to study in order to understand 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. Regulation intensity was differentiated across plants based on the operation licensing dates – this allowed us to construct plausible counterfactuals and evaluate the effect of emission performance standards at both the extensive and intensive margins.

Second, the LCP directive differed from the usual vintage-differentiated regulation in the United States (see Stavins, 2006), because it did not exempt older plants from any form of regulatory intervention. This allowed us to investigate the environmental performance of the oldest combustion plants in the European Union. 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 (ELV) 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 to estimate the effect on stack-level emission concentrations of older plants (Article 4-3) that chose to comply with new environmental standards (ELV treatment). Using difference-in-differences, we find that average SO_2, NOx, and dust emission concentrations were 39%, 10%, and 25% lower respectively after the policy deadline. Furthermore, keeping the same counterfactual of opt-out plants, we find that emissions intensity of relatively newer plants under Article 4-1 did not change significantly (with the exception of SO_2 concentrations). Consequently, we argue that the response of the oldest fleet under Article 4(3) to emission standards was much stronger than that from Article 4(1) plants.

Third, the directive took the form of a typical CAC regulation in which the prescribed emission limits are more stringent for newly built plants than for existing plants. Combustion plants that were brought into operation between July 1987 and November 2003 were subject to lenient emission standards laid down in Article 4(1). Meanwhile, newer plants that started to operate post November 2002 were subject to significantly tighter emission limits values under Article 4(2). We are unable to apply the core D-i-D empirical model, used to evaluate the response to standards applied under Articles 4-3 and 4-1, because new plant operators could have anticipated the regulation before the compliance deadline of 2008. There are strong reasons for this. There is a time gap between when the directive was issued (2001) and the effective date of compliance (2008), possibly giving rise to anticipation effects for plants built after LCPD was issued. Anticipation of standards is much more plausible for new plants than old plants because upgrading or retrofitting older combustion units is costlier and takes more time. New plant operators had perfect foresight of the EPS required under the LCP directive before the policy deadline of 2008, therefore pre-trends in emissions concentrations could be potentially contaminated if operators made early clean investments in anticipation.

Another reason for anticipation is the policy interaction with the IPPC directive - which required permits to operate new combustion plants or make changes to existing installations since 30 October 1999. The IPPC necessitated compliance with emission performance standards under the LCP directive. Unfortunately, we only observe emissions and plant-level operations starting in 2004 and therefore are unable to observe the full impact of the directive pre-deadline. Nevertheless, we take into account that plants were not completely myopic and investigate the difference in response to standards of plants that were licensed close to the date of 2003, starting when plants were subject to Article (2). The variation in performance standards across plants (near the 2003 cutoff date) offers us a natural experiment 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 answer whether combustion plants subject to more stringent EPS were progressively cleaner due to the policy. We find strong evidence that tighter standards prompted newer plants to reduce emission concentrations of local pollutants from 2004 to 2015.

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 seek to go beyond the analysis found in Meyer and Pac (2017) and analyze the LCP directive comprehensively. In this paper, we pay critical attention to the performance of the oldest thermal combustion fleet (older than 1987) in the EU by comparing emissions concentrations of installations that opted-out to those that chose to comply with performance standards. We further explore that whether the LCPD created a perverse incentive for older stations to continue highly polluting operations without requiring performance standards. Those that opted out of the emission rate standards and eventually shutdown by the end of 2015 were more likely to be coal and lignite power plants. More importantly, these plants were not more likely to shutdown (as intended by the Article 4(3) requirements) than similar plants that chose to comply. This gives us some evidence that the LCP directive gave rise to the "old-plant" effect, deferring dirty plant shutdowns or replacements.

In the next section, we briefly review some 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. Section 5 estimates the causal effect of emission standards under Articles 4(3) and 4(1), along with falsification tests. Section 6 investigates the policy impact of tighter standards under Article 4(2) taking potential anticipation effects seriously in the identification strategy. In Section 7 we conduct more robustness checks. Section 8 investigates whether the old opt-

[3] We have reason to be wary of this result: 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.

out combustion plants were more likely to close than plants under different regulation regimes. Lastly, Section 9 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 a 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 in non-EU countries, notably the United States, 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 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. Another 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% (Karplus et al., 2018).

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 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

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

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 this paper.

3 Policy Context

3.1 Large Combustion Plant Directive

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 on average 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.

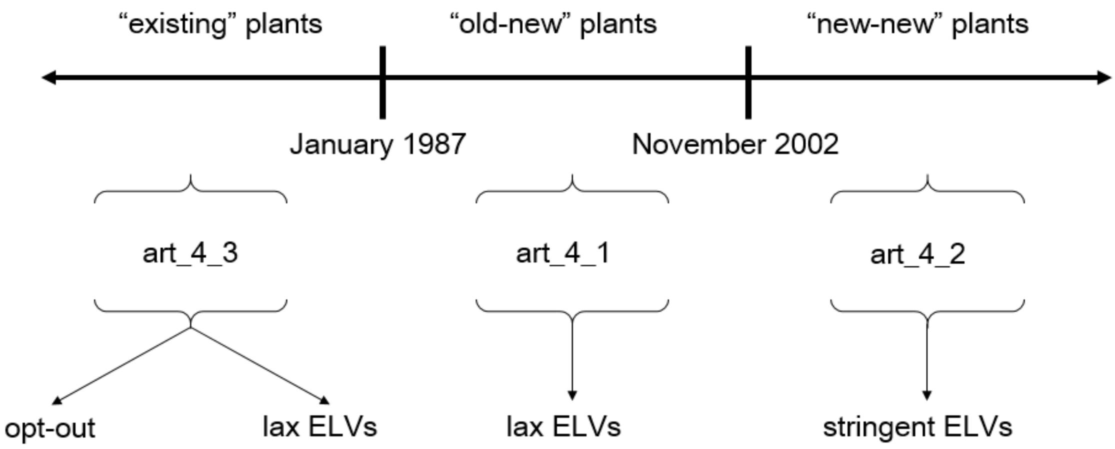
Figure 1 is a pictorial description of regulatory provisions under the LCP directive. A plant that could prove that the construction licence was granted before 27.11.2002 and that the plant went into operation before 27.11.2003 is referred to as an "old-new" plant and was subject to provisions under 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 (NERP) 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

[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



reduce their operation hours and eventually shutdown by 2015.[8] In the analysis that follows, we seek to quantify the impact of emission rules on polluting behavior at the stack/plant level.

Tables 1 to 3 summarize the performance standards stated as emission limit values for SO_2, NOx, and particulates that were set to be achieved by January of 2008. The regulation intensity for each controlled pollutants varied depending on whether the plant would be eventually 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 considerably tighter emission limit values (stricter compliance standards) than do older plants under article 4(1). Moreover, these performance standards varied by the type of fuel input (e.g. solid, liquid, or gaseous) and capacity of the plant as measured by thermal megawatt (MWth) input.

It is important to note that the directive applied not only to the electricity and heating sectors, but all thermal generation from large combustion units, irrespective of the sector. This included, as a result, firms in the iron, steel, paper, sugar, chemicals, and rubber sectors generating power and heat onsite.

