The Spatial Consequences of Industrial Environmental Regulation*

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Abstract

This paper studies how size- and place-based industrial regulation of local air pollution affects emissions, production, and welfare when firms can abate or reallocate emissions across plants, sectors, and regions. I examine South Korea's cap-and-trade system, which, because of limited monitoring and enforcement capacity, covers only large polluting manufacturing and power plants in polluted, densely populated districts. Using a difference-in-differences design, I find pronounced sectoral asymmetry: in regulated manufacturing district-industry pairs, NO_x, SO_x, and TSP emissions fall by 41%, 42%, and 35%, respectively, while emissions from power plants do not decline, consistent with electrification and leakage from manufacturing to power generation. I also document geographic leakage that decays with distance from regulated districts. Because these spillovers prevent reduced-form estimates from recovering aggregate and spatial incidence, I develop a spatial general equilibrium model with multiple manufacturing sectors and upstream power generation. The model implies that leakage accounts for one quarter of the observed emissions response and that a 5 percent improvement in air quality outweighs roughly 1 percent declines in both consumption and production, raising aggregate welfare despite spatially uneven effects. The targeted policy outperforms feasible alternatives, including a spatially uniform regulation.

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1 Introduction

How do size- and place-based industrial environmental regulations affect emissions, output, and welfare when firms can abate or reallocate emissions? How do these effects differ across plants, sectors, and regions? These questions are especially important for local air pollution. Unlike greenhouse gases, pollutants such as NO_x, SO_x, and TSP generate damages that are highly localized and depend on where emissions occur. In practice, since monitoring and enforcement are costly, policies targeting these pollutants are local because the damages from local air pollution are greater in densely populated and highly polluted regions. Further, regulators often focus on large emitters in such locations. Such targeting can be welfare improving when marginal damages vary across space, but its consequences depend on how firms adjust and on where emissions relocate.

I study these issues in the context of South Korea's local air pollutant cap-and-trade system, the Total Volume Control of Pollutants at Place of Business. Beginning in 2020, the system covered emissions of NO_x, SO_x, and TSP from large polluting establishments in polluted, densely populated districts. In reality, coverage is concentrated in manufacturing and power generation due to their significant emissions.[1]. Its relevance also extends beyond Korea because this setting is useful for studying the aggregate and spatial incidence of environmental regulation because it combines two common features of a frontier local air pollution policy, or a cap-and-trade system—size-based coverage and spatial targeting—within an integrated national economy. Reliable emissions measurement and limited enforcement capacity are central design constraints in emissions trading known to be a highly effective market-based regulation (Fowlie et al., 2012), and such systems have expanded rapidly worldwide: as of 2025, more than 38 emissions trading systems were in force globally, with another 20 under development or under consideration, including large polluting countries such as the China, India, and U.S.. Although most of these systems regulate greenhouse gases rather than local air pollutants, the same administrative logic is increasingly shaping air pollution markets as well because large emitters are regulated and there is an analogy to international emissions control even when a trading is nationally global. Further, these adminsitrative constraints can be found in developing countries where such capacity lags behind.

Importantly, under the constraints, such a policy design can be welfare improving because it directly targets major emission sources in places where pollution damages are large. The welfare and distributional consequences depend on how regulated plants adjust, because emissions may be reallocated across plants, sectors, and regions. Regulated plants

[1]Typically, they account for more than 50% of local or global air pollution in developed economies (International Energy Agency, 2024; U.S. Environmental Protection Agency, 2024).

may abate by changing fuel and factor use or by adopting emission control technologies. But regulation may also induce several forms of leakage—the reallocation of emissions from more regulated to less regulated units—across plants, sectors, and regions. Within manufacturing, regulated plants may lose market share to unregulated plants in the same sector or outsource pollution-intensive activities to unregulated upstream suppliers. Industrial electrification may shift emissions from manufacturing to power plants. Across space, emissions may relocate to less regulated locations (the Pollution Haven Effect) because manufacturing plants and power plants can produce in one location and sell in another. Understanding these responses is central to the design of effective environmental policy under administrative constraints. A growing literature studies the effects of such environmental regulations on emissions, economic activity, and welfare. Yet evidence linking these mechanisms within a unified framework remains limited because of the lack of granular data and identification challenges arising from spillovers.

I begin by combining detailed data on emissions, inputs, and outputs for manufacturing plants, power plants, and district-industry pairs and exploit policy variation across emissions thresholds and districts in a difference-in-differences design to estimate the policy's effects on emissions, economic outcomes, abatement, and leakage channels. I find that regulated manufacturing plants increase electricity use, reduce fossil fuel consumption, and intensify the use of emission control measure. By contrast, unregulated affiliated manufacturing plants and regulated power plants exhibit no significant changes along these margins, although their sales increase. The former is consistent with stronger within-manufacturing-firm leakage, and the latter is in line with increased electricity demand from industrial electrification and leakage from manufacturing to power generation. I then examine the policy's effects at the district-industry level. I find pronounced sectoral asymmetry: in regulated manufacturing district-industry pairs, emissions of NO_x, SO_x, and TSP fall by 41%, 42%, and 35%, respectively, relative to unregulated pairs. Sales also decline by 10%, although by less than emissions. By contrast, emissions and sales from power plants do not decline.

I then examine where emissions leak. Leakage is concentrated in manufacturing, as power plants do not reduce emissions and have limited scope to reallocate generation and emissions across locations. Geographically, leakage is strongest in nearby unregulated districts, consistent with spatial decay. These patterns imply that conventional difference-in-differences estimates are biased by violations of the Stable Unit Treatment Value Assumption (SUTVA), requiring an understanding of the geographic distribution of emissions and output. Also they cannot by themselves deliver the counterfactuals needed for policy evaluation.

I therefore develop a spatial general equilibrium model of manufacturing plants and upstream power plants to interpret these channels, evaluate the welfare effects of the policy,

and conduct counterfactual policy experiments. The model builds on Shapiro et al. (2018) and Arkolakis et al. (2023), while extending those frameworks to incorporate abatement through factor substitution, fuel switching, and emission control technologies, and to allow leakage across plants, sectors, and districts. The model is disciplined by abatement elasticities from the reduced-form evidence and additional estimates of substitution elasticities from the production function estimation. These parameters include substitution elasticities across factors and fuels and elasticities governing the use of emission control measures in response to changes in pollution prices. Together, they determine how firms respond to environmental regulation, including the extent of leakage from industry to power generation and allow me to translate the treatment effects into aggregate and spatial outcomes and to evaluate counterfactual policies.

The quantitative analysis yields three main results. First, I provide a structural interpretation of the empirical evidence while accounting for SUTVA violations by decomposing the responses of regulated and unregulated plants and district-industry pairs. The model shows that a quarter of the policy effect on emissions at the district-manufacturing industry pairs come from leakage across districts. Second, I quantify the policy's effects and find that the policy raises aggregate welfare: a 5% improvement in air quality outweighs roughly 1% declines in both consumption and production. The effects are spatially uneven. Regulated districts benefit from cleaner air but bear losses in consumption and production, whereas unregulated districts exhibit the opposite pattern. Third, under administrative constraints, the observed targeted policy outperforms feasible alternatives, including a spatially uniform regulation. For local pollutants, this occurs because targeting and the resulting leakage shift emissions away from the most polluted and densely populated districts, where marginal damages are highest.

Related literature

This paper brings a geographic perspective to two central questions in environmental regulation: abatement and leakage. I study how these channels shape the spatial distribution of emissions and economic activity. The first strand of the literature examines abatement (Copeland et al., 2004), either through the adoption of emission control measures (Greenstone et al., 2023) or through changes in fuel composition (De Simone et al., 2024; Murray Leclair, 2024; Colmer et al., 2025); see Gillingham and Stock (2018) for a review. This work has improved our understanding of how firms move toward cleaner production. My findings, however, show that abatement is accompanied by economically important leakage: when regulation varies across emission volumes, sectors, and regions, emissions and production can be reallocated across plants, sectors, and space.

A second strand studies such leakage (Levinson et al., 2008; Chen et al., 2021; Tanaka

et al., 2022; Yang et al., 2024; Curtis et al., 2025). More recent work emphasizes leakage to upstream sectors, especially power generation, in the context of rising industrial and transport electrification (Holland et al., 2020; Holland et al., 2024; Levinson et al., 2025). Growing regional and international disputes over emission control underscore the importance of these issues, which are particularly salient for local pollutants whose damages are spatially concentrated. I contribute to this literature by showing not only that both abatement and leakage are quantitatively important, but also that part of the leakage arises precisely in response to abatement efforts.

Regional heterogeneity adds a further dimension. Exposure to regulation and the incidence of leakage depend on local conditions, including the concentration of polluting manufacturing activity and the availability of fossil fuel power generation capacity. A third strand of research therefore studies environmental policy and climate shocks in space (Desmet et al., 2015; Conte et al., 2021; Kortum et al., 2021; Cruz et al., 2022; Krusell et al., 2022; Weisbach et al., 2023; Cruz, 2024; Cruz et al., 2024; Farrokhi et al., 2024—see Copeland et al. (2021) and Desmet et al., 2024 for reviews).

This paper bridges these strands in a spatial setting by analyzing how environmental regulation induces abatement—through fuel substitution and emission control measure use—and leakage across plants, sectors, and regions. Empirically, I show that the responses are strongly asymmetric across sectors and document how a size- and place-based air pollution policy reallocates emissions. Manufacturing plants account for most of the decline in emissions, whereas power plants do not reduce emissions because industrial electrification raises electricity demand and shifts emissions toward power generation. Geographic leakage is likewise concentrated in manufacturing. Quantitatively, I develop a unified spatial model of manufacturing and power generation with these channels, which can change the assessment of the actual and counterfactual policies. Estimating the parameters that govern these responses allows me to quantify how the balance between abatement and leakage shapes aggregate and regional welfare.

The paper is also closely related to work on the spatial effects of environmental policy (Fowlie et al., 2012; Shapiro et al., 2018; Xiang, 2023; Arkolakis et al., 2025). I extend this line of research by allowing regulatory variation by size, sector, and location and by incorporating the resulting abatement and leakage channels. The framework therefore tracks how emissions and production are reallocated both within and across manufacturing and power generation and regulated and unregulated regions.[2] The paper also focuses on local

[2]The model is static. A dynamic extension could capture short-run leakage, long-run clean innovation, and richer welfare dynamics (Xiang, 2023). I focus on the adoption of existing abatement technologies—such as fuel switching and end-of-pipe controls including filters and scrubbers—rather than on innovation itself, and I abstract from the fixed and sunk costs associated with large-scale abatement investment. This

air pollution rather than greenhouse gases. Although the two often share common sources, the relevant abatement technologies and the spatial scope of damages differ, which leads to different policy trade-offs. Finally, Arkolakis et al. (2023) study clean growth driven by clean power supply. Shifting the focus from power supply to environmental regulation, I examine how sustainability can arise through industrial electrification together with clean power generation.[3]

The remainder of the article is structured as follows. Section 2 summarizes the institutional background, and Section 3 describes the data. Section 4 explains an identification strategy and provides empirical evidence of the policy effect. Section 5 outlines a quantitative model, and Section 6 quantifies it. Section 2 conducts counterfactual policy experiments and presents the model-based aggregate and distributional effects on emissions and economic activities. Section 8 concludes.

2 Policy Background

Air pollution has become a central policy priority due to its significant effects on economic activity and human well-being. In particular, local air pollutants, such as nitrogen oxide (NO_x), sulfur oxide (SO_x), and total suspended particulates (TSP), are known to contribute to smog and acid rain and damaging human health, infrastructure, and the environment. Hence, Korea has regulated them since the early 1990s with two main instruments: command-and-control regulation of pollutant concentrations and emissions taxes. Neither instrument, however, directly constrained the total quantity of emissions. The Total Volume Control of Pollutants at Place of Business was introduced to address this limitation.

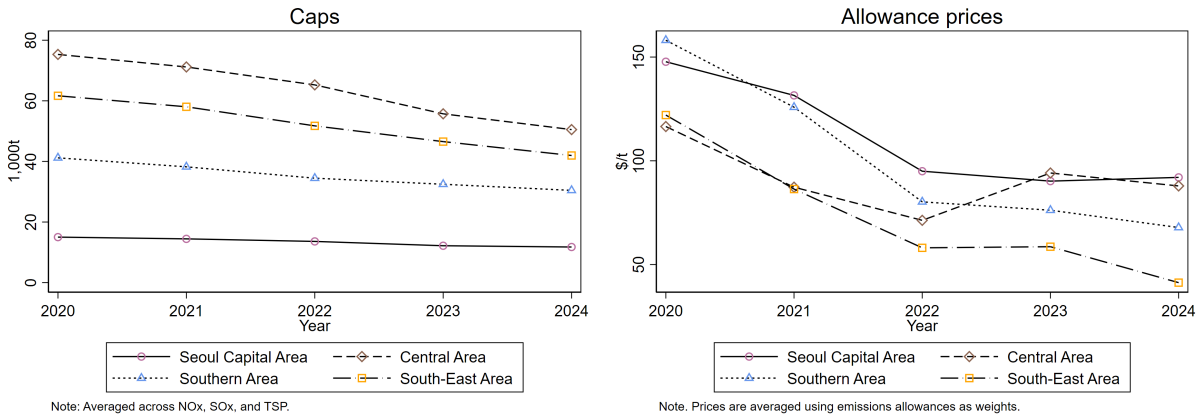
The program is a cap-and-trade system designed to reduce emissions of NO_x, SO_x, and TSP. It freely allocates emissions permits to regulated establishments, with initial allocations based on pre-regulation emissions and caps that subsequently decline over time. Because the program directly constrains the total quantity of emissions, it is better suited to reducing aggregate emissions than earlier instruments (Figure 1). Relative to non-market-based regulation, it also promotes cost effectiveness and compliance flexibility by allowing firms to trade permits according to their abatement costs and their incentives to reallocate production (Fowlie et al., 2012; Gillingham and Stock, 2018). Regulated plants must surren-

emphasis on the intensive margin is well suited to short-run policy instruments, such as pollution taxes and permit trading systems, that operate by changing marginal incentives. By contrast, Arkolakis et al. (2025) study lumpy abatement or technology switching in a dynamic setting with fixed adoption costs.

[3]Following the literature, I classify bio (biological), coal gasification, fuel cell, hydro, marine (ocean), nuclear, solar, waste, or wind as a source of clean power generation and coal, gas, and oil (fossil fuel) as a source of dirty power generation.

der permits annually to match realized emissions. Excess emissions trigger fines, reductions in future permit allocations, and potentially shutdown orders, with penalties increasing in the severity of the violation.

Figure 1: Allowance prices and caps

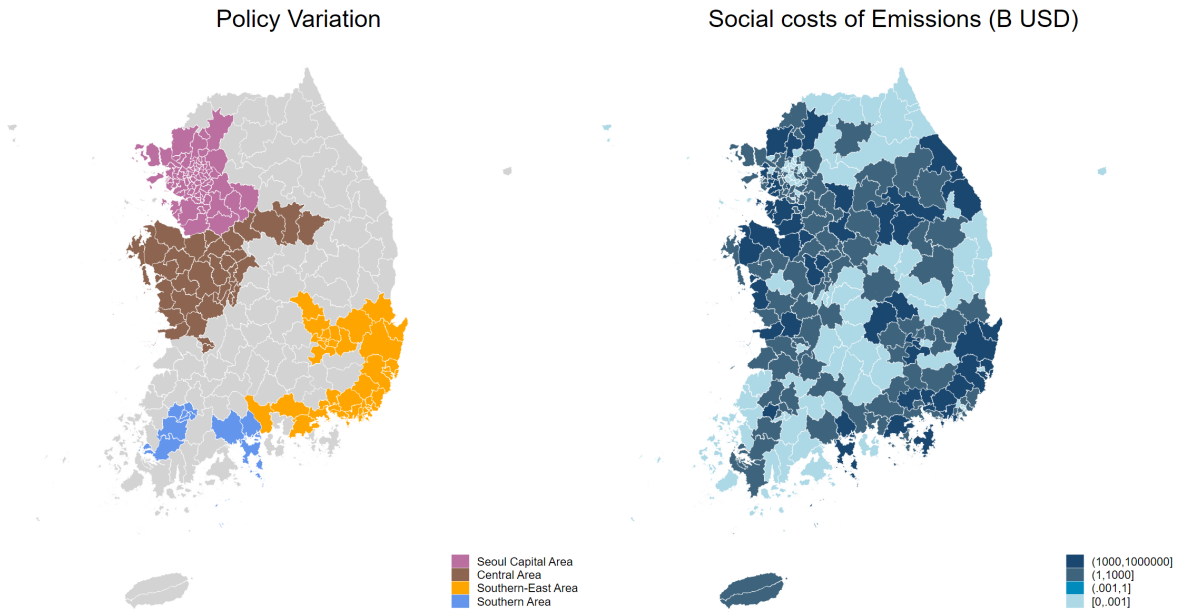


Notes: The first panel shows the average market level pollutant caps in each area over time. Caps are adjusted using past emissions proportionally across sectors. Under a cap-and-trade system, these trajectories of the average caps represent the average policy reduction goals in regulated areas. In the second panel, the average transaction unit price is disclosed as the annual transaction amount divided by the annual transaction volume (excluding free transactions) in each area. I use annual average spot exchange rates to change the unit from Korean won to US dollar. For each year and area, pollutant prices are averaged with emissions allowances as weights. There is no explicit price-stabilizing mechanism. In both, I drop the caps and prices in the Seoul Capital Area from its initial adoption for brevity.
Sources: Ministry of Environment, Federal Serve Bank of St. Louis.

The program reflects two dimensions of government prioritization. First, it targets polluted and densely populated districts. According to the Ministry of Environment, in 2018, the regulated districts accounted for more than 80% of TSP emissions, 88% of the population, and 38% of land area. Figure 2 shows that the social costs of local air pollution are correspondingly higher in regulated districts. The policy was first introduced in the Seoul Capital Area in 2007 and expanded in 2020 to the Central, Southern, and South-East Areas, leaving the remaining districts unregulated.[4] Importantly, the policy areas do not align with standard administrative or policy boundaries (e.g., provinces or the Ministry of Environment's jurisdictions), reducing the risk of confounding from other regional policies. I focus on the 2020 expansion because it substantially broadened the scope of the policy: the number of regulated plants increased from roughly 400 to 1,200. Moreover, the effects of the earlier phase remain unsettled. While this paper is, to my knowledge, the first to evaluate the 2020 expansion, Im (2023) finds significant emission reductions from the initial adoption, whereas Lee (2019) argues that it was ineffective.

[4]Since 2018, TSP has also been regulated in the Seoul Capital Area.