3.2 Potential Compliance Mechanisms

To comply with the directive, plant operators have a number of compliance options. In order to reduce emissions intensity, there could be (1) a change in the fuel-mix used, e.g. increase the

[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.

share of emission compliant fuels like natural gas, (2) installing and using pollutant abatement technology - e.g. retrofitting the plant with scrubber technology designed for each pollutant type to clean the flue gases, (3) increases in operational or fuel efficiency, (4) closure of non-compliant units or a change in the merit order (e.g. temporary production status or peak-use only). In the analysis, we find some evidence on what share of the compliance mechanism for old plants could be attributed to fuel-switching.

3.3 NEC targets & 2008

During the same (observable) 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. However, 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.

The analysis in this paper focuses only on the energy production and distribution sector, so it is likely that the threat to identification due to the NEC targets is low. Nevertheless, the reader may have residual concern that the NEC targets could bias the estimates for the LCP directive. This may be true if we have reason to believe that the NEC targets affected plants regulated under Articles 4(1) and 4(2) differentially. Similarly, NEC targets are a concern if opt-out plants reacted differently from plants that chose to comply with ELVs. We will seek to explain the impact of the LCP directive on stack-level emissions concentrations rather than absolute emissions, so NEC targets should not be a concern.

Figure 2 shows that absolute emissions from the energy production and distribution sector fell at a much higher rate in 2008 and 2009, likely due to the great recession. It is all the more 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 fixed effects to pick up time-specific unobservables.

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

3.4 EU ETS

Generally, threats to identification exist if an event or unobservable factor affect emission concentrations from plants in the selected treatment and controls groups in a systematically different way 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 LCP directive.

3.5 IPPC Directive

The IPPC directive (Directive 96/61/EC of 24 September 1996) is a major threat to identifying the response of new plants to lower pollutant limits values or stricter emission standards at the stack-level. This is because the IPPC directive required operating permits in compliance with best available techniques, including the standards in the LCP directive, for all new plants or those undergoing major changes starting 30 October 1999.

We therefore have strong reason to expect that the policy interaction between the LCP and IPPC directives made it harder to avoid compliance with emission performance standards under Article 4(1) or Article 4(2) for plants with operation dates starting 1999. We are still interested in quantifying the effect of more stringent environmental standards under Article 4(2) and will take anticipation into account in the research design.

Note that IPPC was not a requirement for units that started operating pre-1987 and therefore older plants had no incentive to comply pre-deadline of 2008. Moving forward, the Industrial Emissions Directive integrates the LCPD and the IPPC, along with other directives, in one comprehensive regulation.

4 Data

The data on all large combustion activities come from the European Environment Agency (EEA), which had started an inventory of reported emissions from large combustion plants starting in 2004[10]. This database covers all plants with a rated thermal input of at least 50 MW operating in the European Union, covering 27 countries in 2004 and reaching 29

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

countries by 2015. For each plant, the database reports detailed information on operations including capacity, energy input, fuel input by type, emissions of local pollutants, date plant started operations, and regulation status under the LCPD, including whether the plant opted-out or was part of the NERP. 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[11]. There are six industry classifications provided: Electricity Supply Industry, Combined Heat and Power, District Heating, Iron and Steel, Refineries, and Other (Paper, Sugar, Chemicals, Rubber, etc). See Table 6 for the industries covered.

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.

Note that there were no combustion units 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 Articles 4-3 and 4-1. Table 5 shows the breakdown of plants by regulation status for each member state with at least one opt-out combustion plant.

4.1 From Absolute Emissions to 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 particulate matter, as reported by the plants, we convert tonnes emissions into flow rates (mg per Nm^3). For the dependent variable, we combine information on raw fuel usage (in petajoules) with tonnes

[11] In the raw data there were many plants unidentified in terms of industry. 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. There remain still combustion units for which the industrial sector in unknown.

emissions to construct our outcome variable of interest, emissions intensity. To do this we need estimates of the flue rates associated with specific fuel types. We start with using flue rates assumptions 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

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 Industrial Emissions Directive).

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 key air pollutants concentrations.

4.3 Pre-treatment Statistics

Table 7 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. and Article 4-1. The table suggests that on average opt-out plants were much larger in size (as measured by MWth), used boilers to combust, 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, and used gas turbine as combustion type.

We will control for the size of the plant and construct emission intensity using information on specific-fuel input and their associated flue rates. Using emissions intensity in mg/nM^3 as the dependent variable will allow us to capture the differences in the fuel mixes. Fuel-switching is one of the mechanisms using which plants seek to comply with emission-performance standards. For this reason, we want to avoid controlling for time-varying plant-level fuel input such as fuel type shares to avoid post-treatment bias. Nevertheless, controlling for fuel input shares could inform us about how much of the compliance mechanism adopted by plants was due to fuel-switching.

Table 8 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. Moreover, pre-treatment differences of these key variables are relatively stable across years as well (not shown here).

5 Emissions Control Under Articles 4(3) and 4(1)

5.1 Research Design

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 capacity less than 50MWth.

To construct plausible counterfactuals, we look in the implementation details of the regulation across 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. To investigate the effect of EPS on EU combustion plants (extensive margin), we use a difference-in-differences (DiD) framework. We treat plants that opted-out as the control group and plants that chose to meet the emission-rates under Article 4-3 and Article 4-1 as the treatment groups.

Note that the EPS under Article 4(3) are identical to those under Article 4(1). The only difference is that Article 4(3) plants are older and could choose not to come under performance standards - which were mandatory for Article 4(1) plants.

The base specification is a DiD equation, which uses the reported emissions before the policy deadline (2004 to 2007) for pre-treatment data. Preferred 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 for units subject to Articles 4(3) and 4(1). y_{pt} is the log of emissions intensity at plant p in year t. β 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-related combustion technology are captured by the plant-level fixed effects α_p. 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 to control for time-varying unobservables. $\mathbf{X}_{pt}$ includes time-varying control for plant size or capacity (GWth).

To account for the considerable heterogeneity (unevenness) in the implementation of the LCPD policy across countries (for example, compliance stringency was left to the member states), we 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 environments 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.

5.2 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 cost of operations, SUTVA could be violated if the parent company that owns multiple combustion units chooses to retrofit all plants irrespective of regulation status[12]. The potential biases due to such regulation spillovers can be signed. Namely, we provide lower-bounds of the true impact of EPS under the LCP directive.

It is absolutely necessary that the control and treated groups have common trends in emissions intensity, before the policy deadline. For us to interpret β as the causal effect of emission performance standards, we require 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 graphs and placebo tests to diagnose this. Figure 4 demonstrates a favorable pictures for pre-treatment trends in outcomes for opt-out plants versus those that chose lenient emission limit values under Article 4(3) and Article 4(1). Note that these graphs are limited to those member states that had opt-out plants.

5.3 Results - EPS for Article 4(3) Plants

We estimate the effect of emission-rate standards under Article 4(3) in Tables 9 to 11. For identification we limit the sample to countries that had at any opt-out plants - we call them opt-out member states. These are 17 EU countries, with a total of 241 plants opting out of emission standards (see Table 5). We also exclude plants that were using a gas or diesel engine because the LCP directive did not apply to them.

Table 9 quantifies the average impact of ELVs on emission-intensity of NOx at the plant level. Column (1) is the simplest model, including only the interaction term of interest (Post 2007)*(4-3 ELVs), time and plant fixed effects, and size control using plant capacity in GWth. Column (2) introduces industry by year fixed effects to capture any developments that may be unique to the industry. From Columns (3) and (4), we can see that the estimates for NOx are sensitive to the inclusion of any country-related fixed effects or trends. This is not as apparent in Tables 10 and 11, where we run the same models for SO_2 and particulate matter. Columns (4) shows estimates of equation (1), which is our preferred specification, and further controls for regulation-specific linear trends that are common to each member state. In Table 9, we see a negative change in NOx emission concentrations of about 11%, but the estimate is significant only at the 10% level.

[12] We are unable to test the strength of SUTVA by comparing the performance of thermal plants that are owned by the same firm, but are under different regulation regimes.

To allay concerns that the differences in the distribution of covariates concerning fuel usage are driving the results, we add fuel controls in Column 5. The difference in the estimates from Columns 4 to 5 provide some indication of the importance of fuel-switching for older plants due to the emission-rate standards. In Table 9, after controlling for fuel input shares in Column 5, the coefficient on 4(3) ELV treatment is four percentage points (or 38%) lower than in Column 4. And this estimate is no longer statistically significant - suggesting that fuel-switching was on average a strong compliance mechanism for NOx abatement, than say retrofitting.

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 39% and dust concentrations by 26% relative to opt-out plants. Moreover, based on the differences between Columns 4 and 5, we can attribute about 30% of the reductions in SO_2 concentrations and about 25% of the reductions in dust concentrations to fuel-switching.

5.4 Falsification Test

To conduct falsification tests, we use years 2006 and 2007 as hypothetical policy deadlines for compliance to the LCP directive. We do not expect anticipation to play any significant role for old plants complying with the emission standards: (1) because of high costs for plant operators to retrofit older plants or enhance operational efficiency, and (2) because IPPC was not a requirement for combustion units that started operating pre-1999 and therefore majority of older plants had no incentive to comply before the 2008 compliance deadline.

Since all plants regulated under Article 4(3) and most under Article did not have any other regulatory requirements (e.g. in the IPPC directive), we assume away the possibility of detecting anticipation prior to 2008. We consider therefore this to be a strong test for common trends, in addition to the visual checks in Figure 4. We stick to the preferred specification in equation (1) - the inclusion of fuel controls do not change the result - and the results are presented in Table 12.

As expected, the estimated effects on plant-level emission concentrations before the compliance deadline of 2008, for all three pollutants, are statistically insignificant. On the other hand, estimates in the second row could be an indication that the response was already taking effect after 2006 - inconclusive, however.

5.5 Results - EPS for Article 4(1) Plants

We conduct the identical exercise to estimate the effect of emission-rate standards under Article 4(1) in Table 13. Again, for identification we have limited the sample to opt-out member states only. We find that combustion units regulated under Article 4(1) were prompted to reduce SO_2 emission intensity by 31% under the lenient performance standards. For the other two pollutants under consideration, the effect was statistically insignificant.

In contrast to the observed response by Article 4(3) seen in Table 12, Table 13 suggests that the emission limits values under Article 4(1) were perhaps too lenient. This is not surprising as we see in the right column of Figure 4, the combustion units were on average already relatively clean in 2004. Imposing the same emission performance standards for Article 4(3) and 4(1) plants seems to have fallen short of environmental progress on emissions abatement.

Tables 12 and 13 give us assurance that the post-2008 treatment effects observed are prompted by the emission performance standards under Articles 4(3) and 4(1), rather than something else unobserved.

6 Emissions Control Under Article 4(2)

6.1 Research Design

Now we turn to estimating the effect of tighter emission limits imposed under the LCP directive. We would like to identify the effect of tighter standards on new plants from the change in emission intensities of Article 4(2) units compared with the change in emission intensities of Article 4(1) units. We are unable to exploit the D-I-D framework applied thus far because we expect anticipation to play a role for the following reasons:

- Plants getting operation permits after the LCP directive was announced in 2001 would be already aware of the emission standards required. If plant operators have prior access to information on future compliance requirements and are reasonably forward-looking - we expect them to invest early.
- New plants, as opposed to old existing plants, using newer combustion technology would find it relatively cheaper to invest early (possibly also costly to delay).

- As discussed in Section 3.5, the IPPC directive required new units and those undergoing "substantial changes" to meet technology standards starting 30 October 1999. We expect therefore plants starting operations after 1998 to be more forward-looking (less myopic) in adhering to EPS requirements.

Figure 5 shows that the requirement of common trends does not hold because trends in emissions intensity of article 4(1) plants differ significantly from that of article 4(2) plants during the pre-treatment period, most notably for NOx. In light of the policy interaction between IPPC and LCP directives, we find it difficult to rule out anticipation as one of the explanations for the significant declines in emission intensities of NOx and SO_2 by all plants affected by IPPC before the LCPD deadline - see the right column of Figure 5.

To circumvent the problem of anticipation, we do the following:

- We assume that the regulation assignment rule was arbitrary (plants staring operation after 2002 came under Article 4(2)) and that it was difficult for plants to "game the system." Given this assumption, the regulation status for plants just before and after 2003 is as good as random. Therefore, plants near the cutoff date are similar in unobservable characteristics that affect emission concentrations at the stack-level. The closer to the cutoff date, the stronger our identification assumption - although not rigorously testable. We will control for all possible time-varying and observable plant variables and also impose combustion type fixed effects.

- We do not impose any policy deadline. We compare the performance of the treated versus control plants during the full observed period of 2004 to 2015.

We estimate the following equation for plants near the cutoff date of 2003:

$$y_{pt} = \alpha_0 + \beta \mathrm{S}_p + \boldsymbol{\gamma} \cdot \mathbf{X}_{pt} + \lambda_m + \theta_{ct} + \phi_{it} + \epsilon_{pt} \tag{2}$$

where y_{pt} is the log emission intensity of pollutant of interest. $S_p = 1$ indicates whether the plant came under stringent EPS under Article 4(2). The base category is EPS under Article 4(1). $\mathbf{X}_{pt}$ captures plant-level operations such as fuel input shares by fuel type and plant capacity in GWth. η_m are fixed effects for combustion type. θ_{ct} and ϕ_{it} country and industry fixed effects allowed to vary by year.

6.2 Results

Tables 14, 15, and 16 estimate equation (2) for emission intensities of NOx, ceSO2, and dust respectively. We use plants that started operations either 2003 and 2004 as the treated group. Columns (1) and (2) use all plants that started operations 1999 to 2002 as the control group, while Columns (3) and (4) limits the control group further to only those with 2000 and 2001 as operation start-dates.

Relative to emission limits values under 4(1), stricter emission performance standards caused average NOx concentrations to drop further between 7-16%, SO_2 concentrations to fall by 27-28%, and dust concentrations by 30-40%. These results are robust to re-defining emission intensity as kilotonnes of emissions per petajoule of input do not change the results.