Figure 2: Policy map



Notes: The left map show the spatial variation of the policy and the social costs of emissions (in billion USD in 2018) by area. The gray area of the left map represents unregulated districts. These regulated areas correspond to aggregates of administrative districts in South Korea. There are 250 districts—the smallest self-governing units below 17 metropolitan cities and provinces (e.g., Seoul and Gyeonggi). In the right map, instead of addressing pollutants separately, I use the social cost of emissions summed across pollutants with populations as weights, SCE, as emissions and welfare measures of all three air pollutants in monetary terms, because it is coherent and policy-relevant when different pollutants have different damages: $SCE_i = L_i \times \sum_{p \in \{NO_x, SO_x, TSP\}} SC^p \times S_i^p$ where L_i is population of district i, SC^pgoverns the social cost of pollutant p, and S_i^p is the emissions of pollutant p in district i. This calculation assumes that only local population is exposed to local pollution. The two maps show a positive correlation. One exception to this alignment is Gangwon Province at the right side of the Seoul Capital Area. This area is, in general, exempt from many environmental regulations due to its relatively low development and low population.
Sources: Ministry of Environment, Federal Serve Bank of St. Louis.

The pace at which caps decline differs by market, where a market is defined as an area-pollutant pair and the reduction schedule is set jointly by the central and local governments. Permits can therefore be traded only within these markets. Figure 1 plots allowance prices across areas over time. Given the declining path of permit supply, high initial prices are consistent with effective emissions reductions, which lower permit demand over time. Section 4 provides supporting evidence. At the same time, prices did not collapse but instead stabilized, suggesting that the market remained active (Colmer et al., 2025).[5]

Second, the program targets large emitters through a two-stage rule based on emissions

[5]Pollutant-specific variation is presented in Figures A.1 and A.2.

in the previous two years. An establishment is first designated as a candidate if its combined annual emissions of NO_x, SO_x, and TSP exceed 10 tons. Among these candidates, a given pollutant is regulated if its emissions exceed the pollutant-specific threshold: 4 tons for NO_x, 4 tons for SO_x, or 0.2 tons for TSP. In manufacturing and power generation, plants above these thresholds account for 71%, 66%, and 22% of emissions of NO_x, SO_x, and TSP, respectively, in regulated districts. Interviews with officials at the Ministry of Environment indicate that these thresholds were intended to reflect the maximum quantity of emissions that could be feasibly monitored and controlled under administrative constraints.[6] Such a constraint is prevalent for regulations like cap-and-trade systems because emissions should be measured correctly to control caps and allocate allowances as intended. Also, although this rule is ex-ante sector-neutral, ex-post it generates sectoral concentration in treatment: manufacturing and power plants account for 82% of regulated establishments.[7]

Taken together, these features create several abatement and leakage margins. Within sectors, emissions may shift to unregulated plants as regulated plants lose competitiveness. Because manufacturing and power both produce tradable goods, economic activity and emissions can also be reallocated across locations. Across sectors, emissions may shift from manufacturing to power generation if manufacturing plants reduce on-site fossil fuel use by electrifying production and clean power capacity is insufficient to meet the resulting increase in electricity demand. In that case, fossil fuel power plants face both direct regulation and an indirect demand shock from industrial electrification. Within manufacturing, dirty production stages may also be outsourced to unregulated plants.

These channels matter because they imply different distributional consequences across space. Emissions may relocate from regulated to unregulated districts. Interviews with the government officials suggest that policymakers were aware of this possibility but viewed it as difficult to avoid given the need to prioritize regulation under limited administrative capacity. Such geographic leakage may be less relevant for power plants, whose dispatch is centrally determined by marginal generation costs. A central question is therefore whether the policy induced abatement and leakage across plants, sectors, and districts, and, if so, by how much.

The policy intervention of interest is entry into the cap-and-trade system itself. Treated plants were exempted from part of the pre-existing pollution tax, but this exemption was intended to avoid double regulation at the margin. In practice, the cap-and-trade system is

[6]These government officials work at the Air Quality Management Division of the Korean Ministry of Environment and the Metropolitan Air Quality Management Office of the Korean Ministry of Environment, respectively. The former division is chosen as it governs the overall aspect of the policy, and the latter office is chosen as it manages the policy implementation in the Seoul Capital Area and has the longest experience with this policy since 2007.

[7]I group mining with manufacturing because of their similar resource-based production processes and the frequent switching of plants between the two categories.

more stringent because compliance requires surrendering permits against realized emissions rather than simply paying a higher tax. I therefore define treatment as exposure to the cap-and-trade program, not as exemption from part of the pollution tax. In the baseline analysis, the control group consists of plants that were never brought into the new system. As a robustness check, I also use a cleaner treatment definition that excludes plants in the Seoul Capital Area, which had already been regulated before the 2020 expansion. For additional institutional detail, see Appendix A.

3 Data

This section describes the data used to study the effects of the policy on emissions and economic outcomes in manufacturing and power generation from 2016 to 2023. Appendix B provides additional details on construction, matching, variable definitions, and coverage.

3.1 Policy and Emissions

The Korean Ministry of Environment provides two sets of policy data: a plant-level registry of regulated establishments, including targeted pollutants, locations, sectors, and plant names, and a pollution-market-level panel with emissions, permit allocations, and allowance prices over time. The ministry also provides emissions information through tele-monitoring records and the Stack Emission Management System (SEMS). Tele-monitoring provides real-time emissions for large emitters, and SEMS extends the data with plant operation information as a broader annual emissions inventory covering the universe of establishments and the basis for policy targeting. Pollutant- and source-specific emission factors are available, developed jointly with the National Institute of Environmental Research, for emissions from production processes and fossil fuel use (Tables A.3 - A.14). Although the policy targets local air pollutants, much of these emissions are related to fossil fuel use—coal, gas, and oil—which also makes the setting relevant for decarbonization. In SEMS, fossil fuel use accounts for 83%, 49%, and 58% of NO_x, SO_x, and TSP emissions, respectively, over the sample period.

3.2 Manufacturing and Power Plants

I combine several establishment-level datasets. The main source is Statistics Korea's Statistical Business Register (SBR), which covers the universe of firms and establishments and reports sales, employment, 5-digit industry classifications (also known as the Korean Standard

Industrial Classifications (KSICs)), and locations. For mining and manufacturing establishments, the SBR also reports fuel use and greenhouse gas emissions by fuel type (coal, electricity, gas, oil, renewable, and the rest) based on the Mining and Manufacturing Survey (MMS) sample. I also use the MMS, which provides detailed information on fuel expenditures, materials, wages, and other production inputs, for all plants with more than ten employees and a representative sample of smaller plants. For power generation, I use plant-level data from the Korea Electric Power Corporation (KEPCO), including fuel use, generation capacity, electricity output, and plant locations. I also use administrative records from the Ministry of the Interior and Safety and the Ministry of Environment on emission control measures in manufacturing and power plants. While these metrics do not isolate the technology's utilization rate from the plant's overall hours of operation, these records capture updates in installed abatement equipment and its intensity of use, and provide complementary evidence on firms' abatement responses.

3.3 Final data

I merge these datasets using tax identifiers, locations, and industry classifications. The final panel covers 250 administrative districts, 117 3-digit KSIC industries, and 1,018 regulated manufacturing and power plants. Relative to the existing literature, the data offer broad national coverage and detailed plant-level information at a fine geographic unit. This makes it possible to track changes in emissions and economic activity across regulated and unregulated districts. Their main limitation is standard in this setting: emissions are observed at an aggregate district-industry level for confidentiality reasons, whereas inputs and outputs are observed at the plant level. This constraint is particularly important for local air pollutants, because emissions arise both from fuel use and from production processes, and because end-of-pipe abatement plays an important role.[8] I therefore use district-industry emissions to estimate aggregate policy effects, and plant-level input and output data to study the mechanisms behind those effects. As will be shown later, they are sufficient to guide the model quantification and provide policy implications.

4 Empirical Analysis

This section empirically evaluates the policy effect and investigates its underlying mechanisms. First, I conduct decomposition to show raw trends and give a hint on the mechanisms

[8]Greenhouse gas emissions, however, are typically computed with fuel uses and emissions factors in the literature and most policy implementations.

behind emissions reduction. Second, I use difference-in-differences to study the policy effect more rigorously.

4.1 Decomposition

I conduct decomposition on the social cost of emissions over the regulated and unregulated areas i, setting the year 2016 as the base period:

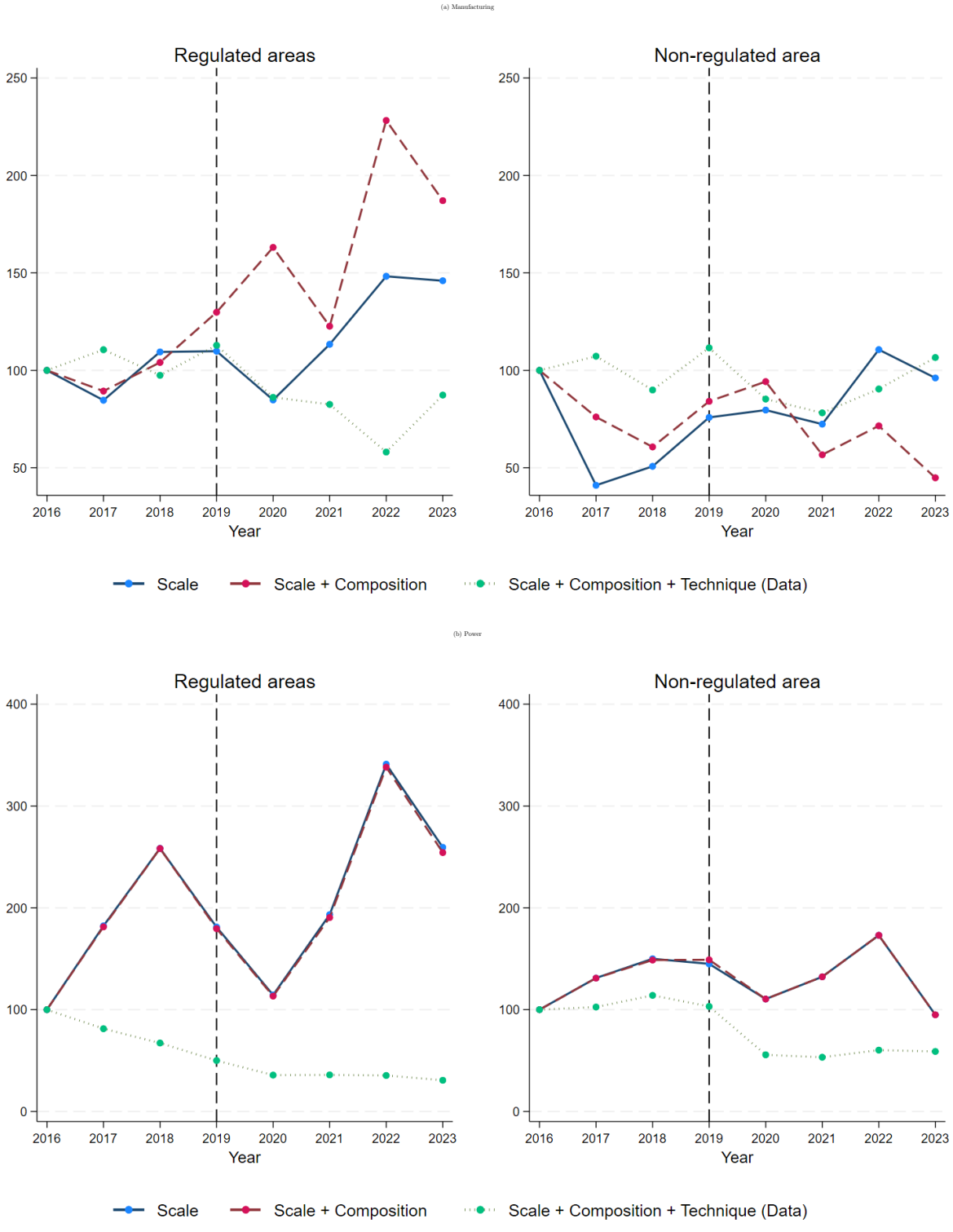
$$SCE_i = \underbrace{Y_i}_{\text{Scale effect}} \sum_{p\in\{NO_x,SO_x,TSP\}} \sum_s \underbrace{\frac{Y_{i,s}}{Y_i}}_{\text{Composition effect}} \underbrace{\frac{L_i \times SC^p \times S^p_{i,s}}{Y_{i,s}}}_{\text{Technique effect}},$$

where Y is output (sales), Y_s is industry output (industry sales) of 3-digit industry s, and S^p_s is emissions of p in industry s. SC^p denotes the social cost of pollutant p emissions that monetizes pollution-induced disutility. It is also the inverse of the marginal benefit of abatement that includes health and other benefits.[9] It varies by pollutant because each pollutant has a different effect. Also, it varies by location because the cost of local air pollution becomes stronger in populated regions due to its geographic scope. Hence, I use the population in the base period, L_i, to capture the exposure to emissions. Then, the scale effect captures changes in SCE_i only allowing changes in output scale Y_i, the composition effect captures changes in SCE_i only allowing changes in industrial composition $Y_{i,s}/Y_i$, and the technique effect captures changes in SCE_i only allowing changes in emissions intensity $S^p_{i,s}/Y_{i,s}$.

Figure 3 shows that emissions in both sectors decrease more in regulated areas relative to those in the unregulated area in line with the decreasing caps shown in Figure 1. There was a decrease in economic activities in 2020 due to the COVID 19, but it was temporary. In addition, in 2020, there was also a national regulation, which was implemented to address the same pollutant emissions of unregulated plants. These plants are either smaller polluters within regulated areas or any polluters outside regulated areas. That explains some decreases in emissions of the unregulated area after the policy implementation. However, their effects are limited because those regulated plants account for a significant portion of emissions as mentioned above.

[9]The literature tends to estimate it using an integrative assessment model, but this is beyond the scope of this paper. So the value is borrowed from the United States Environmental Protection Agency (EPA).

Figure 3: Decomposition results



Notes: By construction, all effects are normalized to 100 in the base year (2016). Combining the scale, composition, and technique effects together results in a raw data trend.
Sources: Ministry of Environment, Statistics Korea.

Several notable decomposition results also emerge. First, in both sectors, there is a more significant improvement in emissions intensity after the policy was implemented in 2020 in the regulated areas. Second, the decrease in emissions is more significant in manufacturing, implying geographic leakage. Note that such leakage is infeasible in power generation because the electricity demand is dispatched based on the marginal power generation cost. Overall, these results suggest many key patterns from the data. However, since this decomposition is descriptive, I will analyze the policy effect more rigorously in the next step.

4.2 Difference-in-differences

For inference, I employ a semi-parametric difference-in-differences approach (Heckman et al., 1997; Heckman et al., 1998), comparing trends between regulated and unregulated units.[10] The units of analysis are plants and district-industry pairs because real-time emissions data are available at an aggregate level while other variables are observed at the plant level. I show the plant level response (abatement and leakage channels) to the policy to capture the mechanisms behind emissions reduction. Then, I provide results on outcome variables (emissions and output) at the district-industry level to capture the overall policy effect. The baseline event study specification normalizes 2019 as the base period. All outcome variables are expressed in logarithms. At the plant level, I use:

$$
\begin{aligned}
y_{p,t} &= \alpha_p + \alpha_t + \sum_{\tau \neq 2019} \beta_\tau \times Treat_p \times Year_\tau + \varepsilon_{p,t}, \\
y_{p,t} &= \alpha_p + \alpha_t + \beta \times Treat_p \times Post_t + \varepsilon_{p,t}.
\end{aligned} \tag{1}
$$

At the district-industry level, I use:

$$
\begin{aligned}
y_{d,s,t} &= \alpha_{d,s} + \alpha_{s,t} + \alpha_{r,t} + \sum_{\tau \neq 2019} \beta_\tau \times Treat_{d,s} \times Year_\tau + \varepsilon_{d,s,t}, \\
y_{d,s,t} &= \alpha_{d,s} + \alpha_{s,t} + \alpha_{r,t} + \beta \times Treat_{d,s} \times Post_t + \varepsilon_{d,s,t}.
\end{aligned} \tag{2}
$$

In both specifications, $Treat_u$ is a binary indicator equal to 1 if unit u (plant p or district d - 3-digit industry pair s) is treated and 0 otherwise. $Treat_p$ is equal to 1 when plant p is treated by the policy, and $Treat_{d,s}$ is equal to 1 when district d is treated by the policy.

Further, note that, since large polluters tend to be establishments of large firms, a significant portion of regulated manufacturing plants has unregulated affiliated plants, in particular, in the same industries: 66% and 50%.[11] This is important in understanding leakage in

[10] Regression discontinuity is not possible because real-time emissions data at the plant level are limited.

[11] Firms are defined based on corporation. For those that are not corporation, the common ownership is

manufacturing because within-firm leakage is known to be stronger than across-firm leakage (Chen et al., 2021; Curtis et al., 2025).[12] In addition, a majority of such unregulated affiliated plants in the same 3-digit KSICs is in regulated areas: 86%. They are polluters just below the thresholds. If there was strong within-firm leakage, it could have mitigated the policy effect in regulated districts.

Hence, this setup compares regulated district-industry pairs with unregulated pairs, regulated manufacturing plants with unregulated unaffiliated ones, unregulated affiliated manufacturing plants with unregulated unaffiliated ones, and regulated power plants with unregulated ones. r denotes provinces, t indexes calendar years, and $Post_t$ equals 1 for years after 2019. Standard errors are clustered by unit u. The coefficients of interest are β_τ and β, which capture the average policy effect on regulated units relative to controls in event time τ and on average over the post-policy period, respectively.[13]

4.2.1 Identification

The empirical strategy relies on several identifying assumptions. First, the no-anticipation assumption must hold. The 2020 expansion was plausibly unexpected at the plant level, especially outside the Seoul Capital Area. For Seoul Capital Area—where the regulation existed earlier—I treat 2020 as a policy-intensity update and present robustness that excludes this area and reports heterogeneity. The enabling statute was enacted on April 2, 2019 and became effective on April 3, 2020, but plant level caps for 2020–2024 were disclosed only on October 20, 2020, when the Ministry of Environment announced allocations to establishments and set the reduction path. Public hearings held in early 2020 concerned area-level Basic Plans (and were rescheduled on March 5, 2020 due to COVID-19) rather than plant-specific caps. Finally, eligibility relied on absolute, recent-year criteria for sizable sources in the new control zones, which are difficult to fine-tune just before implementation. In 2020 (the initial year), the emissions allowance at the plant level equaled the maximum of 2018 and 2019 emissions. Taken together—late disclosure of plant level caps, procedural (not plant-specific) hearings, and threshold-based eligibility—the rollout appears to constitute a limited-anticipation shock suitable for difference-in-differences.

used. Business group ("Chaebol") is not used because the definition is highly extensive. It decreases the number of firms tenfold, and as this broad definition implies there is no significant response in unregulated and affiliated plants.