7 Further Robustness Checks

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

7.1 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 time 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. Both groups were subject to identical emission limit values. Then the difference between these two groups should not be the regulation, but rather improvements in technology over time. Once we control for plant-fixed effects, we do not expect to find Article 4(1) plants to respond on average more than those under Article 4(3) - especially since Article 4(1) plants were already on average cleaner than the older plants. Table 18 confirms this and demonstrates that there are no significant differences in emission intensities of local pollutants between the treatment and control groups. These results provide further assurance that we are correctly attributing the effects we find to emission performance standards under the LCP directive.

8 Shutdown of Grandfathered Plants

In this section we will explore whether the old and dirty opt-out plants were "grandfathered" under the LCP directive. Under Article 4(3), opt-out plants avoided environmental standards, but were supposed to limit operating hours to 20,000 and close by the end of 2015. Did this happen?

Table 18 shows that a large share of the 241 opt-out plants did not actually close down by the initial required date of 2015. We still observed 60% of the combustion units operating in 2016. More interestingly, we observe that plants which were subject to emission-rate standards were shutting down in large numbers during the same period. About 82 combustion units under Article 4(3) that chose to comply with emission standards were closed by the end of 2007. Generally, we observe a high number of Article 4(3) ELV plants closing operations in the LCPD policy-active period.

A natural question arises: did the LCP directive indeed promise the closure of opt-out plants or did it offer non-compliant plants a perverse incentive to continue dirty operations relative to those complying with ELVS? We investigate the determinants of the (endogenous) shutdown decision using the full EEA dataset in a linear probability model:

$$\text{shutdown}_{pt} = \alpha_0 + \alpha_3 4(3)_p + \alpha_1 4(1)_p + \alpha_2 4(2)_p + \boldsymbol{\gamma}_{\boldsymbol{X}} \cdot \mathbf{X}_{pt} + \lambda_m + \theta_{ct} + \phi_{it} + \epsilon_{pt} \tag{3}$$

where $4(3)_p = 1$, $4(1)_p = 1$, and $4(2)_p = 1$ indicate that the combustion unit was subject to EPS under Articles 4(3), 4(1), and 4(2) respectively. Here the base category is opt-out status under Article 4(3). $\mathbf{X}_{pt}$ capture a host of plant-level operations and outcomes such as fuel input shares by fuel type, emissions intensities of NOx, SO_2, particulate matter, whether the plant was part of NERP, and plant capacity in GWth and absolute energy input in petajoules. η_m are fixed effects for combustion type. θ_{ct} and ϕ_{it} country and industry fixed effects allowed to vary by year. $shutdown_{pt}$ is a binary (0 or 1) dependent variable indicating whether the plant closed at the end of the reporting year. We assume that the plant was shutdown if we do not observe it the next reporting year.

We estimate this linear probability model by ordinary least squares in Table 19 for both the full sample and then again limiting the estimation sample to only opt-out member states. The results reveal that opt-out plants were more likely to shutdown during the policy period than newer combustion plants complying to emission rate standards under Article 4(1) and 4(2). But surprisingly opt-out plants did not close more often than those of similar age under Article 4(3). Given the estimates are stable across the two samples, we have confidence about the robustness of our qualitative findings. We find evidence in this section that the LCP directive "grandfathered" the oldest and dirtiest power stations and allowed them to keep running over the long run.

9 Conclusion

Effective pollution control in the complex regulatory context of the European Union is an important policy objective. The Large Combustion Plant Directive was a major EU environmental policy. This paper offers the first impact assessment of this policy 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 evaluate whether the policy instrument succeeded in pollution control by the oldest thermal power generators and whether stricter emission standards were a significant catalyst for improved environmental performance.

We use combustion plants that opted-out of lenient emission limit values as the counterfactual and demonstrate that older units under Article 4-3 (licensed before 1987) complying with emission performance standards responded with significantly cleaner emission concentrations post compliance-deadline. The results are strongest for SO_2 and PM concentrations, but also hold for NOx. Moreover, emission performance standards imposed on newer units (under Article 4-1, licensed after 1987 and before 2002) did not react as much as older units - most likely, because the standards imposed were too lenient.

Given the policy interaction between the LCP directive and the IPPC directive, which required new units and those undergoing "substantial changes" to meet technology standards starting 30 October 1999, we have strong priors that combustion plants with operation permits starting 1999 were not as myopic in complying with the directive. To evaluate the effect of tighter emission performance standards under Article 4-2 on new plants we take this policy interaction between the LCP and IPPC directives and limit our estimation sample to those combustion plants that started operation after 1998. Then we measure the change in emissions intensity of new plants licensed just after 2002 relative to those licensed just before 2002 - allowing us to estimate the local treatment effect near the applicable cut-off date for tighter emission limits values. The result indicate that tighter standards applied to new plants had an economically meaningful impact on all measures of local pollutant emission concentrations.

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. 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.

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. Those that opted out of emission rate standards and eventually shutdown by the end of 2015 were more likely to be coal and lignite power plants. Furthermore, these plants were not more likely to shutdown (as intended by the Article 4(3) requirements) than similar plants that chose to comply with standards. This gives us some evidence that the LCP directive gave rise to the "old-plant" effect, deferring plant shutdowns or replacements that would otherwise be crucial for environment protection.

Given that we find that plants under Article 4(1) did not respond significantly to the Large Combustion Plant Directive, future research should investigate whether the additional requirements and more stringent standards under the Industrial Emissions Directive encouraged these existing plants to reduce emissions concentrations further or shutdown.

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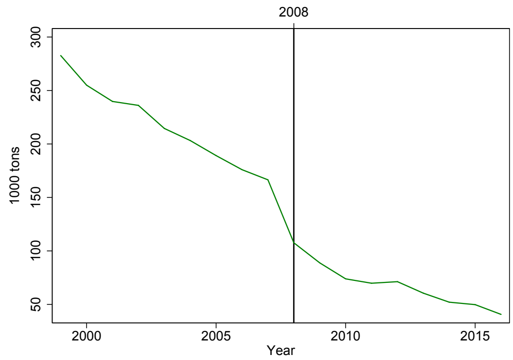
Figure 2: Trends in Absolute Emissions by EU Region

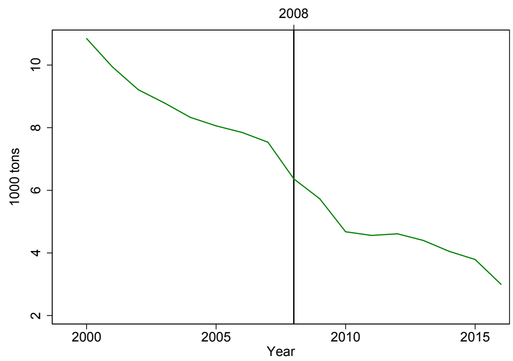
(a) NOx emissions in Western EU

(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?