[12]The firm ownership in power generation is not considered because within-firm leakage is not feasible. The electricity demand is rationed based on the marginal generation cost (dispatch). So power generation cannot be reallocated as production in manufacturing.

[13]Note that the research design treats multi-pollutant regulations as a single composite policy using size and regional variations to estimate the overall effect. Identifying the contribution of each regulation and the interaction among them requires a structural framework because of the high colinearlity among regulations. Section 5 shows the corresponding mechanisms and embeds them for quantification.

Second, the parallel trend assumption requires that pre-regulation trends in outcomes were similar between treated and controlled units. I employ a matching technique for the plant level analysis (see Appendix B.2.3) and use fixed effects for the district-industry level analysis. The availability of rich pre-regulation covariates and observations at the plant level enables credible matching while the panel structure of the district-industry level data makes fixed effects estimation natural and efficient. As will be shown later, these complementary approaches—grounded in distinct identifying assumptions—yield consistent and robust conclusions.

Table 1: Summary statistics: plant

Manufacturing	Pre-matching			Post-matching		
Regulated	Targeted	Never	StdDif (mean)/Ratio (var)	Targeted	Never	StdDif (mean)/Ratio (var)
ln Measure use	1.34	0.97	0.13	1.32	1.23	0.04
(*s.e.*)	3.15	2.60	1.21	3.13	2.90	1.08
ln Electricity	7.39	2.73	2.31	7.23	3.55	1.81
(*s.e.*)	2.24	1.77	1.26	2.18	2.19	0.99
ln Electricity share	-0.97	-0.26	-0.79	-0.93	-0.34	-0.65
(*s.e.*)	1.03	0.75	1.38	0.98	0.89	1.09
ln Sales	11.62	7.88	2.25	11.47	8.95	1.41
(*s.e.*)	1.79	1.51	1.19	1.72	1.81	0.95
N	779	80,238		721	721	
Manufacturing	Pre-matching			Post-matching		
Unregulated affiliated	Targeted	Never	StdDif (mean)/Ratio (var)	Targeted	Never	StdDif (mean)/Ratio (var)
ln Measure use	1.98	0.97	0.32	1.98	1.96	0.01
(*s.e.*)	3.56	2.60	1.37	3.56	3.52	1.01
ln Electricity	5.72	2.73	1.38	5.72	4.89	0.38
(*s.e.*)	2.51	1.77	1.42	2.51	2.15	1.17
ln Electricity share	-0.54	-0.26	-0.31	-0.54	-0.34	-0.22
(*s.e.*)	0.99	0.75	1.32	0.99	0.59	1.66
ln Sales	10.71	7.88	1.66	10.71	10.62	0.06
(*s.e.*)	1.87	1.51	1.24	1.87	1.66	1.13
N	310	80,238		310	310	
Power generation	Pre-matching			Post-matching		
Regulated	Targeted	Never	StdDif (mean)/Ratio (var)	Targeted	Never	StdDif (mean)/Ratio (var)
ln Measure use	0.27	0.002	0.26	0.19	0.19	0.003
(*s.e.*)	1.42	0.14	10.12	1.26	1.25	1.01
ln Sales	10.74	2.77	3.57	10.72	9.23	0.67
(*s.e.*)	2.62	1.76	1.49	2.64	3.56	0.74
N	138	53,745		136	136	

Notes: Observations correspond to those of the year 2019. Fuel use is measured in ton of oil equivalent, sales are measured in 1,000 U.S. dollars, and emission control measure use is measured in hours per year. ln Emission control measure use is defined as ln Emission control measure use multiplied by 1{Measure update}. Exchange rates are sourced from Federal Reserve Bank of St. Louis. StdDif stands for the standardized difference between two groups. Ratio stands for the ratio of the variance of a covariate in the treated group to that in the matched control group.
Sources: Ministry of Environment, Ministry of the Interior and Safety, Statistics Korea, Federal Reserve Bank of St. Louis.

Tables 1 and 2 present summary statistics in 2019 at both levels. For manufacturing plants, I focus on those that have electricity use. At the plant level, regulated plants are

larger in scale but exhibit more abatement efforts and lower emission intensities (Lyubich et al., 2018). It also aligns with the policy motivation that large polluting manufacturing plants are concentrated in polluted and populated regions. At the district-industry level, regulated manufacturing has higher emissions and sales and lower emissions intensities than unregulated, while regulated power generation has higher sales and lower emissions and emissions intensities. The latter reflects the fact that dirty power plants are located far from populated districts, which hints at potential leakage in power generation.

Table 2: Summary statistics: district × industry

	Manufacturing		*Power generation*	
	Targeted	Never	Targeted	Never
ln NO_x emissions	3.77	3.14	11.36	12.26
$(s.e.)$	3.34	3.17	2.57	1.74
ln SO_x emissions	-1.53	-1.67	7.60	9.82
$(s.e.)$	3.97	3.94	4.17	3.09
ln TSP emissions	-2.75	-2.86	7.64	8.87
$(s.e.)$	3.81	3.67	3.00	1.95
ln Sales	7.06	6.64	10.35	11.05
$(s.e.)$	2.38	2.46	3.38	2.90
N	10,586	3,061	89	12

Notes: Observations correspond to those of the year 2019. Emissions are measured in kilograms, and sales are measured in 1,000 U.S. dollars. Exchange rates are sourced from Federal Reserve Bank of St. Louis.
Sources: Ministry of Environment, Statistics Korea, Federal Reserve Bank of St. Louis.

One important caveat is that spillovers may arise through market reallocation and outsourcing across plants and may therefore propagate to sectors and regions, violating the Stable Unit Treatment Value Assumption (SUTVA). As a result, untreated plants may also respond to the policy, so the difference-in-differences estimates must be interpreted with care. To isolate within-firm leakage, I compare regulated and unregulated unaffiliated plants and unregulated affiliated and unregulated unaffiliated plants separately. Still, across-firm leakage may remain, so I do not interpret the difference-in-differences estimates causally. Instead, I treat them as reduced-form evidence on differential responses of treated and untreated units in the presence of spillovers, and use the structural framework in Section 6 to quantify these responses.

4.2.2 Plant level result

This section provides the evidence of the policy effect in terms of abatement and leakage for manufacturing and power plants. Figure 4 reports the plant level regression results (see Table A.15 for the average treatment effects on the treated (ATTs)). Regulated manufacturing

plants shows two abatement mechanisms: (i) cleaner fuel mix via industrial electrification and (ii) greater use of end-of-pipe emission control measures. The policy increased the electricity use and the share by 151% and 13%, indicating industrial electrification.[14] This change is consistent with substitution toward a cleaner energy source from manufacturers' perspective. In addition, the policy induced an update of emission control measure installation and a more extensive use of the measure. Regulated plants are more likely to update its emission control measure installation toward more extensive use by 25%.

Several pieces of evidence support this technology adoption channel further. Complementary evidence from the Ministry of Environment's reports on environmental investments by large polluters confirms this trend. A review of these reports shows a sharp increase in large-scale abatement projects initiated by regulated plants ex-post.[15] These investments predominantly targeted multi-pollutant control technologies like filters and scrubbers—costing an average of $100,000 U.S. dollars per installation—rather than long-term R&D. The scale and focus of these expenditures suggest they were a direct, high-priority response to the regulation. This interpretation was confirmed by the government official from the Air Quality Management Division of the Korean Ministry of Environment, who noted that regulated plants substantially increased their investment in emission control measures following the policy.

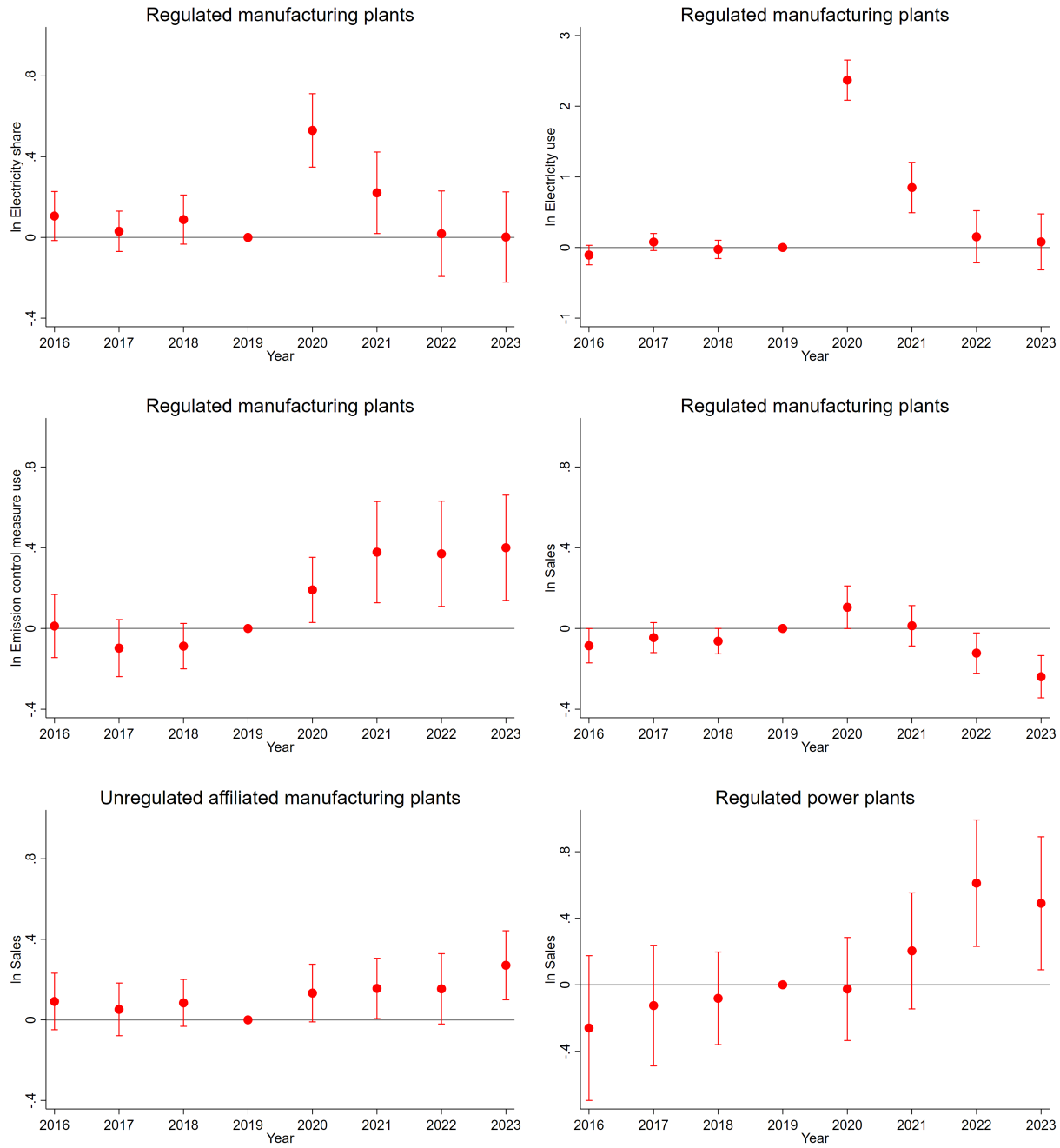
These abatement efforts are less susceptible to spillovers because unregulated plants are unlikely to abate emissions actively. However, they were accompanied by downsizing where we have potential spillovers through leakage. While the average post-treatment effect is not statistically significant, the event-study indicates that the effect on sales becomes negative in later periods. It was beyond pure leakage, due to the abatement efforts and costs. Specifically, there could have been leakage within manufacturing and from manufacturing to power generation. For the former, I investigate within-firm leakage by analyzing how unregulated and affiliated plants in the same industries responded to the policy. While the average post-treatment effect is not statistically significant, the sign is positive, and the event-study indicates that the effect on sales becomes positive at longer horizons. This finding implies stronger within-firm leakage relative to across-firm leakage. But there was no visible abatement effort when I examine electricity intensity or measure use. For the latter, I examine regulated power plants and find a similar pattern. This finding can be interpreted as leakage from manufacturing to power generation because the industrial electricity demand increased and regulated power plants did neither abate nor get downsized, implying a mitigation of the

[14] I use electricity share as a measure of fuel composition because there are some plant that do not use fossil fuels at all.

[15] This information can be found in the ministry website.

regulation on these dirty power plants. Lastly, note that all these changes tend to become stronger over time in line with the policy design that makes the caps decreasing over time.

Figure 4: Event dynamics: plants



Notes: The 95% confidence intervals are shown jointly with the point estimates.

Before moving on to the next section, I discuss how to interpret these findings together. First, the industrial electrification might reflect the fact that most emission control measures

are run with electricity. However, the gap between changes in electricity share and electricity use implies that fossil fuel use decreased. Therefore, it was more than an increase in electricity demand from more intensive use of emission control measures. Moreover, the fact that emissions decreased and electricity use increased matters because it captures the sectoral asymmetry. Second, increases in electricity share decreased in later periods. However, it accompanies downsizing. Hence, electricity was still used more intensively than before. In addition, emission control measures were used more intensively, possibly mitigating fuel composition changes to some degree (see Section 5.2.1). Third, initially, regulated manufacturing plants abated without any large drop in sales. But as the policy became more stringent by design, their loss and leakage became stronger, implying that emissions reduction required was beyond what these plants could have dealt with without any loss in sales. Fourth, the sales of regulated power plants increased in later periods as the policy intensity increased, which should be understood with leakage from industry to power generation and an increase in the electricity price following an increase in the policy intensity. The latter reflects that, in reality, there are various real-time auction prices between power plants and the government and that those regulated increased their bids as their costs increased. In the next section, I study the aggregate effects of these abatement and leakage channels.

4.2.3 District-industry level result

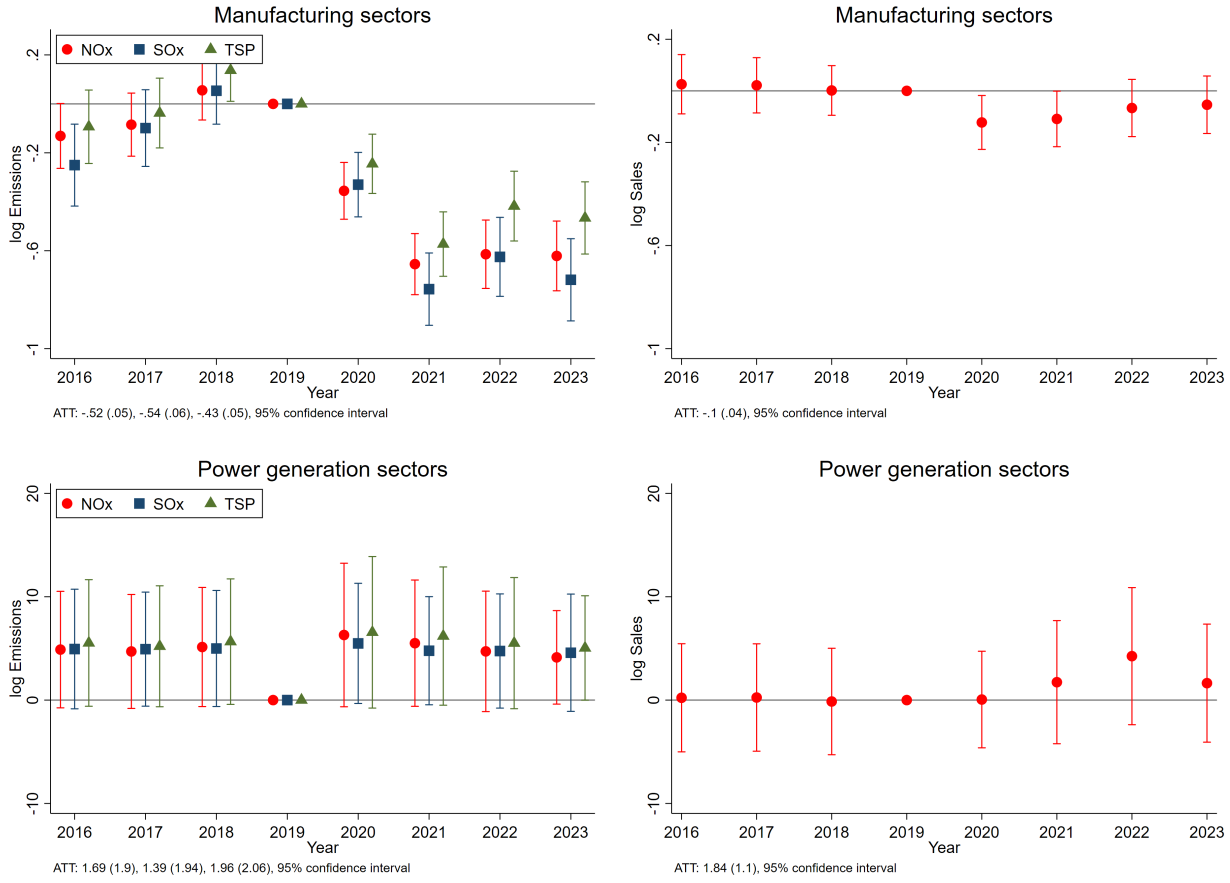
This section provides the evidence of the policy effect in terms of emissions and output for district-manufacturing-industry and district-power-industry pairs, respectively. Regression results are summarized in Figure 5 (see Table A.16 for the ATTs). First, the policy decreased the emissions of NO_x, SO_x, and TSP in regulated district-manufacturing-industry pairs by 41%, 42%, and 35%, relative to those of unregulated ones. The results imply a substantial reduction in emissions from regulated plants relative to a potential increase among unregulated plants—an outcome that was ex-ante uncertain given potential within-district leakage. The magnitudes of such declines also confirm that regulated plants were major emitters prior to the policy.

Second, there is again a significant sectoral difference. The overall emissions reduction was driven by manufacturing, while power generation emissions remained unchanged. Although the power generation sample is small and confidence intervals are wide, this is consistent with the earlier evidence that power plants do not exhibit meaningful changes over the same period and that the electricity demand increased from manufacturing. Given that the policy targeted large polluters accounting for most emissions, this pattern suggests that part of the manufacturing emissions reduction was achieved through electrification, effectively shifting emissions from industry to power generation.