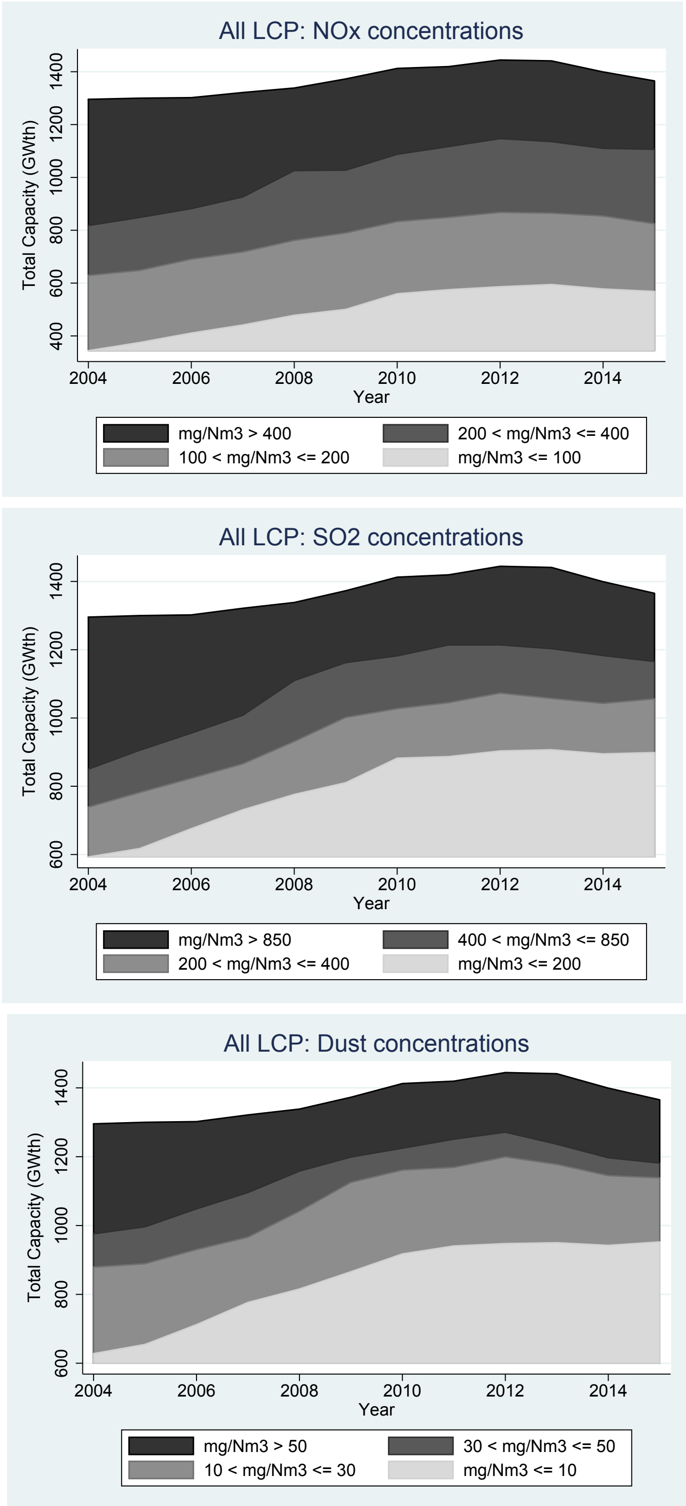


Table 1: Emission Limit Values for SO_2 by Regulation Status under LCPD

	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 All Member States

	4-3 Opt out	4-3 ELVs	4-1 ELVs	4-2 ELVs	Unknown	Total
Austria	0	58	42	29	28	157
Belgium	3	72	35	33	4	147
Bulgaria	3	27	0	1	3	34
Cyprus	7	4	11	3	0	25
Czech Republic	0	93	26	3	7	129
Germany	0	315	197	59	228	797
Denmark	2	59	53	17	21	152
Estonia	3	12	1	8	2	26
Spain	23	73	30	129	4	259
Finland	23	106	61	44	9	243
France	29	134	85	54	53	355
Greece	4	34	15	27	0	80
Croatia	0	15	3	2	0	20
Hungary	0	31	11	19	9	70
Ireland	0	17	10	8	3	38
Italy	20	176	178	156	66	596
Lithuania	0	29	3	3	12	47
Luxembourg	0	0	1	0	0	1
Latvia	0	23	1	13	6	43
Malta	4	0	6	1	0	11
Netherlands	0	106	81	45	36	268
Poland	39	50	10	12	26	137
Portugal	6	9	13	20	2	50
Romania	41	116	13	15	8	193
Sweden	0	76	21	8	129	234
Slovenia	5	9	2	3	0	19
Slovakia	11	40	26	14	0	91
United Kingdom	18	207	182	60	27	494
Kosovo	0	5	0	0	0	5
Total	241	1896	1117	786	683	4721

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

Table 5: Regulation Status by Opt-Out Member States

	4-3 Opt out	4-3 ELVs	4-1 ELVs	4-2 ELVs	Closed by 2015
Belgium	3	72	35	33	3
Bulgaria	3	27	0	1	1
Cyprus	7	4	11	3	1
Denmark	2	59	53	17	1
Estonia	3	12	1	8	2
Spain	23	73	30	129	0
Finland	23	106	61	44	21
France	29	134	85	54	11
Greece	4	34	15	27	0
Italy	20	176	178	156	14
Malta	4	0	6	1	4
Poland	39	50	10	12	7
Portugal	6	9	13	20	6
Romania	41	116	13	15	0
Slovenia	5	9	2	3	0
Slovakia	11	40	26	14	8
United Kingdom	18	207	182	60	16
Total	241	1128	721	597	95

Note: The table shows the number of plants under each status category. The last column identifies the number of opt-out plants that shutdown by 2015. We assume that operations were closed if we do not observe the plant in 2016.

Table 6: Distribution of EU Combustion Plants by Industry

Industry	# of Plants
CHP	811
District Heating	461
Electricity Supply	1354
Iron/Steel	62
Other (Paper, Sugar, Rubber, Chemicals)	928
Refineries	116
Other Unknown	387
Total	4040

Note: The table shows the number of plants observed in each industrial sector from 2004 to 2015, provided the regulation status is known.