Sales moved similarly for power generation. Manufacturing sales did not increase either, but the magnitude of the emissions reductions strongly points to emissions intensity improvements, rather than simple changes in production output. This gap suggests abatement mechanisms, such as the use of filters and scrubbers, and fuel substitution, as shown above.

It is important to note that these estimates might be biased due to potential geographic leakage, where polluting activity may have shifted from regulated to unregulated district-industry pairs. Such leakage can arise within sectors through market reallocation or across sectors through outsourcing of dirty production. Overall, such leakage would increase emissions in the control group, causing the estimates to overstate the true effects. In the next section, I study this spatial aspect of leakage.

Figure 5: Event dynamics: district-industry



Notes: The 95% confidence intervals are shown jointly with the point estimates.

4.3 Geographic leakage

This section investigates where emissions were leaked. Since leakage is likely to decrease in distance (based on the logic of a gravity model), such leakage can be examined by exploiting variation in distance from regulated districts and comparing post-policy trends across unregulated district-industry pairs after excluding treated ones:

$$y_{d,s,t} = \alpha_{d,s} + \alpha_{s,t} + \sum_{\tau \neq 2019} \beta_\tau \times Closeness_d \times Year_\tau + \varepsilon_{d,s,t}, \tag{3}$$

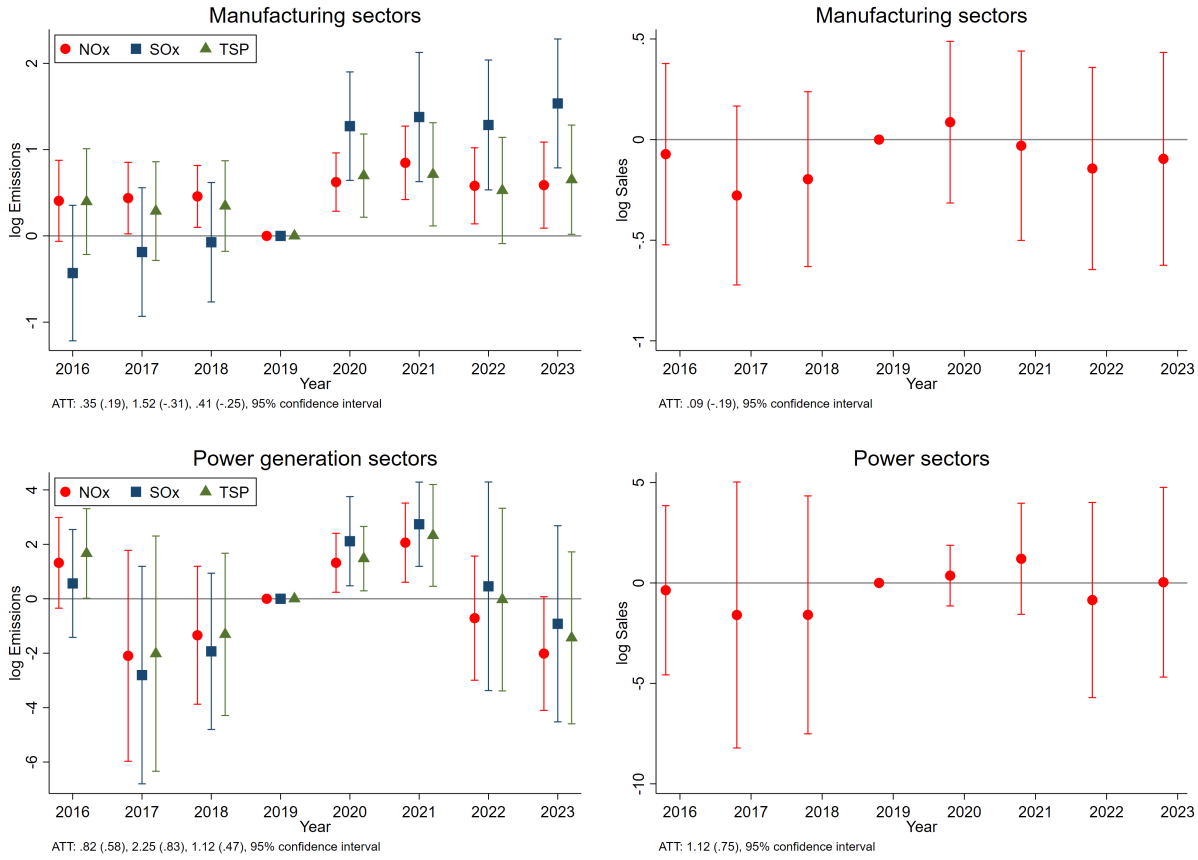
where $Closeness_d$ is $(-1) \times$ ln distance from any regulated districts, and standard errors are clustered by district-industry pair. Here bilateral distance is measured with district centroids. I remove those located highly close to regulated districts to address any noise.

Figure 6 captures significant geographic leakage (see Table A.17 for the ATTs). In manufacturing pairs, the elasticity of SO_x with respect to distance from regulated districts is 1.52—meaning a 1% decrease in distance corresponds to a 1.52% increase in SO_xemissions.[16] This suggests that the baseline estimates comparing regulated and unregulated units overstate net reductions once leakage is accounted for. Furthermore, geographic variation in emissions shows that manufacturing, rather than power generation, drove this leakage. Although the power generation sample is small and confidence intervals are wide, this is consistent with the result above. In addition, electricity markets operate through dispatch. Hence, the reallocation is starkly different from that of manufacturing (see Appendix A). Such geographic leakage requires an understanding of how the policy changes the geographic distribution of emissions and output across space, a key of the analysis. Lastly, note that manufacturing emissions moved more than manufacturing sales, implying outsourcing of dirty production process. Thus, leakage within manufacturing requires an understanding of leakage within and across manufacturing industries, which will be addressed in Section 5 with an input-output linkage.[17]

[16] This elasticity is comparable to the trade elasticity found in the literature. The latter measures how trade flows are correlated with distances.

[17] This finding suggests we should examine both emissions and sales, especially after a regulation because they can diverge thereafter.

Figure 6: Geographic leakage: district-industry



Notes: The 95% confidence intervals are shown jointly with the point estimates.

4.4 Robustness checks

This section presents robustness checks on the difference-in-differences analysis. As above, I proceed with the two levels: plants and district-industry pairs. Before proceeding further, I address factors that could have confounded the policy effect. First, the COVID-19 effect might have confounded the policy effect. However, the empirical evidence shows that there was more than downsizing. Fuel composition has changed, and emissions control measures have been updated and used more intensively. Furthermore, although the COVID-19 effect was temporary, emissions reduction and abatement efforts have persisted. Second, other environmental regulations could have confounded (see Arkolakis et al. (2025) for a comprehensive review of environmental policies in South Korea). Among others, I focus on one potential confounder, which has a similar size variation and accounts for a significant portion of greenhouse gas emissions, although the pollution of interest is different. For the rest, see Appendix C.

There have been a greenhouse gas trading system and a pilot program of it. The pilot program started in 2007 as quotas, and it transitioned to the trading system in 2015. The system had three phases: 2015-2017 (1st phase); 2018-2020 (2nd phase); 2021-2025 (3rd phase). Since these polices had different timings, regulated different pollutants, and were global, they are less likely to confound the policy effect. But they also had size variation, and a significant portion of the regulated plants by the The Total Volume Control of Pollutants at Place of Business was regulated. Out of 940 regulated manufacturing plants, 531 plants were in the trading system and 621 were in the pilot program. Out of 153 regulated power plants, 109 were in the trading system, and 115 were in the pilot program. So I conduct several sub-sample analyses to see if these plants responded differently in the plant level analysis.

4.4.1 Plant level

First, I check sectoral heterogeneity (Tables A.18 and A.19) for regulated and unregulated affiliated manufacturing plants. As expected, sectors exhibit heterogeneous effects, but none of these effects are in the opposite direction with significance. The average treatment effect is not driven by heavy industries highly dependent on fossil fuels; several light industries contribute to reduction through production process emissions abatement. As will be shown in Sections 5 and 6, light industries such as paper manufacturing find it easier to substitute fuels. However, I do not differentiate power plants by fuel empirically because the sample size is small. Second, I check if plants in the Seoul Capital Area shows different patterns because the area was subject to the initial policy adoption since 2007 (Table A.20). I exclude them from the sample to address potential anticipatory and long-term effects, but the result is robust. Third, I consider the two greenhouse gas regulations that have been implemented earlier and could have confounded the main estimates. I conduct a sub-sample analysis and find a robust result (Tables A.21 and A.22). Also, I exactly match plants by policy areas to control for area-specific time trends, or other potential confounding policy effects, as I do with province-year fixed effects for district-industry pairs. They are regional units that can be regarded as local markets or major policy units. I do not impose this in the baseline plant level regression because the regional unit is unique to the policy, and this restriction decreases the size of the treatment group significantly. Still, I find a similar result, which reassures that the policy effect was not driven by other regional effects (Table A.23).

Fourth, I check the responses of multiplant manufacturing firms. I start by investigating unregulated affiliated plants in different 3-digit KSICs to see if there was leakage to vertically integrated plants. They show no meaningful responses. Based on this finding, I investigate the responses of regulated manufacturing plants without any unregulated affiliated plants in

the same 3-digit KSICs (Table A.24). It is an exercise designed to capture any difference arising from within-firm leakage. Again, I find another robust result. Fifth, I perform different matching methods to address any bias specific to a matching method and find a robust result (Table A.25). Sixth, I drop plants that were regulated but became exempt later to see if the policy effect is permanent, but the effect seems temporary (Table A.26). Finally, I check other variables. For example, the exit of a regulated plant show no response because regulated plants are large and capable of decreasing emissions. I also use labor as another scale variable, or the use of factors other than fuels, and it shows a similar response as in sales. This finding supports the claim that productivity improvement is not a major response. I further check if there was firm-level technology choice, which can be another type of spillovers, and I find that there was no such response. In general, the estimates are stable and within the 95% confidence interval of the benchmark specification.

4.4.2 District-industry level

First, I check sectoral heterogeneity (Tables A.27 and A.28). As expected, sectors exhibit heterogeneous effects, but none of these effects are in the opposite direction with significance. However, I find notable differences across manufacturing industries. The average treatment effect is not driven by heavy industries highly dependent on fossil fuels; several light industries contribute to reduction through production process emissions abatement. Second, I check if pairs in the Seoul Capital Area shows different patterns because the area was subject to the initial policy adoption since 2007 (Tables A.29 and A.30). I exclude them from the sample to address potential anticipatory and long-term effects, but the result is robust. Third, I control for the initial level differences to make pairs more comparable. As in Appendix C, it also helps to address potential effects from other regulations, although they must have been weak as the most of emissions can be explained by regulated plants. As a result, I find a robust pattern (Table A.31). Lastly, I check other variables. For example, the entry and exit of a plant show no response because regulated plants are large and capable of decreasing emissions. I also use labor as another scale variable, and it shows a similar response as in sales. In general, the estimates are stable and within the 95% confidence interval of the benchmark specification.

4.5 Taking stock

Taken together, these reduced-form findings suggest the following story. First, regulated manufacturing plants reduced both emissions and sales. Emissions fell more than sales, indicating effective abatement through industrial electrification and intensive emission con-

trol measure use. Second, unregulated plants increased their emissions and sales, especially within firm networks. This entailed significant intra- and inter-regional leakage, which was most concentrated in districts bordering the regulated districts, rather than in those far away. Third, power plants did not decrease emissions and sales. They satisfied the extra demand from industrial electrification and were able to keep their sales and emissions as before. This interpretation aligns with the institutional setting of Korea's electricity market: when electricity demand rises, fossil fuel power plants are typically dispatched. Hence, emissions and output of the power sector can avoid a policy shock (direct shock) with an increase in demand (indirect shock). If clean power plants entered quickly to satisfied the demand, the sales and emissions of regulated power plants should have dropped.

These findings resonate with the broader literature. Leakage within manufacturing and across regions has been widely documented (Tanaka et al., 2022; Yang et al., 2024). Stronger within-firm leakage is also a pattern found in the literature (Chen et al., 2021; Curtis et al., 2025). Leakage from manufacturing to power generation connects to the emerging literature on electrification and its environmental consequences (Holland et al., 2020; Holland et al., 2024; Levinson et al., 2025). A key policy implication is that, with sufficient clean power generation, industrial electrification offers a viable path to reducing emissions. The coexistence of abatement and leakage differs slightly from the theoretical predictions of Xiang (2023) and Arkolakis et al. (2025), where leakage dominates in the short run and clean innovation and large scale abatement drive long-run decarbonization. This is because marginal abatement and technology adoption can occur more quickly for local air pollutants.

However, these findings have two caveats. Because they are based on difference-in-differences estimates, potential spillovers to unregulated plants, or leakage, could have biased results. While directly estimating these spillovers is ideal, it is a challenge inherent to the policy targeting, which by design involves linkages between treated and control plants, sectors, and regions. A practical alternative is to select a control group that is less susceptible to such effects. However, this choice will make the control group less comparable because such a group should be physically distant and in different industries. Furthermore, the evidence cannot evaluate the welfare effects of the policy and alternative policy designs alone. To address these, the next section uses a structural framework based on these empirical results, embedding leakage and conducting a welfare analysis with counterfactual policy experiments.

5 Quantitative Spatial Model of Manufacturing and Power Generation

I develop a spatial general equilibrium model, integrating the manufacturing and emissions model of Shapiro et al. (2018) with the manufacturing and power generation model of Arkolakis et al. (2023). I extend this setting to include abatement channels (factor and fuel substitution and emission control measure use) and leakage channels across plants, sectors, and districts. One of the key mechanisms is the race between industrial electrification and clean power supply, which jointly determines aggregate and spatial sustainability.

5.1 Environment

The economy consists of N discrete districts with the corresponding representative households. Representative households derive utility from consuming varieties of goods but experience disutility from local air pollution. Also, there are manufacturing and power generation sectors. Manufacturing sectors are divided into J sub-sectors based on output type, and power generation sectors into F sub-sectors based on energy source.[18] Firms are heterogeneous in productivity, and regulation primarily targets larger—but cleaner—plants in specific locations, allowing leakage toward smaller, dirtier, and unregulated firms within or across districts. Throughout the analysis, subscripts denote sectors, districts, and fuel types, while superscripts index other relevant dimensions.

5.2 Manufacturing firms

Firms follow the timing described below. In district i and sector j, each potential entrant pays an entry fixed cost $f_{i,j}^{E}$ in capital structure. Upon entry, the firm draws a productivity level ϕ and supplies a differentiated variety (Armington, 1969). This variety is an aggregate of plant varieties within the firm, and the firm can produce in places l other than its headquarters location and sells to destination districts n. This multiregional production is allowed to address within-firm leakage. If regulated, the corresponding plants abate or leak to reduce emissions. Each plant is thus characterized by its headquarters location i, plant location l, sector j, and productivity draws ϕ and z.

[18] I abstract from fuel extraction, reflecting Korea's status as a small open economy importing approximately 95% of its coal, gas, and oil annually, with full imports of oil and gas over the past decade. Hence, supplies of fossil fuels are assumed perfectly elastic. Their markets are perfectly competitive, and they are fully mobile.

5.2.1 Operation

A plant minimizes total operating cost that includes both production and abatement. Technology exhibits constant returns to scale (CRS). Specifically, the firm produces using a Constant-Elasticity-of-Substitution (CES) production function of capital k, energy e, labor ℓ, and material (intermediate good composite) m:

$$\begin{aligned} q_{il,j}(\phi,z) =& \phi z\left(1-a_{il,j}(\phi,z)\right) \\ &\times\left(\alpha_{j,K}k_{il,j}^{\frac{\rho_j-1}{\rho_j}}(\phi,z)+\alpha_{j,E}e_{il,j}^{\frac{\rho_j-1}{\rho_j}}(\phi,z)+\alpha_{j,L}\ell_{il,j}^{\frac{\rho_j-1}{\rho_j}}(\phi,z)+\alpha_{j,M}m_{il,j}^{\frac{\rho_j-1}{\rho_j}}(\phi,z)\right)^{\frac{\rho_j}{\rho_j-1}} \end{aligned} \tag{4}$$

where $a_{il,j}(\phi,z)\in[0,1)$ is the share of resources diverted to emission control measures and $\alpha_{j,K}+\alpha_{j,E}+\alpha_{j,L}+\alpha_{j,M}=1$. Energy is a CES composite over fuel types $f\in\mathbb{F}=\{$Coal, Electricity, Gas, Oil$\}$ measured in tons of oil equivalent (toe):

$$e_{il,j}(\phi,z)=\left(\sum_{f\in\mathbb{F}}\alpha_{j,f}\left(e_{il,j,f}(\phi,z)\right)^{\frac{\lambda_j-1}{\lambda_j}}\right)^{\frac{\lambda_j}{\lambda_j-1}}, \tag{5}$$

where $\lambda_j>\rho_j>0$. I focus on these four fuels for parsimony and coverage. In particular, electricity is the key fuel because it is universally used and observed across plants and years.

Emissions of pollutant p follow the spirit of Copeland et al. (2004). I extend their formulation to differentiate process emissions $\kappa_j^p q_{il,j}(\phi,z)$ and fossil-fuel emissions $\sum_{f\in\mathbb{F}}\kappa_f^p e_{il,j,f}(\phi,z)$, allowing for both factor and fuel substitution. κ_j^p denotes the emissions factor of pollutant p associated with the production process of good j, while κ_f^p represents the emissions factor of pollutant p for fuel f. Electricity use is unregulated and treated as clean from the perspective of manufacturing firms. Hence. the emissions of pollutant p are given by:

$$s_{il,j}^p(\phi,z)=\left(1-a_{il,j}(\phi,z)\right)^{\frac{1}{\alpha_j^p}}\left(\underbrace{\kappa_j^p q_{il,j}(\phi,z)}_{\text{Production process}}+\underbrace{\sum_{f\in\mathbb{F}}\kappa_f^p e_{il,j,f}(\phi,z)}_{\text{Fossil fuel use}}\right), \tag{6}$$

where $p\in\{NO_x,\ SO_x,\ TSP\}$ and $0<\alpha_j^p<1$. The term $a_{il,j}(\phi,z)$ captures emission control measure use that differs from factor and fuel substitution (e.g., filters, scrubbers, or improvements in fuel intensity) but abates emissions with additional variable costs. The common use of the measure implies strict complementarity across pollutants in abatement, consistent with multi-pollutant measure operation verified in Section 4. The parameters α_j^p determine

the effectiveness of emission control measures and, together with ρ_j (production-factor substitution) and λ_j (fuel substitution), govern the responsiveness of emissions and economic activity to regulation. These three elasticities induce different responses of regulated plants and are central to the type of abatement and leakage.

Optimization The optimization problem of the plant can be expressed as a cost-minimization problem. Given its productivity ϕ and z, the plant minimizes total production cost—comprising factor expenditures and pollution taxes—by choosing production inputs (capital, energy, labor, and materials) and making abatement decisions (fuel composition and measure use), subject to the production technologies in Equations 4 and 5:

$$\min_{k,e,\ell,m;\{e_f\},(1-a)} \underbrace{rk}_{\text{Capital expense}} + \underbrace{\sum_{f\in\mathbb{F}} p_f e_f}_{\text{Energy expense}} + \underbrace{w_l \ell}_{\text{Labor expense}} + \underbrace{p^M_{l,j} m}_{\text{Material expense}} + \underbrace{\sum_{p\in\Lambda} s^p \tau^p_l}_{\text{Emissions expense}} .$$

The rental rate of capital is denoted by r; $p_f$is the price of fuel f; w_l is the wage in district l; and $p^M_{l,j}$ is the price of materials in sector j.

Environmental regulations are modeled as a set of pollution taxes, and the associated tax revenue is assumed to be lost due to administrative cost, rent seeking, and more.[19] Each plant faces up to three local air pollutant regulations, based on its emissions volume and location. $\hat{s}^p_{il,j}(\phi, z)$ denotes pre-regulation emissions and $\bar{T}^p_j$the threshold for pollutant p. Pollution taxes are applied only to establishments whose emissions exceed the thresholds: $\hat{s}^p_{il,j}(\phi, z) \geq \bar{T}^p_j$. Because pollution tax rates τ^p_l vary by pollutant and location, the set of regulated pollutants $\Lambda_{il,j}(\phi, z)$ depends on locations i and l, sector j, and productivity ϕ and z.

Solving this optimization problem yields the unit production cost that forms the foundation for the equilibrium analysis:

$$\mu_{il,j}(\phi, z) = \underbrace{\frac{1}{(1 - a_{il,j}(\phi, z))}}_{\text{Measure use cost}} \underbrace{\frac{1}{\phi z}}_{\text{Productivity}} \underbrace{\frac{1}{G_{il,j}(\phi, z)}}_{\text{Effective factor cost}} + \underbrace{\sum_{p\in\Lambda_{il,j}(\phi,z)} (1 - a_{il,j}(\phi, z))^{\frac{1}{\alpha^p_j}} \tau^p_l \kappa^p_j}_{\text{Pollution tax on production process}} . \quad (7)$$

Given Dixit–Stiglitz preferences, the price of variety is $p_{iln,j}(\phi, z) = \mathcal{M}_j \mu_{il,j}(\phi, z) d_{ln,j}$ where

[19] I abstract from permit trading, since both pollution taxes and emissions-trading systems are market-based instruments that affect firms through identical marginal incentives. Even under a pure tax regime, emissions can shift from manufacturing to power generation if electricity demand rises sufficiently: power-sector emissions increase with marginal generation—which is typically fossil-based—while manufacturing firms lower their own emissions by substituting toward electricity. Furthermore, the tax revenue loss assumption is consistent with the fact that in a cap-and-trade system with free allocation of permits, there is no tax revenue.

$\mathcal{M}_j = \eta_j/(\eta_j - 1)$ is the sector-specific markup, and $d_{ln,j}$ denotes the iceberg trade costs from l to n. Given this pricing rule, the plant's revenue is the sum of destination-specific revenues and the firm's global profit is the sum of destination-specific profits:

$$R_{il,j}(\phi, z) = \sum_n R_{iln,j}(\phi, z),$$
$$\pi_{il,j}(\phi, z) = \sum_n \frac{R_{iln,j}(\phi, z)}{\eta_j}.$$

Theoretical motivation This section examines how a manufacturing plant responds to the policy in order to derive the economic intuition behind each adjustment channel and illustrate how reduced-form difference-in-differences estimates may over- or under-state the true policy effect depending on the direction and magnitude of leakage. The analysis log-linearizes the equilibrium conditions around an ex-ante symmetric industry equilibrium, focusing on shocks to pollution taxes.

I consider a one-sector manufacturing economy with single-plant firms and assume standard parameter ranges with $1 < \rho < \lambda$. There are two ex-ante symmetric districts, i and l, each hosting an exogenously given unit mass of active firms ($M_i = M_l = 1$). The analysis focuses on product market equilibrium, holding factor costs fixed at unity and normalizing expenditures such that $X_i = X_l = 1$. I abstract from the policy variation by emission size. Then, a change in emissions can be decomposed into abatement—via emission control measure use, fuel substitution, and shift in electricity use intensity—and scale:

$$d\ln s_i^p(\phi) = \underbrace{\underbrace{d\ln\frac{s_i^p(\phi)}{\sum_f \kappa_f^p e_{i,f}(\phi)}}_{\text{Emission control measure use}} + \underbrace{d\ln\frac{\sum_f \kappa_f^p e_{i,f}(\phi)}{e_{i,e}(\phi)}}_{\text{Fuel composition}} + \underbrace{d\ln\frac{e_{i,e}(\phi)}{R_i(\phi)}}_{\text{Electricity use intensity}}}_{\text{Abatement}} + \underbrace{d\ln R_i(\phi)}_{\text{Scale}},$$

the channel of which will be characterized with the model.

Solution 1. A change in measure use can be characterized as:

$$d\ln\frac{s_i^p(\phi)}{\sum_f \kappa_f^p e_{i,f}(\phi)} = \sum_p \eta_i^p(\phi)\, d\ln\tau_i^p,$$

where $\eta_i^p(\phi) < 0$ captures the responsiveness of emissions to emission control measure use. Its sign is negative because firms employ such measures to reduce emissions. Its usage is more pronounced when abatement is more effective $\left(\text{low } \alpha_j^p\right)$, when process-based emissions dominate fuel-based emissions $\left(\kappa_j^p > \kappa_f^p\right)$, or when substituting across fuels is more difficult

(low λ). Light industries such as paper manufacturing generate a greater share of emissions from production process, while heavy industries such as chemicals rely more on fossil fuels and cannot easily substitute away from them.

Solution 2. A change in fuel composition can be expressed as:

$$d\ln\frac{e_{i,f}(\phi)}{e_{i,e}(\phi)} = \sum_p \gamma_{i,f}^p(\phi)\, d\ln\tau_i^p,$$

where $\gamma_{i,f}^p(\phi)$ measures the degree of relative substitution between fuel $f \neq e$ and electricity e. It is negative because when fuel f is dirty, an increase in τ_i^p raises its effective cost, inducing firms to substitute away from it relative to the benchmark energy source, electricity. Similarly, the change in electricity use intensity—interpreted as a form of energy use intensity—can be expressed as:

$$d\ln\frac{e_{i,e}(\phi)}{R_i(\phi)} = \sum_p \Xi_i^p(\phi)\, d\ln\tau_i^p,$$

where $\Xi_i^p(\phi) > 0$ measures the elasticity of electricity use with respect to the pollution tax. The parameter comparative statics are the opposite of those of measure use.

Solution 3. A change in the price index can be written as:

$$d\ln P_i = \sum_p \Phi_i^p d\ln\tau_i^p,$$

where $\Phi_i^p > 0$ captures the increase in unit production cost induced by the policy, which can come from any costly abatement channels. Hence, a change in the revenue at the plant level can be expressed as:

$$d\ln R_i(\phi) = \sum_p \Upsilon_i^p(\phi)\, d\ln\tau_i^p,$$

where $\Upsilon_i^p(\phi) < 0$ reflects a reduction in revenues following higher costs. This is where leakage matters because unregulated firms benefit from the policy through an increase in the sectoral price index ($\Phi_i^p > 0$), which improves their relative competitiveness. As a result, a difference-in-differences estimator that compares regulated and unregulated units may overstate the true policy effect on emissions, since part of the observed change arises from this leakage rather than abatement. The response magnitude, summarized by $\Upsilon_i^p(\phi)$, depends on preference parameters—in particular, the elasticity of substitution σ. When varieties are more substitutable (high σ), competition is stronger, and a given increase in

unit cost induces a larger decline in firm level revenue.

This decomposition matters because each channel conveys different aggregate implications. When firms rely on emission control measures, emissions are more likely to leak within sectors. Greater electrification tends to shift emissions toward the power sector. While I abstract from outsourcing within manufacturing for tractability, it constitutes an additional leakage channel. Outsourcing activity tends to rise with pollution taxes and is stronger when measure use and fuel substitution are limited.[20] Also, these results hold beyond this simplification under standard parametization. A similar logic applies to the power generation sector, with a key difference that there is a positive demand additionally. Once multiplant firms are considered, leakage will be more concentrated within firms because of the difference in the elasticities of substitution ($\eta > \sigma$).

The internal consistency between the model's comparative statics and the empirical evidence helps quantification in Section 6. Finally, the quantitative analysis in Section 7 generalizes this setting and evaluates the full-fledged equilibrium effects of the regulation.

5.3 Power plants

5.3.1 Electricity generation

Power plants are indexed by fuel type $f \in$ {Clean, Coal, Gas, Oil}, where Clean aggregates non-fossil fuel sources such as hydro, nuclear, solar, and wind. Within each fuel type, plants are heterogeneous in productivity z, interpreted as inverse fuel intensity. Unlike manufacturing plants—where electricity serves as a cleaner substitute—power plants are tied to a fixed fuel type and cannot switch between fuels.

The timing is as follows. Potential entrants of each fuel type pay an entry cost $f^E_{i,f}$ in units of capital structure and draw productivity z. A power plant in location i using fuel f is characterized by this productivity draw. These plants generate electricity up to their capacity. To reduce dimensionality, I assume an engineering relationship between capacity k and productivity z, reflecting that larger and more efficient plants tend to have higher capacity (see Christensen et al. (1976)). Electricity is exclusively used as an input by manufacturing plants and is not directly consumed by households.

[20] There remains a possibility that firms respond to the policy by improving productivity. Although this possibility cannot be entirely ruled out, it is unlikely to be a dominant channel. Most observed responses align more closely with mechanisms unrelated to productivity growth. For instance, firms engaged in extensive abatement activities—such as adopting emission control measures or altering fuel mixes—which would likely have been offset had productivity gains been substantial. In the current framework, any productivity improvements are effectively absorbed into the term $(1 - a)$, representing emission control measure use not related to factor and fuel substitution.

A power plant with productivity z generates electricity using a constant-returns-to-scale (CRS) technology:

$$y_{i,f}(z) = (1 - a_{i,f}(z)) \min \left\{ k_{i,f}(z), z e^{\mathcal{E}}_{i,f}(z) \right\}, \tag{8}$$

where $e^{\mathcal{E}}_f$ denotes fuel use (toe). The emissions of pollutant p are:

$$s^p_{i,f}(z) = (1 - a_{i,f}(z))^{\frac{1}{\alpha^p_f}} \kappa^{\mathcal{E},p}_f e^{\mathcal{E}}_{i,f}(z), \tag{9}$$

where $0 < \alpha^p_f < 1$, and $\kappa^{\mathcal{E},p}_f$ denotes emissions factors of pollutant p in the power generation sector with energy source f. α^p_f is the elasticity between emission control measure use and emissions in the power generation sector, which determines how efficiently the power sector can address emissions to increased electricity demand when industrial electrification induces leakage from manufacturing to power generation and it is hard to supply additional clean power generation capacity (in the short run without entry and exit).

A power plant using a clean energy source produces electricity up to its capacity at zero marginal cost and does neither pollute nor abate:

$$y_{i,f}(z) = k_{i,f}(z).$$

The profit maximization can be rewritten as:

$$\min_{e^{\mathcal{E}}_f;\left(1-\alpha^p_f\right)} \underbrace{p_f e^{\mathcal{E}}_f}_{\text{Fuel expense}} + \underbrace{\sum_{p \in \Lambda_{i,f}(z)} s^p_{i,f}(z) \tau^p_i}_{\text{Emissions expense}}$$

Then, the unit power generation cost can be derived as:

$$\nu_{i,f}(z) = \underbrace{\frac{1}{(1 - a_{i,f}(z))}}_{\text{Measure use cost}} \underbrace{\frac{1}{z}}_{\text{Productivity}} \underbrace{\left(p_f + \sum_{p \in \Lambda_{i,f}(z)} (1 - a_{i,f}(z))^{\frac{1}{\alpha^p_f}} \kappa^{\mathcal{E},p}_f \tau^p_i \right)}_{\text{Effective fuel price}}. \tag{10}$$

5.3.2 Electricity market systems

I model the government-controlled wholesale and retail markets as a single market without real-time auctions and an intermediary role by the government for tractability. But the following two key systems remain. Dispatch follows a merit-order rule (MOD): plants with lower marginal costs are dispatched first, up to capacity. Under this rule, the system

marginal price (SMP) sets the electricity price to the marginal cost of the last generating unit needed to meet aggregate demand, yielding a uniform nationwide price: $p_e = \nu(\tilde{z})$ where $\tilde{z}$ is the productivity of the marginal unit dispatched.[21] From the perspective of electricity consumers, electricity generated from fossil fuels and that produced from clean energy are perfect substitutes in both usage and market valuation. The total electricity demand from industry, D_e, is allocated in the ascending order of generation costs, clearing the market at the SMP:

$$\sum_f \sum_i M_{i,f} \mathbb{E}_{z \geq \tilde{z}} \left[y_{i,f}(z) \right] = D_e, \tag{11}$$

where $M_{i,f}$ denotes the number of active plants in district i using fuel f.[22] Note that, for these market features, I abstract from multiregional production in the power generation sector. Within-firm leakage is structurally impossible.

Without growth in clean capacity, any increase in electricity demand is more likely to be met by fossil fuel plants, creating unintended emissions. Hence, the race between the pace of industrial electrification and the expansion of clean generation capacity is central to evaluating both the policy effect and potential leakage into the power sector. How much industrial electrification raises p_e depends on the relative strength of additional demand and changes in generation costs—a question examined in the quantitative analysis. Industrial electrification thus can arise from differences in abatement technology and productivity across sectors.

After rationing, the profit of a power plant can be expressed as:

$$\pi_{i,f}(z) = \left(p_e - \nu_{i,f}(z) \right) y_{i,f}(z).$$

5.4 Households

Representative households derive utility from consuming final goods but experience disutility from local air pollution:

$$u_n = \underbrace{Q_n}_{\text{Utility from consumption}} \times \underbrace{\frac{1}{SCE_n}}_{\text{Disutility from emissions}}. \tag{12}$$

[21] In practice, electricity prices in Korea vary only over time (e.g., through time-of-use pricing) and across broad user categories—such as residential or industrial consumers—typically defined at the 1-digit industry level.

[22] Transmission constraints are abstracted from the analysis, given Korea's near-100% grid coverage. For further discussion, see Arkolakis et al. (2023).

Plant varieties are combined into firm varieties, firm varieties are combined into sectoral goods using Dixit–Stiglitz preferences (Dixit et al., 1977), and, then, firm varieties are combined across sectors under Cobb-Douglas preferences. In sector j , let σ_j denote the elasticity of substitution across firm varieties ω and η_j denote the elasticity of substitution across plant varieties within firms $\tilde{\omega}$. The latter CES aggregate is introduced to capture the fact that within-firm leakage is stronger than across-firm leakage within the same industries. Aggregators and corresponding ideal price indices are given by:

$$Q_n = \Pi_k Q_{n,k}^{\gamma_k}, \; P_n = \Pi_k \left(P_{n,k}/\gamma_k\right)^{\gamma_k}, \tag{13}$$

$$Q_{n,j} = \left(\sum_i \int_{\omega\in\Omega_{i,j}} Q_{in,j}^{\frac{\sigma_j-1}{\sigma_j}}(\omega)\, d\omega\right)^{\frac{\sigma_j}{\sigma_j-1}}, \; P_{n,j} = \left(\sum_i \int_{\omega\in\Omega_{i,j}} P_{in,j}^{1-\sigma_j}(\omega)\, d\omega\right)^{\frac{1}{1-\sigma_j}},$$

$$Q_{in,j}(\omega) = \left(\sum_l \int_{\tilde{\omega}\in\Omega_{in,j}(\omega)} q_{iln,j}^{\frac{\eta_j-1}{\eta_j}}(\tilde{\omega})\, d\tilde{\omega}\right)^{\frac{\eta_j}{\eta_j-1}}, \; P_{in,j}(\omega) = \left(\sum_l \int_{\tilde{\omega}\in\Omega_{in,j}(\omega)} p_{iln,j}^{1-\eta_j}(\tilde{\omega})\, d\tilde{\omega}\right)^{\frac{1}{1-\eta_j}}$$

where $\eta_j > \sigma_j > 1$ and $\sum_k \gamma_k = 1$. $\Omega_{in,j}$ is the set of firm varieties of headquartered in location i and sold in market n in sector j, and γ_k denotes the sectoral expenditure share. The corresponding demands at the firm- and plant-level are:

$$\begin{aligned} Q_{in,j}(\omega) &= \left(\frac{P_{in,j}(\omega)}{P_{n,j}}\right)^{-\sigma_j} Q_{n,j}, \\ q_{iln,j}(\tilde{\omega}) &= \left(\frac{p_{iln,j}(\tilde{\omega})}{P_{in,j}(\omega)}\right)^{-\eta_j} Q_{in,j}(\omega) \\ &= \left(\frac{p_{iln,j}(\tilde{\omega})}{P_{in,j}(\omega)}\right)^{-\eta_j} \left(\frac{P_{in,j}(\omega)}{P_{n,j}}\right)^{-\sigma_j} Q_{n,j}, \end{aligned} \tag{14}$$

respectively.

The household in district n faces the budget constraint:

$$\underbrace{P_n Q_n}_{\text{Consumption}} = \underbrace{rK_n}_{\text{Capital income}} + \underbrace{w_n L_n}_{\text{Labor income}} + \underbrace{\Pi_n}_{\text{Firm profits}}, \tag{15}$$

where K_n and L_n are the capital and labor endowments that are inelastically supplied. Capital is fully mobile across sectors and districts, being rented at a competitive rate r, which serves as the numeraire. Labor is mobile across sectors but immobile across districts, being supplied at wage w_n. This immobility makes households fully bear the policy impact on welfare. Households own both manufacturing and power plants.

Emissions affect welfare through a damage function, which is quantified with the social cost of emissions. I impose a linear relationship to divide changes in consumption, production, and emissions clearly (see Nordhaus (2015) for another form). Aggregate emissions are defined as $S_n^p = \sum_j S_{n,j}^p + \sum_f S_{n,f}^p$ where $S_{n,j}^p$ and $S_{n,f}^p$ denote total emissions of p in location n and manufacturing sector j and power generation using fuel f, respectively.