Table 7: Summary Statistics of Key Plant Features - Opt Out MS

	Regulation Status											
	Article 4(3) - Opt out				**Article 4(3) - ELVs**				**Article 4(1) - ELVs**			
	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max
Size (MWth)	719.87	1140.92	50	7889	465.36	938.55	0	12600	328.99	471.14	0	5500
Energy Input (pt)	7.14	14.40	0	122.71	6.53	17.56	0	280.97	5.58	9.61	0	92.69
Solid Fuel %	41.66	47.07	0	100	25.14	41.25	0	100	10.83	29.13	0	100
Liquid Fuel %	34.16	44.88	0	100	23.65	36.15	0	100	12.65	29.93	0	100
Natural Gas %	20.62	37.20	0	100	35.28	44.41	0	100	62.83	46.47	0	100
Other Gases %	3.07	15.10	0	100	13.51	28.93	0	100	8.87	25.93	0	100
Biomass %	0.50	2.78	0	30.56	2.43	12.78	0	99.86	4.83	18.80	0	100
Boiler	0.78	0.42	0	1	0.64	0.48	0	1	0.37	0.48	0	1
Gas Turbine	0.03	0.17	0	1	0.10	0.31	0	1	0.51	0.50	0	1

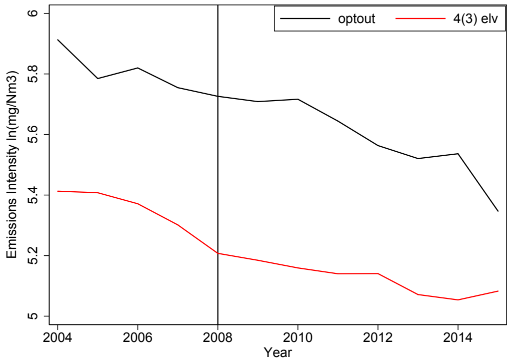
Note: The table reports average values from pre-treatment years (2004 - 2007) and the sample is limited to opt-out member states.

Table 8: Summary Statistics of Key Plant Features - All EU28

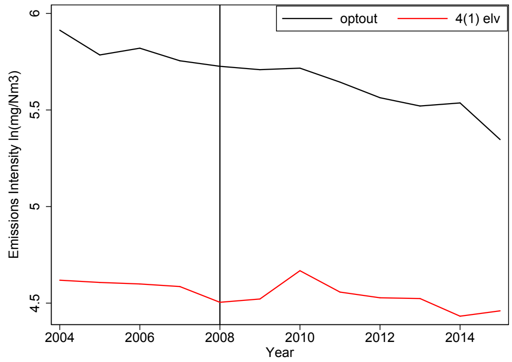
	Regulation Status							
	Article 4(1) - ELVs				**Article 4(2) - ELVs**			
	Mean	SD	Min	Max	Mean	SD	Min	Max
Size (MWth)	324.71	486.09	0	5500	391.95	369.12	0	2400
Energy Input (pt)	5.26	9.76	0	121.25	5.52	6.63	0	38.99
Solid Fuel %	12.53	31.43	0	100	5.90	20.79	0	100
Liquid Fuel %	10.94	28.27	0	100	10.91	29.28	0	100
Natural Gas %	61.08	46.83	0	100	71.27	43.80	0	100
Other Gases %	11.24	29.67	0	100	5.42	21.10	0	100
Biomass %	4.20	17.84	0	100	6.50	21.82	0	100
Boiler	0.45	0.50	0	1	0.33	0.47	0	1
Gas Turbine	0.45	0.50	0	1	0.57	0.50	0	1