5.5 General Equilibrium

This section defines the general equilibrium of the model and derives expressions for aggregate variables. Intermediate inputs or materials are modeled as a composite of intermediate goods that capture input–output linkages and, consequently, outsourcing through roundabout production. Sector j's composite material input is given by:

$$m_{il,j}(\omega) = \prod_{k=1}^{J} \left(m_{il,kj}(\omega)\right)^{\gamma_{kj}}, \; p_{l,j}^M = \Pi_k \left(\frac{P_{l,k}}{\gamma_{kj}}\right)^{\gamma_{kj}},$$

where $\sum_k \gamma_{kj} = 1$. γ_{kj} denotes the share of sector k's output used as an intermediate in sector j, and $m_{il,kj}$ represents the quantity of inputs from sector k used by plants in sector j headquartered in location i and producing in location l.

At the firm level, free entry ensures that expected global profits equal the fixed entry cost. Manufacturing firms enter until:

$$\mathbb{E}_{\phi,z}\left[\sum_l \pi_{il,j}(\phi, z)\right] \leq r f_{i,j}^E, \tag{16}$$

which binds when $M_{i,j} > 0$. Firm productivity draws ϕ are independently and identically distributed (i.i.d.) according to a Pareto distribution with scale parameter $T_{i,j}$ (location–sector shifter) and shape parameter $\zeta_j > 1$. Plant productivity draws z are i.i.d. according to a log-normal distribution with mean 0 and variance σ_z^2. Analogously, free entry in the power sector satisfies:

$$\mathbb{E}_{z \geq \tilde{z}}\left[\pi_{i,f}(z)\right] \leq r f_{i,f}^E, \tag{17}$$

which is equal to when $M_{i,f} > 0$. Unlike above, there is an additional condition in the expectation because of the SMP and MOD. Productivity draws z follow a Pareto distribution with scale parameter $T_{i,f}$ and shape parameter $\zeta_f > 1$.

Market clearing conditions hold in all markets. Labor markets in each location l should clear:

$$L_l = \sum_j M_{i,j} \mathbb{E}_{\phi,z}\left[\ell_{il,j}(\phi, z)\right], \tag{18}$$

where $\ell_{il,j}(\phi, z)$ denotes the labor demand at the plant level. Similarly, the product market clears in each i and j:

$$X_{l,j} = \underbrace{\sum_{k=1}^{J} \gamma_{jk} M_{i,k} \mathbb{E}_{\phi,z}\left[p_{i,k}^{M} m_{il,k}(\phi, z)\right]}_{\text{Intermediate use}} + \underbrace{\gamma_j (w_l L_l + r K_l)}_{\text{Final consumption}}, \tag{19}$$

where there is no trade surplus.

Then, the spatial general equilibrium of the economy across sectors, fuel types, and districts can be defined. See Appendix D for detailed derivations and Appendix F for the numerical solution procedure.

Definition

Given a set of capital and labor endowments $\{K_{l,j}, L_{l,j}\}$, a set of fuel prices $\{p_f\}$, and a set of pollution taxes $\{\tau_l^p\}$, an equilibrium is a vector of prices for sectoral goods $\{P_{l,j}\}$, a rental rate r, a vector of wages $\{w_n\}$, an electricity price p_e, and an allocation $\{e_{il,j,f}(\phi, z), 1 - a_{il,j}(\phi, z)\}$, $\{\ell_{il,j}(\phi, z), k_{il,j}(\phi, z), m_{il,j}(\phi, z), e_{il,j}(\phi, z)\}$, $\{1 - a_{l,f}(z)\}$, $\{e_{l,f}^{\mathcal{E}}(z)\}$, and $\{X_{l,j}, M_{l,j}, M_{l,f}\}$ such that:

1. The free entry conditions are satisfied (Equations 16 and 17).
2. The price indexes are satisfied (Equation 13).
3. Electricity, labor, and product markets clear (Equations 11, 18, and 19).

For quantification, I will consider two types of equilibria. Prior to the regulation, firms make all extensive margin (entry and exit) and intensive margin changes (input and abatement choices). After the regulation, such extensive margins are fixed, firms only adjust their variable inputs. This choice is in line with the facts that the span of period is relatively short (Chen et al., 2021) and that there were no significant changes in entry and exit in Section 4.

6 Quantification

In preparation for the model analysis in Section 7, this section describes calibration and estimation strategies, presents the resulting parameter estimates, and evaluates the model's fit to the data. The model is implemented with $P = 3$ regulated local air pollutants, $J = 10$ sub-manufacturing sectors grouped by technological and input similarities, $F = 4$

power generation types grouped by fuel use, and $N = 250$ districts corresponding to Korea's administrative districts, which align with the policy's regional unit. The monetary unit is 1,000 USD. I quantify the model in two steps. First, in the pre-regulation economy, I calibrate and estimate parameters not directly related to the regulation. These parameters include firm entry costs, firm and plant productivity parameters, demand, factor, and fuel substitution elasticities. Second, in the post-regulation economy, I estimate parameters directly related to the regulation based on the parameters from the the-regulation economy. These parameters include emission control measure elasticities and the policy intensity.

6.1 Calibration

Parameters are calibrated using pre-regulation data to capture the characteristics of the pre-regulation economy. I use the average of four years (2016–2019) to avoid contamination from idiosyncratic shocks or transitory fluctuations. Emission factors are sourced from official policy documents issued by the Ministry of Environment. I use pre-regulation emissions across sources, sectors and fuels, and districts to use the production process emissions factors (ton) and scale emissions accordingly. Under this setting, I set $\bar{T}_j^p$ and $\bar{T}_f^p$ to capture each sectoral pollutant emissions in regulated districts by comparing total emissions allowances and total emissions in these sectors in 2019.

Capital and labor endowments, K_l and L_l, are taken from the MMS and SBR by taking annual averages of tangible capital and employment for those that have headquarters. For labor, I use the number of regular employees whose tasks are either in mining or manufacturing. Fuel prices p_f and $p_f^{\mathcal{E}}$ (excluding electricity p_e) are sourced from the Korea Energy Economics Institute. Iceberg trade costs $d_{ln,j}$ between plant l and destination n in sector j follow those of Arkolakis et al. (2023) while multiregional production frictions $\gamma_{il,j}$ between headquarters i and plant l in sector j are calibrated using multiregional production sales. Input–output linkages for both intermediate materials and final consumption, γ_{kj} and γ_j , are based on the Input–Output Table compiled by the Bank of Korea in 2016. The elasticities of substitution between firm varieities σ_j are borrowed from Broda et al. (2006).

For manufacturing, I calibrate entry costs, $f_{i,j}^E$, and productivity location parameters, $T_{i,j}$, by matching the numbers of active firms and their average sales (annual averages) in the model to the corresponding data moments of the MMS and SBR for those that have headquarters. I also use the maximum of sales share to calibrate the standard deviation σ_j of the log-normal distribution. For power generation, I calibrate entry costs, $f_{i,f}^E$, and productivity location parameters, $T_{i,f}$, by matching the numbers of active firms and their average variable profits (annual averages) in the model to the corresponding data moments

of the Economic Census and SBR. For power generation capacity, I assume a log-linear relationship between capacity and productivity, $\ln k_{i,f}(z) = a \ln z_{i,f}$, which reflects that larger power plants are more productive. The parameter $a = 0.12$ is calibrated using data on inputs, outputs, and capacity for fossil fuel power plants. This value is within the range of those in the engineering literature. Finally, I add a constant residual electricity demand borrowed from the KEPCO because the power generation sales are not differentiated by final users.

6.2 Estimation

I estimate key parameters in environmental economics that tie abatement and economic activity for quantification. First, following the production function estimation literature, I estimate the elasticities of substitution in demand and production in the pre-regulation economy. Second, based on the parameters calibrated and estimated in the pre-regulation economy, I estimate the policy intensities and emission control measure elasticities by matching key empirical moments—post-regulation moments and difference-in-differences estimates—in the post-regulation economy.

6.2.1 Production function

To estimate the three CES elasticities, I focus on the pre-regulation period (2016–2019) to simplify estimation by excluding the emission control measure use term, which is only active when pollution taxes τ_l^p are positive. This setting implies that these CES parameters are in response to price changes, which are more general than changes in pollution taxes.

The estimation procedure generalizes two modeling assumptions. First, I allow factor costs to vary at the plant level. Second, I allow the price of material to differ from the composite of sectoral good prices. Overall, this relaxation aligns the estimation approach with standard practices in the production function literature.

Demand and production elasticities The estimation proceeds in two steps, extending Murray Leclair (2024). For simplicity, I omit indices for productivities ϕ and z, sector j , and locations i and l. I apply a normalization common in the CES function estimation (León-Ledesma et al., 2010).

First, I adapt the method of De Loecker et al. (2016) and Grieco et al. (2016) to express the unobserved object in terms of observed objects using first order conditions from the plant's cost-minimization problem. I substitute energy and material with factor ratios and control for transmission bias from unobserved Hicks-neutral productivity z to observed inputs

(Doraszelski et al., 2013; Doraszelski et al., 2018). Incorporating a time-varying shock u_t with $\mathbb{E}_t[u_t] = 0$, the revenue function can be expressed in logarithmic form as:

$$\ln R_t = \ln \frac{\eta}{\eta - 1} + \ln \left(w_t \ell_t \left(1 + \frac{\alpha_K}{\alpha_L} \left(\frac{k_t}{\bar{K}} / \frac{\ell_t}{\bar{L}} \right)^{\frac{\rho-1}{\rho}} \right) + p_t^M m_t + p_t^E e_t \right) + u_t. \tag{20}$$

The main parameters of interest are the elasticity of substitution in demand η and the elasticity of substitution in the outer production function ρ. For consistency of the estimates, both parameters are estimated using nonlinear least squares (NLLS). I also estimate the ratio α^K/α^L and take the geometric mean of factor ratios, normalizing the input shares such that $\alpha_K + \alpha_E + \alpha_L + \alpha_M = 1$, in line with the standard geometric-mean normalization of the CES function.

The identification relies on an assumption that the unobserved factors driving input prices are not systematically correlated with the firm's unobserved productivity—firms are price takers in input markets. Such variation can arise from differences in supplier relationships, geographic cost factors, and other idiosyncratic productivity shocks.[23]

Once the elasticity of substitution ρ is known, the unobserved energy input ratio energy can be uniquely recovered. The elasticity of substitution in the inner production function λ is also of central interest. I estimate λ using a specification that includes a time-varying error term ε_t with $\mathbb{E}[\varepsilon_t] = 0$:

$$\ln \left(\frac{e_t}{\bar{E}} \right) = \frac{\lambda}{\lambda - 1} \ln \left(\sum_{f \in \mathcal{F}} \alpha_f \left(\frac{e_{f,t}}{\bar{e}_f} \right)^{\frac{\lambda-1}{\lambda}} \right) + \varepsilon_t. \tag{21}$$

The estimation is conducted via NLLS. During this step, I recover the fuel-share parameters α_f.[24] See Appendix E for more details.

Productivity dispersion parameters As above, I focus on the pre-regulation period for this estimation using the 2016 MMS and SBR for manufacturing and the 2015 Economic Census and SBR for power generation, respectively. In the manufacturing sector, I exploit the properties of the Pareto and log-normal distributions and CES demand to estimate the shape parameter ζ_j, focusing on the right tail of the sales distribution. If firm productiv-

[23] As emphasized by Grieco et al. (2016), this assumption allows unobserved input price variation to correlate with firm size, productivity, and location—excluding quantity discounts. However, because the policy targets large polluting establishments that may possess some bargaining power, I estimate the production function separately for a sample of multiplant firm establishments as a robustness check. The results are robust to these changes. See Figure A.5.

[24] In this second estimation step, I drop observations with only one fuel type because corners add noise without substitution information.

ity follows a Pareto distribution with shape parameter ζ_j and plant productivity follows a log-normal distribution with mean 0 and standard deviation σ_z, then the tail index is $\zeta_j/(\eta_j - 1)$.[25] Similarly, in the power generation sector, I estimate the shape parameter ζ_f using the relationship between productivity and capacity. Given the log-linear capacity function, if productivity follows a Pareto distribution with shape parameter ζ_f, then the tail index is ζ_f/a, since capacity is likely to bind for plants with high productivity.

6.2.2 Simulated method of moments

The remaining parameters are directly related to the regulation, which are estimated by simultaneously matching model-generated moments to their empirical counterparts. I rely on the reduced form estimates from Section 4 to identify the policy intensity parameter t and the emission control measure use elasticities in manufacturing α_j^p. The policy intensity is defined as $\tau_l^p = t * |\text{Cap reduction rate}_l^p|$, where the reduction rates across pollutants and policy districts are taken from the policy document (Table A.1). Unlike the CES elasticities, these measure elasticities are specific to changes in pollution prices.

This paragraph provides intuition for which empirical moment helps to identify each of these parameters, though all moments are jointly determined in equilibrium by all of these parameters. The estimate on emission control measure use helps identifying the levels of α_j^p while the estimates on emissions across pollutants and sectors facilitate an identification of the patterns of α_j^p. The average of the estimates on emissions inform the magnitude of the policy intensity t. Lastly, I estimate the measure elasticities in power generation α_f^p by matching the amounts of power generation emissions relative to those of manufacturing emissions across pollutants and fuels. I do not use the reduced form estimates on emissions here because they are not well identified due to the lack of observations.

6.3 Results

Estimated parameters are summarized in Tables 3 and 4. The plant level demand elasticity, $\eta > \sigma > 1$, ranges from 2.91 to 6.55 across sectors, and is larger than the firm level demand elasticity, making the nested CES well-defined. The elasticity of substitution in the outer production function, ρ, ranges from 1.05 to 1.40, while the elasticity of substitution in the inner production function, λ, ranges from 1.99 to 4.31. Since $\lambda > \rho > 0$, the CES nests in the production function are well defined. Both parameters indicate substitutability among factors and fuels. The finding that ρ is close to unity aligns with the literature, which often

[25] By the Breiman's theorem, if ϕ has a Pareto-type tail with index ζ_j and z is independent with $\mathbb{E}\left[z^{\zeta_j+\epsilon}\right] < \infty$ for $\epsilon > 0$, then ϕz has the same tail index ζ_j. Log-normal z satisfies the finite-moments condition.

interprets energy as being complementary to other inputs (Ryan, 2018). The condition $\lambda > 1$ holds as required by the model's theoretical guidance. They are particularly substitutable in light industries, such as textiles, apparel, and leather, because heavy industries, such as basic and fabricated metals, find it hard to change fuel types that are necessary to run furnaces, for example. This is consistent with assumptions in related studies (e.g., Krusell et al. (2022)). Murray Leclair (2024) similarly estimates an inner elasticity of 2.22 for the Indian steel industry. Lastly, I also estimate these parameters by confining the sample to single-plant firms to address firm technology differences arising from differences in size or the number of affiliated plants (Figure A.5).

Table 3: Parameters from production function estimation

Industry	Demand elasticity η	Factor elasticity ρ	Fuel elasticity λ	Pareto shape parameter ζ
Manufacturing				
Mining/quarrying	2.91 (0.32)	1.30 (0.03)	1.99 (0.33)	2.09 (0.31)
Food/beverages/tobacco	5.07 (0.13)	1.40 (0.02)	2.30 (0.14)	8.34 (0.27)
Textiles/apparel/leather	4.36 (0.13)	1.05 (0.01)	4.16 (0.69)	7.03 (0.15)
Wood/paper/printing/media	6.55 (0.25)	1.14 (0.01)	2.18 (0.13)	12.29 (0.44)
Petro/chem/pharma/rubber/plastics	6.64 (0.19)	1.24 (0.01)	2.02 (0.10)	9.77 (0.15)
Non-metallic minerals	3.52 (0.07)	1.40 (0.03)	2.07 (0.15)	4.07 (0.09)
Basic/fabricated metals	5.70 (0.12)	1.18 (0.01)	2.02 (0.08)	7.39 (0.14)
Electronics/instruments/electrical	4.91 (0.11)	1.17 (0.01)	4.31 (0.73)	4.56 (0.07)
Machinery/transport (incl. auto)	5.71 (0.12)	1.19 (0.005)	3.18 (0.22)	7.91 (0.08)
Furniture/misc./repair	5.60 (0.29)	1.15 (0.01)	2.18 (0.20)	11.11 (0.49)
Power generation				
Coal				0.23 (0.01)
Gas				0.23 (0.01)
Oil				0.23 (0.01)
Non-fossil power generation				0.14 (0.02)

Notes: Standard errors are in parentheses. The numbers of observations are dropped for brevity.

The productivity shape parameter, ζ, ranges from 2.09 to 12.29 in manufacturing, satisfying $\zeta_j > \sigma_j - 1$ for finite profits and 0.14 to 0.23 in power generation. Non-fossil power generation exhibits greater dispersion than fossil fuel generation, reflecting input specificity and heterogeneity across its sources (Arkolakis et al., 2023). The emission control measure elasticity in manufacturing, α_j^p, ranges from 0.01 to 0.29, which is larger than those reported in prior studies (Shapiro et al., 2018; Farrokhi et al., 2024), because factor and fuel substitution effects are separated in this model. That in power generation, α_f^p, ranges from 0.54 to 0.86.

While empirical estimates of ρ_j and λ_j are rare, Murray Leclair (2024) provides one of the few applications by estimating these parameters for the Indian steel industry—a setting characterized by high fossil-fuel intensity and relatively weak environmental regulation. The Korean context, by contrast, represents an advanced economy with stringent regulations and substantial potential for electrification. The absence of comparable estimates in such a setting underscores the importance of obtaining these results. Shapiro et al. (2018) and Farrokhi et al. (2024) provide estimates of emission control measure elasticities α_j^p, but focus on sectoral differences, without factor and fuel adjustments, which matters for leakage to power generation. The estimates of α_f^p are relatively new in the economics literature, which matters for green transition in the economy where electrification is a key.

Table 4: Parameters from moment matching estimation

Industry	Emission control measure elasticity α^{NO_x}	α^{SO_x}	α^{TSP}
Manufacturing			
Mining/quarrying	0.08	0.29	0.04
Food/beverages/tobacco	0.03	0.11	0.01
Textiles/apparel/leather	0.03	0.11	0.01
Wood/paper/printing/media	0.01	0.05	0.01
Petro/chem/pharma/rubber/plastics	0.01	0.05	0.01
Non-metallic minerals	0.01	0.05	0.01
Basic/fabricated metals	0.01	0.04	0.01
Electronics/instruments/electrical	0.02	0.06	0.01
Machinery/transport (incl. auto)	0.02	0.08	0.01
Furniture/misc./repair	0.04	0.16	0.02
Power generation			
Coal	0.64	0.83	0.73
Gas	0.59	0.86	0.77
Oil	0.54	0.85	0.75

6.3.1 Model fit

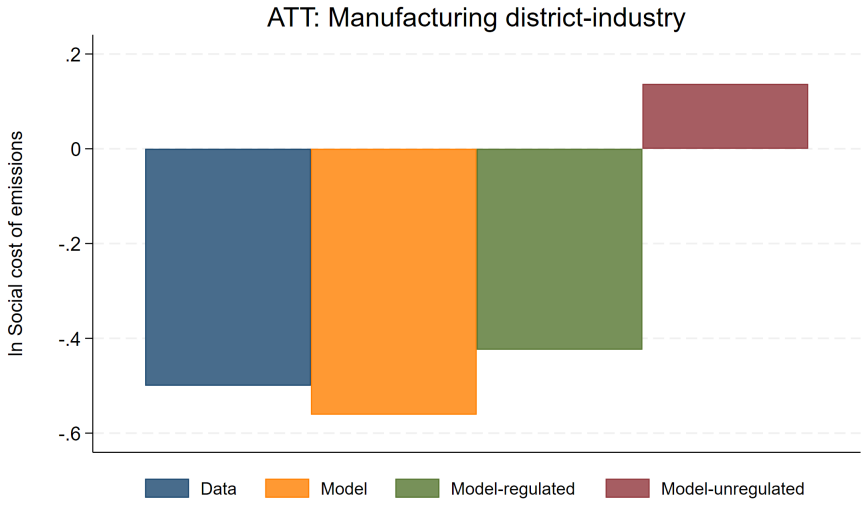
This section briefly shows how much the calibrated and estimated parameters can help the model to match targeted and untargeted moments. The estimation matches several targeted moments tightly. In the first stage, I evaluate the model on the numbers of firms and sales in manufacturing and power generation sectors. Figures A.6 and A.7 shows high correlations across sectors, fuels, and districts, in manufacturing and power generation sectors. In the second stage, I evaluate the difference in differences estimate using the model. In the second

stage, I show how closely the model-based reduced-form estimates match those of the data. In particular, part of this fit will be analyzed in Section 7 so I defer the model fit. As an out-of-sample forecast, I compare manufacturing emissions across sectors and districts, and power generation emissions across fuels and districts. Figure A.7 shows that they are well matched. Hence, the model also exhibits its quantitative fit for untargeted moments.

7 Counterfactual policy experiments

This section quantifies the policy effect and provides an interpretation to the reduced-form results, and conducts two counterfactual policy experiments. In this exercise, I compare different steady states. The initial steady state is the pre-regulation economy where there is no environmental regulation ($\tau_l^p = 0$ for all p and l). Then, I compute a new steady state, or the post-regulation economy, holding the entry and exit fixed to reflect a short-run change in the economy. I begin by quantifying the effect of the actual policy, Total Volume Control of Pollutants at Place of Business. This exercise provides an interpretation of the empirical results, which violates the SUTVA assumption. Also, it quantifies the welfare and distributional consequences.

Figure 7: Decomposition: Effects on Social cost in Manufacturing



Notes: The difference-in-differences estimate on the social cost of emissions and its model counterparts are plotted.

7.1 Total Volume Control of Pollutants at Place of Business

This is the baseline counterfactual analysis where the original policy effect is quantified. I use a structural approach to show how the reduced form estimate could have been biased. Then, I conduct a welfare analysis in aggregate and across regions.

7.1.1 Reduced form Interpretation

Once the model is quantified, it can provide an interpretation of the reduced-form estimates in Section 4 by modeling the SUTVA violation. Among others, I focus on the manufacturing sector emissions because emissions are the variable of interest and manufacturing sectors are where leakage is explicit. Since the estimates of difference-in-differences on emissions are across district-industry pairs, I decompose the difference-in-differences estimates into changes in regulated pairs (difference) and unregulated pairs (difference).

In Figure 7, the first two columns capture the difference-in-differences estimates in the data and the model: the model estimate (-0.56) closely matches the data estimate (-0.50). The last two columns divide the model estimate and capture a difference in regulated pairs and a difference in unregulated pairs. According to the model analysis, the policy effectively decreases the social cost of emissions in regulated pairs by 0.42, but it induces an increase in the other by 0.14. This finding aligns with a significant geographic leakage from regulated firms in regulated pairs to unregulated firms in unregulated pairs as found in Section 4. For this reason, understanding how the policy changes the geographic distribution of emissions and output across space is an important aspect of the analysis.

However, emissions can increase even in regulated districts because there are small unregulated polluters and leakage tends to decrease in distance. Also, the reduced-form estimates cannot capture level changes. Table 5 shows a decomposition result that addresses these two aspects. In regulated districts, emissions decreased by both regulated manufacturing and power plants. However, unregulated manufacturing plants within regulated districts and unregulated districts increased. Lastly, note that power generation emissions, in general, are smaller than manufacturing emissions. This point differs from greenhouse gas emissions because of the presence of production process emissions specific to manufacturing plants.

Table 5: Policy effect

Regulated districts	Sector	Manufacturing			Power generation			All
	Regulation status	Regulated	Unregulated	All	Regulated	Unregulated	All	All
	Social cost	-15	6	-2	-20	-0.1	-2	-2

Unregulated districts	Sector	Manufacturing			Power generation			All
	Regulation status	Regulated	Unregulated	All	Regulated	Unregulated	All	All
	Social cost		5	5		0.0002	0.0002	2

Notes: The outcomes are aggregated for each category, and then percentage changes are computed from the pre-regulation equilibrium. Hence, the numbers differ from the difference-in-difference estimates.

7.1.2 Welfare and Distributional consequences

I evaluate welfare by tracking district-level changes in consumption measured in real income, emissions measured in the social cost, and production measured in quantities (Figure 8). All outcomes comove with the policy's spatial variation, but emissions changes follow it more closely, are larger in magnitude, and are more skewed. This is because emissions are what are regulated across districts. However, even in regulated districts, emissions sometimes increase. Note that large polluters regulated by the policy are cleaner in terms of emissions intensity. Hence, this is the case when leakage to dirtier manufacturing and power plants mitigates emissions reduction by regulated plants.

The first three rows of Table 6 summarize these changes at aggregated levels. There are two notable aspects. First, regulated districts gain in net, because, although they lose more in consumption and production than unregulated districts, they gain much more from cleaner air. As noted above, the fact that emissions changes are larger implies that they can have a more powerful impact on welfare than other changes. Under government constraints, the priority of the policy, in fact, increases the overall welfare through cleaner air (4.97%) despite consumption and production losses (0.60% and 0.66%). This is because regulated districts are more populated and local air pollution has geographically concentrated effects.

7.2 Counterfactual policy experiments

Setting the above quantification as a baseline, I conduct counterfactual policy experiments by computing new steady states, or post-regulation economies. I keep all parameters as in the baseline except pollution taxes as they are the key to counterfactuals. Throughout these exercises, I respect the following two features of the policy. First, I reflect the government constraint (e.g., monitoring frictions) by keeping the number of regulated plants and the number of regulated pollutants as in the baseline. Second, as before, I consider the number

of residents, because of the locality of the regulated pollutants.

I conduct two counterfactual policy experiments. First, I impose Pigouvian pollution taxes only in regulated districts and set them equal to the social cost of emissions. Second, I impose a uniform pollution tax across all districts to limit geographic leakage and characterize its distributional consequences. Table 6 summarizes the results.

7.2.1 Pigouvian pollution taxes in regulated districts

In this exercise, I keep regulated plants and districts as before, but impose Pigouvian pollution taxes by equating them to the level of the social cost of emissions for each pollutant. Policies addressing this market failure (environmental externalities) can maximize social welfare by regulating emissions until the marginal cost of complying with policy equals the marginal social benefit of reducing pollution emissions (Pigou, 1932).[26] However, note that the actual policy only targets large polluters in polluted and populated districts. In this case, simple Pigouvian pollution taxes are no longer optimal because of leakage to dirtier plants. Consumption losses are much larger than gains from cleaner air than before. Also, emissions and consumption decrease in unregulated districts due to higher prices. Overall, the counterfactual policy is contractionary without higher gains in cleaner air. Hence, it is sub-optimal, and the optimal ones should be quantitatively calculated.

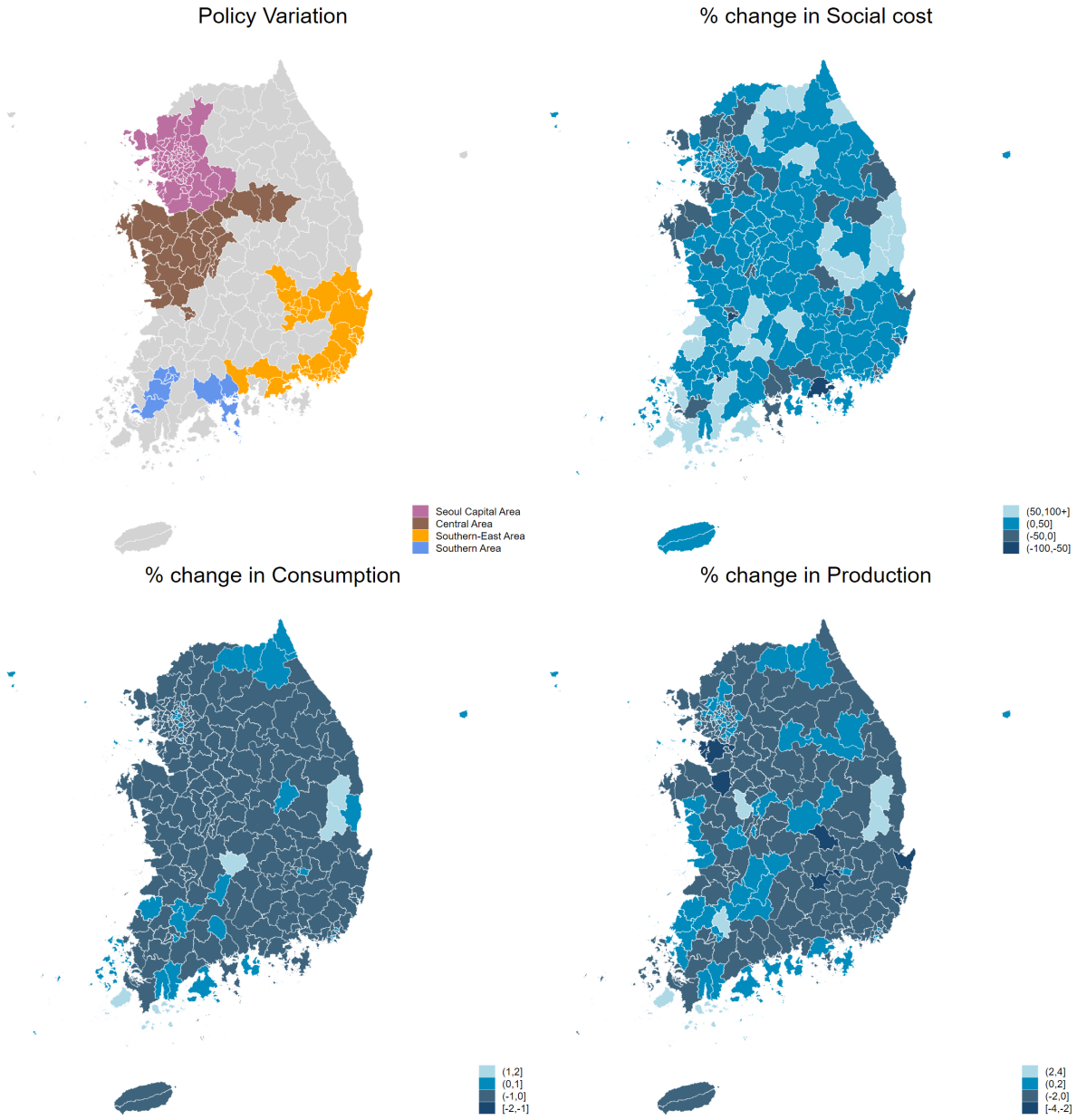
7.2.2 Uniform pollution taxes in all districts

Now I remove any regional variation from the original policy by selecting large polluters in all districts including unregulated ones and imposing the median pollution taxes of the baseline to all districts to explore geographic leakage. Since most environmental regulations are local, this experiment, when compared to the baseline, can provide a lesson on how consumption, emissions, and production move differently in response. A key pattern is that, as the regional variation is relaxed, the trade-off between cleaner air and lower consumption and production decreases. As they comove, the overall welfare gain decreases. Hence, geographic leakage based on population and the scope of pollution can be beneficial, and from the perspective of the policy maker, prioritizing populated and polluted districts can enhance the aggregate welfare.[27]

[26] This exercise relates to standard theory on pollution markets that allowance prices reflect marginal abatement costs and that an efficient policy sets the price of pollution permits equal to the marginal social benefit of reducing emissions (Dales, 1968; Crocker, 1966; Montgomery, 1972). Muller et al. (2009) and Shapiro et al. (2025) put this theory into data and conduct a similar analysis.

[27] Migration or labor mobility across districts can attenuate the policy effect. Although this paper does not address this margin, the outcome above provides a prediction. If people are mobile, they will move to districts with net gains (regulated districts) until welfare is equalized across space. However, in practice, many local environmental regulations assume labor immobility, at least in the short run, because, once labor

Figure 8: Distributional consequences by district



Notes: The left panel of the first map captures the policy variation across districts, and the right panel shows percentage changes in the social cost of emissions. The left panel of the second map captures percentage changes in consumption, and the right panel depicts percentage changes in production. The outcomes are aggregated for each category, and then percentage changes are computed from the pre-regulation equilibrium.

is mobile, it is hard to evaluate or predict the policy effect.

Table 6: Welfare analysis

Policy variation	Policy intensity	Districts	Social cost	Consumption	Production
Actual	(Baseline) Actual	Aggregate	-4.97	-0.60	-0.66
		Regulated	-5.04	-0.61	-0.76
		Unregulated	+2.03	-0.53	-0.25
	(Counterfactual 1) Pigouvian	Aggregate	-3.69	-7.87	-7.19
		Regulated	-3.71	-7.91	-7.26
		Unregulated	-2.26	-7.38	-6.93
Regionally uniform	(Counterfactual 2) Median	Aggregate	-6.75	-7.87	-7.20
		Regulated	-6.80	-7.91	-7.27
		Unregulated	-2.26	-7.38	-6.92

Notes: The outcomes are aggregated for each category, and then percentage changes are computed. Regulated and unregulated districts are those of the actual policy.

8 Conclusion

Industrial environmental regulation aims to reduce local air pollution, but, in practice, such policies are often targeted toward large manufacturing and power plants in densely populated, highly polluted areas because monitoring and enforcement capacity is limited. Their effects therefore depend not only on abatement at regulated plants but also on leakage across plants, sectors, and regions. Understanding these responses is central to evaluating the incidence and welfare consequences of size- and place-based environmental policy.

In this paper, I study these issues in the context of South Korea's 2020 expansion of its local air pollutant cap-and-trade system. Using detailed data on emissions, inputs, and outputs and a difference-in-differences design, I find pronounced sectoral asymmetry. In regulated district-manufacturing-industry pairs, the policy reduced emissions by 43–54 percent across major pollutants, relative to unregulated pairs, through both abatement and leakage. By contrast, emissions from power generation did not decline, consistent with increased electricity demand from industrial electrification and leakage from manufacturing to the power sector. I also document geographic leakage with spatial decay, implying that reduced form estimates alone cannot recover the policy's aggregate incidence or welfare effects.

To address this, I develop a spatial general equilibrium model with multiple manufacturing sectors and upstream power generation sectors, incorporating the abatement and leakage channels documented in the data, and evaluate welfare and counterfactual policies. I estimate key parameters, such as factor and fuel substitution and emission control measure use elasticities, using a production function estimation approach and the reduced form estimates. The model shows that a quarter of the policy effect on emissions at the district-manufacturing industry pairs come from leakage across districts.

The model also implies that the policy raises aggregate welfare: a 5 percent improvement

in air quality outweighs roughly 1 percent declines in both consumption and production. These effects are spatially uneven. Regulated districts benefit from cleaner air but bear losses in consumption and production, whereas unregulated districts exhibit the opposite pattern. Aggregate welfare nonetheless rises because leakage shifts emissions away from the most polluted and densely populated districts, where marginal damages are highest. Counterfactual exercises show that, under administrative constraints, the implemented policy—which targets large emitters in the most polluted and densely populated districts—outperforms feasible alternatives, including a spatially uniform regulation.

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A Policy details

A.1 Rules on caps

Initial caps, in principle, are allocated based on past emissions volumes. To protect early adopters, plants that already invested in abatement technology are assessed against their five-year average emissions. I abstract from the initial allocation of permits for two reasons. First, under standard conditions, a Coasian argument implies that the equilibrium allocation of abatement across firms is cost effective and independent of the initial distribution of permits, although the initial allocation may still affect the distribution of compliance burdens (Coase, 1960). Second, I do not have a credible empirical strategy to identify the causal effect of permit allocation itself. For related discussions, see Hahn et al. (2011) and Fowlie et al. (2013).

Then, following allowances are benchmarked to "best available technology" standards, which are formally revised every three years in government-led consultations with regulated plants. Importantly, each area's reduction goal is based on its emissions and population, which is the source of the policy variation by district. While plants participate, their role is limited to assessing feasibility rather than shaping the benchmarks. Also, lobbying has been prohibited in Korea. Although informal influence cannot be fully excluded, these institutional features together suggest limited scope for policy endogeneity.

A.2 Allowance prices

The NO_x and SO_x prices fall in a similar order of magnitude to allowance prices in major emissions-trading systems (ETS), such as the EU ETS, California, and China's national ETS. However, these are not directly comparable because they cap different pollutants (NO_x and SO_x vs CO_2), with different damages, sector coverage, monitoring rules, and compliance designs. A more directly comparable benchmark is the U.S. Cross-State Air Pollution Rule (CSAPR) market for NO_x and SO_2. Korea's NO_x and SO_x levels are above typical U.S. annual CSAPR allowance prices but below U.S. ozone-season NO_x allowance prices, which can be much higher. Overall, Korea's NO_x and SO_x allowance prices are comparable in magnitude to other pollution markets. TSP has been rarely regulated so it is hard to find a counterpart. One exception can be found in Greenstone et al. (2023).

A.3 Other details

In the pollution markets, banking is allowed for one year while borrowing is prohibited. Measurement, reporting, and verification (MRV) mainly rely on sensors at plant outlets;

where unavailable, third-party verification uses input and output and measure use records. Brokerage is not allowed. A plant or a firm can buy or sell its allowances on a website designed and controlled by the Korean Ministry of Environment by posting the prices it wants to buy or sell.