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

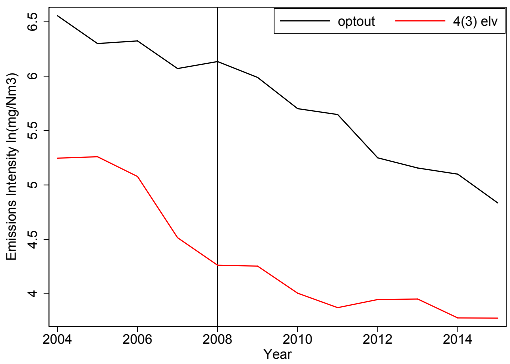
Figure 4: Diagnosis of Trends I



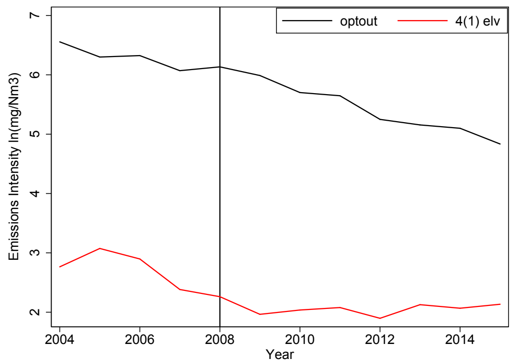
(a) NOx - Opt Out MS



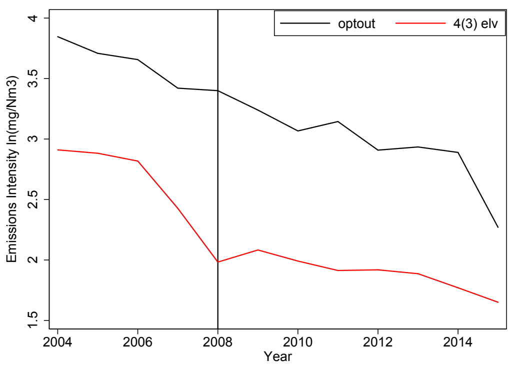
(b) NOx - Opt Out MS



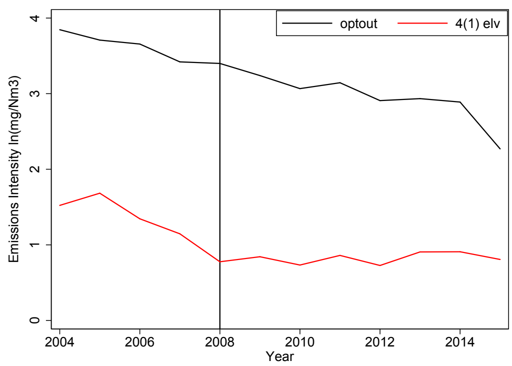
(c) SO2 - Opt Out MS



(d) SO2 - Opt Out MS

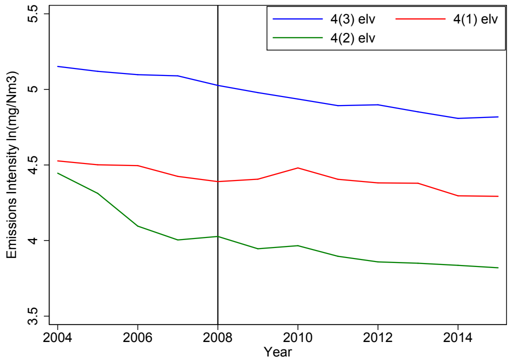


(e) Dust - Opt Out MS

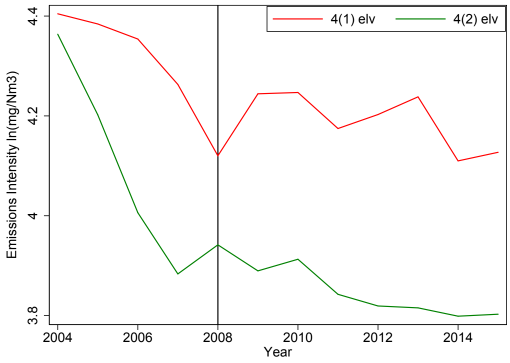


(f) Dust - Opt Out MS

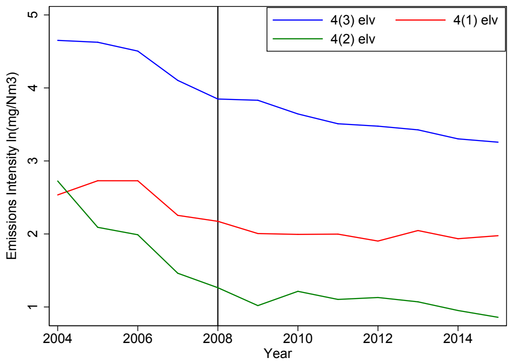
Figure 5: Diagnosis of Trends II



(a) NOx - All LCP

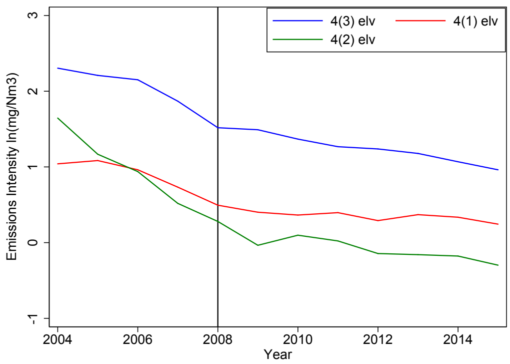


(b) NOx - Affected by IPPC



(c) SO2 - All LCP

(d) SO2 - Affected by IPPC



(e) Dust - All LCP

(f) Dust - Affected by IPPC

Note: The RHS column plots emission intensities for all plants that starting operating after 1998. The RHS sample gets limited to those combustion units for which we have information on the operation date. LHS plots the trends for all large combustion plants in the full database and reveal similar trend differences between 4(1) ELV and 4(2) ELV plants.

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

	Dependent variable: ln (NOx)				
	(1)	(2)	(3)	(4)	(5)
(Post 2007)*(4-3 ELVs)	-0.110***	-0.105***	-0.072	-0.105*	-0.065
	(0.041)	(0.042)	(0.045)	(0.058)	(0.052)
Size Control	Yes	Yes	Yes	Yes	Yes
Fuel Control	No	No	No	No	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
Plant FE	Yes	Yes	Yes	Yes	Yes
Industry-by-Year FE	No	Yes	Yes	Yes	Yes
Country-by-Year FE	No	No	Yes	Yes	Yes
Regulation-Country Specific Trend	No	No	No	Yes	Yes
N	11,361	11,361	11,361	11,361	11,361
R^2 (within-plant)	0.7636	0.7664	0.7764	0.7774	0.8193

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. The sample is limited to EU countries with opt-out plants under Article 4(3). 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. Size control is the size of the plant in GWth. Fuel controls include the fuel input share of solid, biomass, liquid, other gases, and natural gas (%). The total number of clusters/plants used in estimation were 1283. 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

	Dependent variable: ln (SO_2)				
	(1)	(2)	(3)	(4)	(5)
(Post 2007)*(4-3 ELVs)	-0.270**	-0.289**	-0.218*	-0.394***	-0.276***
	(0.113)	(0.117)	(0.122)	(0.104)	(0.083)
Size Control	Yes	Yes	Yes	Yes	Yes
Fuel Control	No	No	No	No	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
Plant FE	Yes	Yes	Yes	Yes	Yes
Industry-by-Year FE	No	Yes	Yes	Yes	Yes
Country-by-Year FE	No	No	Yes	Yes	Yes
Regulation-Country Specific Trend	No	No	No	Yes	Yes
N	9,765	9,765	9,765	9,765	9,765
R^2 (within-plant)	0.8606	0.8642	0.8725	0.8737	0.9140

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. The sample is limited to EU countries with opt-out plants under Article 4(3). 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. Size control is the size of the plant in GWth. Fuel controls include the fuel input share of solid, biomass, liquid, other gases, and natural gas (%). The total number of clusters/plants used in estimation were 1170. Standard errors in parentheses are clustered at the plant level and robust to heteroskedasticity. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 11: Estimated Effect of ELVs Under Article 4(3) Regulation

	Dependent variable: ln (Dust)				
	(1)	(2)	(3)	(4)	(5)
(Post 2007)*(4-3 ELVs)	-0.319***	-0.258***	-0.240***	-0.256**	-0.192**
	(0.087)	(0.088)	(0.086)	(0.103)	(0.089)
Size Control	Yes	Yes	Yes	Yes	Yes
Fuel Control	No	No	No	No	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
Plant FE	Yes	Yes	Yes	Yes	Yes
Industry-by-Year FE	No	Yes	Yes	Yes	Yes
Country-by-Year FE	No	No	Yes	Yes	Yes
Regulation-Country Specific Trend	No	No	No	Yes	Yes
N	9,274	9,274	9,274	9,274	9,274
R^2 (within-plant)	0.7945	0.7980	0.8104	0.8117	0.8481

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. The sample is limited to EU countries with opt-out plants under Article 4(3). 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. Size control is the size of the plant in GWth. Fuel controls include the fuel input share of solid, biomass, liquid, other gases, and natural gas (%). The total number of clusters/plants used in estimation were 1107. 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 ELVs Under Article 4(3) Regulation

	Dependent variable: ln (mg/nM^3)								
	NOx	SO_2	Dust	NOx	SO_2	Dust	NOx	SO_2	Dust
(Post 2007)*(4-3 ELVs)	-0.105*	-0.394***	-0.256**						
	(0.058)	(0.104)	(0.103)						
(Post 2006)*(4-3 ELVs)				-0.073	-0.133	-0.118			
				(0.061)	(0.115)	(0.110)			
(Post 2005)*(4-3 ELVs)							-0.003	-0.032	0.022
							(0.046)	(0.104)	(0.100)
Size Control	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Fuel Control	No	No	No	No	No	No	No	No	No
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Plant FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry-by-Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country-by-Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Regulation-Country Specific Trend	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	11,361	9,765	9,274	11,361	9,765	9,274	11,361	9,765	9,274
R^2 (within-plant)	0.7774	0.8737	0.8117	0.7774	0.8735	0.8116	0.7773	0.0.8735	0.8116

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. The sample is limited to EU countries with opt-out plants under Article 4(3). Combustion plants that were licensed post-January 1987 are not included in the analysis. We exclude plants that were using a gas or diesel engine. Size control is the size of the plant in GWth. 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 ELVs Under Article 4(1) Regulation

	Dependent variable: ln (mg/nM^3)								
	NOx	SO_2	Dust	NOx	SO_2	Dust	NOx	SO_2	Dust
(Post 2007)*(4-1 ELVs)	-0.045	-0.307**	-0.176						
	(0.068)	(0.124)	(0.126)						
(Post 2006)*(4-1 ELVs)				-0.097	-0.197	0.026			
				(0.083)	(0.138)	(0.138)			
(Post 2005)*(4-1 ELVs)							-0.045	-0.054	0.109
							(0.062)	(0.123)	(0.130)
Size Control	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Fuel Control	No	No	No	No	No	No	No	No	No
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Plant FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry-by-Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country-by-Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Regulation-Country Specific Trend	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	8,196	5,932	5,545	8,196	5,932	5,545	8,196	5,932	5,545
R^2 (within-plant)	0.7563	0.9058	0.8548	0.7564	0.9058	0.8547	0.7563	0.9058	0.8548

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. The sample is limited to EU countries with opt-out plants under Article 4(3). We exclude plants that were using a gas or diesel engine. Size control is the size of the plant in GWth. 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

Plants Affected by IPPC

	Dependent variable: ln (NOx)			
	(1)	(2)	(3)	(4)
	kt/pt	mg/nM^3	kt/pt	mg/nM^3
	1999-2004	1999-2004	2001-2004	2001-2004
4(2) ELVs	-0.162***	-0.160***	-0.070*	-0.066
	(0.037)	(0.037)	(0.042)	(0.042)
Fuel Controls	Yes	Yes	Yes	Yes
Size Control	Yes	Yes	Yes	Yes
Combustion FE	Yes	Yes	Yes	Yes
Industry x Year FE	Yes	Yes	Yes	Yes
Country x Year FE	Yes	Yes	Yes	Yes
4(2) Treated Plants	130	130	130	130
4(1) Control Plants	240	240	103	103
No. of Clusters	213	213	177	177
N	3,525	3,525	2,183	2,183
R^2	0.3584	0.5482	0.4167	0.6295

Notes: The dependent variable is the log of emissions intensity, defined either as emissions per energy input unit (kilotonnes per petajoule) or mg/nM^3. We exclude plants that were using a gas or diesel engine. Size control is the size of the plant in GWth. Fuel controls include the fuel input share of solid, biomass, liquid, other gases, and natural gas (%). Combustion FE are capturing the type of combustion plant (boiler, gas turbine, furnace, etc). Standard errors in parentheses are clustered at the country-by-year 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

Plants Affected by IPPC

	Dependent variable: ln (SO_2)			
	(1)	(2)	(3)	(4)
	kt/pt	mg/nM^3	kt/pt	mg/nM^3
	1999-2004	1999-2004	2001-2004	2001-2004
4(2) ELVs	-0.276**	-0.273**	-0.284**	-0.278**
	(0.115)	(0.115)	(0.123)	(0.123)
Fuel Controls	Yes	Yes	Yes	Yes
Operation Controls	Yes	Yes	Yes	Yes
Combustion FE	Yes	Yes	Yes	Yes
Industry x Year FE	Yes	Yes	Yes	Yes
Country x Year FE	Yes	Yes	Yes	Yes
4(2) Treated Plants	104	104	104	104
4(1) Control Plants	204	204	88	88
No. of Clusters	201	201	144	144
N	2,412	2,412	1,489	1,489
R^2	0.6312	0.6906	0.5738	0.6474

Notes: The dependent variable is the log of emissions intensity, defined either as emissions per energy input unit (kilotonnes per petajoule) or mg/nM^3. We exclude plants that were using a gas or diesel engine. Size control is the size of the plant in GWth. Fuel controls include the fuel input share of solid, biomass, liquid, other gases, and natural gas (%). Combustion FE are capturing the type of combustion plant (boiler, gas turbine, furnace, etc). Standard errors in parentheses are clustered at the country-by-year 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

Plants Affected by IPPC

	Dependent variable: ln (Dust)			
	(1)	(2)	(3)	(4)
	kt/pt	mg/nM^3	kt/pt	mg/nM^3
	1999-2004	1999-2004	2001-2004	2001-2004
4(2) ELVs	-0.309***	-0.305***	-0.409***	-0.403***
	(0.107)	(0.106)	(0.110)	(0.109)
Fuel Controls	Yes	Yes	Yes	Yes
Operation Controls	Yes	Yes	Yes	Yes
Combustion FE	Yes	Yes	Yes	Yes
Industry x Year FE	Yes	Yes	Yes	Yes
Country x Year FE	Yes	Yes	Yes	Yes
4(2) Treated Plants	94	94	94	94
4(1) Control Plants	191	191	82	82
No. of Clusters	196	196	149	149
N	2,116	2,116	1,297	1,297
R^2	0.5127	0.6017	0.5157	0.6112

Notes: The dependent variable is the log of emissions intensity, defined either as emissions per energy input unit (kilotonnes per petajoule) or mg/nM^3. We exclude plants that were using a gas or diesel engine. Size control is the size of the plant in GWth. Fuel controls include the fuel input share of solid, biomass, liquid, other gases, and natural gas (%). Combustion FE are capturing the type of combustion plant (boiler, gas turbine, furnace, etc). Standard errors in parentheses are clustered at the country-by-year level and robust to heteroskedasticity. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 17: 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)	0.014	0.009	0.060	0.054	0.089	0.073
	(0.034)	(0.033)	(0.077)	(0.069)	(0.072)	(0.069)
Size Control	Yes	Yes	Yes	Yes	Yes	Yes
Fuel Control	No	Yes	No	Yes	No	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Plant FE	Yes	Yes	Yes	Yes	Yes	Yes
Industry-by-Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Country-by-Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Regulation-Country Specific Trend	Yes	Yes	Yes	Yes	Yes	Yes
N	27,253	27,253	20,688	20,688	19,632	19,632
R^2 (within-plant)	0.7326	0.7587	0.8835	0.9127	0.8313	0.8534

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. Size control is the size of the plant in GWth. 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 18: Plant Shutdowns by Last Reporting Year

Shutdown Year	4(3) Optout	4(3) ELV	4(1) ELV	4(2) ELV
2004	0	4	0	0
2005	0	6	0	0
2006	0	5	0	0
2007	0	82	15	8
2008	3	44	22	21
2009	9	47	9	8
2010	3	34	9	2
2011	4	27	9	1
2012	10	59	32	14
2013	19	66	30	7
2014	11	45	15	8
2015	35	134	62	40
Total	95	553	203	109

Note: The table shows the number of plant shutdowns by regulation status.
We assume that plant was shutdown, if it was not reported to the EEA the next year.

Table 19: Were Opt-out Plants More Likely to Shutdown?

Linear Probability Model

	Dependent variable: Shutdown	
	(1) - All EU	(2) - Optout MS
Article 4(3)	-0.004	-0.004
	(0.003)	(0.003)
Article 4(1)	-0.010***	-0.009***
	(0.003)	(0.003)
Article 4(2)	-0.013***	-0.009**
	(0.004)	(0.004)
Opt Out	Omitted	Omitted
Fuel Controls	Yes	Yes
Emissions Intensity	Yes	Yes
NERP	Yes	Yes
Operation Controls	Yes	Yes
Combustion FE	Yes	Yes
Industry x Year FE	Yes	Yes
Country x Year FE	Yes	Yes
N	34,509	21,692
R^2	0.1860	0.2043
Clusters	3,973	2,624

Notes: This table reports estimates of Equation (2). The dependent variable is a binary variable (1 or 0) indicating whether the plant was closed by the end of the reporting year. We assume that plant was shutdown, if it was not reported to the EEA the next year. Operation controls consist of the size of the plant in GWth and absolute energy input in petajoules. Fuel controls include the fuel input share of solid, biomass, liquid, other gases, and natural gas (%). Emissions intensity controls for emission intensities of the three local pollutants considered in this paper. NERP is a dummy variable if the plant was part of the National Emission Reduction Plan. Combustion FE are capturing the type of combustion plant (boiler, gas turbine, furnace, etc). Standard errors in parentheses are clustered at the plant level and robust to heteroskedasticity. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.