Lastly, although the markets include all regulated plants even not in the manufacturing and power generation sectors, the fact that prices were high and stable and the fact that 82% of regulated plants were in those two sectors imply that the regulation was effective to regulated manufacturing and power plants. They could have sold their allowances if their marginal abatement costs were lower or bought them if their costs were higher. This is because the allowance prices reflect the equilibrium marginal abatement costs (Shapiro et al., 2025).

A.4 Power generation

Korea's electricity market is inherently two-sided: a wholesale market operates between power plants and the government, while a retail market connects the government to final consumers such as households and manufacturing plants. The wholesale market operates through two commonly-used mechanisms: system marginal pricing (SMP) and merit-order dispatch (MOD). Lower-cost plants enter first and renewable typically dispatch before fossil fuels (MOD), and the electricity price is set to the marginal cost of the last generating unit (SMP). Yet given limited clean capacity, short-run demand surges likely call on dirtier power plants because their marginal costs are higher and clean power plants have been in use already.

Note that the regulated power plants cannot be newly dispatched after the policy implementation because they are selected based on their past emissions. If they are not dispatched in the policy equilibrium, the electricity prices should be higher, and those regulated should have lower sales and less emissions. If they are still in the dispatch, the electricity prices should be the same as before or higher, leading to the same or higher sales and emissions. Findings in Section 4 will guide us here because, without a large drop in sales or an increase in the exit, the latter is more likely to be the case.

Further, clean generation accounts for 36% in 2012 and 43% in 2024. Uneven distribution of clean and dirty power plants implies additional demand can be met by dirtier facilities elsewhere (Figure A.3). So leakage depends on whether this capacity was sufficient and where it was.

B Data appendix

B.1 District-industry level data

B.1.1 Data cleaning

Industrial and district concordances between the SEMS and the census data are carried out with the 2023 classifications to have both pieces of information at the district-3-digit-KSIC level. Industrial concordance requires further understanding of each dataset. The SEMS is categorized by emission source while the census data are categorized by the classification of a product with the highest sales. Most classifications are directly transferable at the 3-digit KSIC in manufacturing and the 5-digit in power generation. I differentiate fossil fuel power plants as those that have 35113, 35120, 35130, 35200, and 35300 as its 5-digit KSIC. The rest is allocated using emissions source and fuel use categories along with the corresponding emission factors. There are two assumptions behind this task. First, I assume the industry of the best selling product is the same as that of the main activity. This assumption is necessary for concordance to connect emissions and economic activity. Second, I impose a standard assumption and use sales as a proxy to emissions within district-industry pairs. This assumption helps to divide and allocate emissions from production process to the 3-digit KSICs when granular quantity information is not available. I drop those that have 1-digit KSICs because it is hard to divide such emissions. Since this concordance is carried out at a fine grid (the district $\times$ 3-digit KSIC level), this assumption is less likely to be highly restrictive. Most importantly, the result is robust whether I conduct such concordance or not.

B.1.2 Data details

SEMS incorporates tele-monitored emissions when available and otherwise imputes emissions using information on fuel use, production processes, emission factors, abatement measures, and activity types.[28] The match is complete at the district-industry level.

B.2 Plant level data

B.2.1 Data cleaning

This paper conducts three data cleaning procedures. First, it fills out missing location in the SBR if necessary. For example, from smaller location codes, districts can be found if missing. Second, I use firm and plant ids, districts, KSICs, and histories to identify the

[28] This information can be found in the ministry website.

same plants within firms in specific districts. Third, industrial and district concordances are considered in line with those classification in 2023 (the most recent year available). For KSICs, I empty those before 2017, because the $10th$ KSIC was implemented in 2017. Then, I fill out empty places with those of 2017, 2018, and 2019 for each plant. Fourth, I clean establishment level information using firm ids, latitudes and longitudes, KSICs, and years by finding the corresponding pairs one-to-one and taking averages for fuel use and sales to address establishment level changes such as M&A and split. Fifth, I merge with the MMS and the measure use dataset using plant ids and latitudes and longitudes.

B.2.2 Data details

Emissions are also observed at the plant level, but primarily for large polluters. This sample covers too few untreated plants to form a sufficiently large control group. While the fuel use survey has informed industrial environmental policies, it has never been directly used for direct policy implementation. Misreporting is unlikely because the agency cross-checks records with other relevant data (e.g., real-time monitored data) to scrutinize the survey answer. Indeed, Section 4 will show a coherent picture across different outcome variables. This issue is more likely to be prominent in developing countries where cross-checks are challenging. For such an issue, see Duflo et al. (2013).

At the plant level, 15 of the 1,033 treated manufacturing and power plants are not matched because they had closed before the sample period but remained on the policy list. To account for mergers, acquisitions, and splits, I supplement the census with records from the Data Analysis, Retrieval and Transfer System of the Korean Financial Supervisory Service. Business lease is considered from the perspective of the lender because that is how the data are constructed.

B.2.3 Matching

Following Heckman et al. (1997) and Heckman et al. (1998), I estimate the average treatment effect on the treated using a matched difference-in-differences estimator with one-to-one nearest-neighbor Mahalanobis distance matching. Matching at the plant level proceeds in two steps. First, I exactly match plants by industries (3-digit KSICs) to control for industry-specific time trends. I exactly match plants by the emission control measure update status to capture the corresponding update more clearly. This choice also helps to compare regulated plants with potential candidates, because the measure information has been concentrated in such large polluters.

Second, I apply Mahalanobis distance matching to control for differences in plant size.

Following the policy, I use the maximum of 2018 and 2019 sales, because sales are a proxy of emissions and size when emissions are not available at the plant level. Therefore, the control groups are, in general, smaller polluters in the same areas, as in Table 1. It is also shown that the matching substantially improves balance and common support, reducing differences in both size and significance between the treated and control groups.

C Additional robustness checks

Since 1991, the Clean Air Act implemented several measures to curb local air pollution. The cap-and-trade policy is a part of the law implemented in later years. First, there has been the banning the use of sulfur oil and solid fuels in certain districts to address local air pollution. Since the policy does not have any time variation, unit fixed effects should address the effect of this ban. Also, a comparison within administrative regional units will help to cleanse the effect further. There has been a concentration regulation at the pipe level and a pollution tax on the amount of emissions at the establishment level. The former sets the criteria for the concentration of emissions for all polluting sources and regulates (a command-and-control regime). Excess emission charges are imposed to those violating the concentration criteria. The latter consists of basic emission charges for the establishments emitting regulated pollutants. So the concentration regulation relates to the concentration, while the basic emission charge and the cap-and-trade relate to the amount of regulated emissions.

These two policies also have regional variation, which does not fully align with that of the cap-and-trade. More importantly, these two regulations became more stringent in 2020, but those under the cap-and-trade system became exempt from the basic emission charge. In other words, these policies targets smaller polluters not regulated by the cap-and-trade system. However, the policy improvement was global, which should have been addressed by either the industry and year fixed effects or the region and year fixed effects. Also, the fact that those regulated by the cap-and-trade accounted for a large portion of emissions lessens a concern that emissions reduction was driven by these two policies. In addition, an authorization began to be required for large polluting establishments to install or modify emissions sources in regulated areas since 2020. To get authorized, they have to use the Best Available techniques economically achievable (BAT). Originally, it was only is the Seoul Capital Area, but it expanded. But this is about controlling additional emissions not reducing the existing ones, and I did not find any evidence of the policy effect on the entry and exit of an establishment.

Furthermore, there has been the Integrated Pollution Preventation and Control Direc-

tive in 2017, integrating the source-level emissions sources to the establishment level and increasing its sectoral coverage over time. Still, there was a chance that a more stringent criterion was applied from this integration based on the BAT. But the policy was global, and the timing was different. Hence, the industry and yer fixed effects should have address its effect. Lastly, there have been some efforts to decrease particulate emissions since 2019. But they are seasonal, have different timings, and their regional variations are across provinces, whose effects should be captured by the province and year fixed effects.

Overall, these policies are unlikely to be the main force, because the emissions allowances of regulated plants explain the majority of emissions in regulated areas. However, still districts and sectors might have been differently exposed to (semi-) global policies. So I additionally control for the baseline emissions in the district- industry pair analysis to address the potential effect in more exposed pairs and find a similar result (Tables A.31 and A.32).

D Theory

This section contains several derivations omitted in the main text for brevity.

D.1 Manufacturing firms

The cost minimization problem of a plant with firm productivity ϕ and location in i and plant productivity z in location l and industry j can be written as:

$$\begin{aligned}
&\min_{k,e,\ell,m;e_f,(1-a)} \left(rk + \sum_{f\in\mathbb{F}} p_f e_f + w_l \ell + p^M_{l,j} m \right) \\
&\qquad + \sum_{p\in\Lambda_{il,j}(\phi,z)} \tau^p_l \left(1-a\right)^{\frac{1}{\alpha^p_j}} \left(\kappa^p_j q_{il,j} + \sum_f \kappa^p_f e_f \right) \\
&\qquad s.t. \\
&q_{il,j} = \phi z \left(1-a\right) \left(\alpha_{j,K} k^{\frac{\rho_j-1}{\rho_j}} + \alpha_{j,E} e^{\frac{\rho_j-1}{\rho_j}} + \alpha_{j,L} \ell^{\frac{\rho_j-1}{\rho_j}} + \alpha_{j,M} m^{\frac{\rho_j-1}{\rho_j}} \right)^{\frac{\rho_j}{\rho_j-1}}, \qquad \text{(A.1)} \\
&e = \left(\sum_{f\in\mathbb{F}} \alpha_{j,f} \left(e_f\right)^{\frac{\lambda_j-1}{\lambda_j}} \right)^{\frac{\lambda_j}{\lambda_j-1}}.
\end{aligned}$$

The first order conditions with respect to k, e, ℓ, and m are:

$$\begin{aligned} r &= \alpha_{j,K} k^{\frac{-1}{\rho_j}} H_{il,j}(\phi, z), \\ p^E_{il,j}(\phi, z) &= \alpha_{j,E} e^{\frac{-1}{\rho_j}} H_{il,j}(\phi, z), \\ w_l &= \alpha_{j,L} \ell^{\frac{-1}{\rho_j}} H_{il,j}(\phi, z), \\ p^M_{l,j} &= \alpha_{j,M} m^{\frac{-1}{\rho_j}} H_{il,j}(\phi, z), \end{aligned}$$

where

$$\begin{aligned} H_{il,j}(\phi, z) =& \phi z (1-a) \left(\alpha_{j,K} k^{\frac{\rho_j - 1}{\rho_j}} + \alpha_{j,E} e^{\frac{\rho_j - 1}{\rho_j}} + \alpha_{j,L} \ell^{\frac{\rho_j - 1}{\rho_j}} + \alpha_{j,M} m^{\frac{\rho_j - 1}{\rho_j}} \right)^{\frac{\rho_j}{\rho_j - 1} - 1} \\ & \times \left(\mu_{il,j}(\phi, z) - \sum_{p \in \Lambda_{il,j}(\phi, z)} \tau^p_l (1-a)^{\frac{1}{\alpha^p_j}} \kappa^p_j \right). \end{aligned}$$

Taking ratios between factors of production, I can express all production factors in terms of labor and prices:

$$\begin{aligned} \frac{k}{l} &= \left(\frac{r}{w_l} \right)^{-\rho_j} \left(\frac{\alpha_{j,K}}{\alpha_{j,L}} \right)^{\rho_j}, \\ \frac{e}{l} &= \left(\frac{p^E_{il,j}(\phi, z)}{w_l} \right)^{-\rho_j} \left(\frac{\alpha_{j,E}}{\alpha_{j,L}} \right)^{\rho_j}, \\ \frac{m}{l} &= \left(\frac{p^M_{l,j}}{w_l} \right)^{-\rho_j} \left(\frac{\alpha_{j,M}}{\alpha_{j,L}} \right)^{\rho_j}. \end{aligned} \tag{A.2}$$

The first order conditions with respect to e_f and $(1-a)$ are:

$$\tilde{p}^f_{il,j}(\phi, z) = H_{il,j}(\phi, z) \alpha_{j,E} e^{\frac{-1}{\rho_j}} \left(\sum_{f \in \mathbb{F}} \alpha_{j,f} (e_f)^{\frac{\lambda_j - 1}{\lambda_j}} \right)^{\frac{\lambda_j}{\lambda_j - 1} - 1} \alpha_{j,f} (e_f)^{-\frac{1}{\lambda_j}},$$

and

$$\begin{aligned} \sum_{p \in \Lambda_{il,j}(\phi, z)} \tau^p_l \frac{(1-a)^{\frac{1}{\alpha^p_j} - 1}}{\alpha^p_j} \left(\sum_f \kappa^p_f e_f \right) =& \phi z \left(\alpha_{j,K} k^{\frac{\rho_j - 1}{\rho_j}} + \alpha_{j,E} e^{\frac{\rho_j - 1}{\rho_j}} + \alpha_{j,L} \ell^{\frac{\rho_j - 1}{\rho_j}} + \alpha_{j,M} m^{\frac{\rho_j - 1}{\rho_j}} \right)^{\frac{\rho_j}{\rho_j - 1}} \\ & \times \left(\mu_{il,j}(\phi, z) - \sum_{p \in \Lambda_{il,j}(\phi)} \tau^p_l \left(\frac{1}{\alpha^p_j} + 1 \right) (1-a)^{\frac{1}{\alpha^p_j}} \kappa^p_j \right), \end{aligned}$$

where the effective fuel price of fuel f, $\tilde{p}^f_{il,j}(\phi,z) = p_f + \sum_{p\in\Lambda_{il,j}(\phi,z)} (1-a_{il,j}(\phi,z))^{\frac{1}{\alpha^p_j}} \kappa^p_f \tau^p_l$.

Using the first order conditions with respect to e and e_f, fuel e_f demand can be derived as:

$$\frac{e_{il,j,f}(\phi,z)}{e_{il,j}(\phi,z)} = \left(\frac{\tilde{p}^f_{il,j}(\phi,z)}{p^E_{il,j}(\phi,z)\,\alpha_{j,f}}\right)^{-\lambda}. \tag{A.3}$$

With this expression, $p^E_{il,j}(\phi,z)$ can be derived from the energy aggregate:

$$p^E_{il,j}(\phi,z) = \left(\sum_{f\in\mathbb{F}} \alpha_{j,f}\left(\frac{\tilde{p}^f_{il,j}(\phi,z)}{\alpha_{j,f}}\right)^{1-\lambda_j}\right)^{\frac{1}{1-\lambda_j}}, \tag{A.4}$$

where $p^E_{il,j}(\phi,z)\,e_{il,j} = \sum_{f\in\mathbb{F}}\left(\frac{\tilde{p}^f_{il,j}(\phi,z)}{\alpha_{j,f}}\right) e_{il,j,f}$.

By taking a ratio of the two first order conditions with respect to e_f and e_e, the relative fuel demand can be written as:

$$\frac{e_{il,j,f}(\phi,z)}{e_{il,j,e}(\phi,z)} = \left(\frac{\tilde{p}^f_{il,j}(\phi,z)}{\tilde{p}^e_{il,j}(\phi,z)}\right)^{-\lambda_j}\left(\frac{\alpha_{j,f}}{\alpha_{j,e}}\right)^{\lambda_j},$$

which decreases in the effective fuel price of f, $\tilde{p}^f_{il,j}(\phi,z)$ and increases in the average productivity of fuel f, $\alpha_{j,f}$. Then, the energy aggregate can be re-expressed as:

$$e_{il,j}(\phi,z) = e_{il,j,e}(\phi,z)\left(\sum_{f\in\mathbb{F}}\alpha_{j,f}\left(\frac{\tilde{p}^f_{il,j}(\phi,z)}{\tilde{p}^e_{il,j}(\phi,z)}\right)^{1-\lambda_j}\left(\frac{\alpha_{j,f}}{\alpha_{j,e}}\right)^{\lambda_j-1}\right)^{\frac{\lambda_j}{\lambda_j-1}}.$$

The unit production cost can be derived from the first order condition with respect to ℓ and the factor ratios (Equation A.2):

$$\mu_{il,j}(\phi,z) = \frac{1}{(1-a_{il,j}(\phi,z))}\frac{1}{\phi z}\frac{1}{G_{il,j}(\phi,z)} + \sum_{p\in\Lambda^p_{il,j}(\phi,z)} \tau^p_l\,(1-a_{il,j}(\phi,z))^{\frac{1}{\alpha^p_j}}\,\kappa^p_j, \tag{A.5}$$

which does not depend on $q_{il,j}(\phi,z)$.

Using the fuel demand (Equation A.3), the energy price (Equation A.4), factor ratios (Equation A.2), and the unit production cost (Equation A.5), emission control measure use can also be characterized. When $\tau^p_l > 0$ and $\hat{s}^p_{il,j}(\phi,z) \geq \bar{T}^p_j$ for at least one p, $(1-a_{il,j}(\phi,z))$

is a solution to the following equation:

$$\left(\mu_{il,j}\left(\phi,z\right)-\sum_{p\in\Lambda_{il,j}^{p}(\phi,z)}\frac{\tau_{l}^{p}\left(1+\alpha_{j}^{p}\right)\left(1-a_{il,j}\left(\phi,z\right)\right)^{\frac{1}{\alpha_{j}^{p}}}\kappa_{j}^{p}}{\alpha_{j}^{p}}\right)\phi z\left(G_{il,j}\left(\phi,z\right)\right)^{\rho_{j}}\left(\alpha_{j}^{E}\right)^{-\rho_{j}}\left(p_{il,j}^{E}\left(\phi,z\right)\right)^{\rho_{j}}$$

$$=\sum_{p\in\Lambda_{il,j}^{p}(\phi,z)}\frac{\tau_{l}^{p}\left(1-a_{il,j}\left(\phi,z\right)\right)^{\frac{1}{\alpha_{j}^{p}}-1}\left(\sum_{f}\kappa_{f}^{p}\left(\frac{\tilde{p}_{il,j}^{f}(\phi,z)}{p_{il,j}^{E}(\phi,z)\alpha_{j,f}}\right)^{-\lambda_{j}}\right)}{\alpha_{j}^{p}}. \tag{A.6}$$

$G_{il,j}\left(\phi,z\right)=\left(\left(\alpha_{j,K}\right)^{\rho_{j}}\left(r\right)^{1-\rho_{j}}+\left(\alpha_{j,E}\right)^{\rho_{j}}\left(p_{il,j}^{E}\left(\phi,z\right)\right)^{1-\rho_{j}}+\left(\alpha_{j,L}\right)^{\rho_{j}}\left(w_{l}\right)^{1-\rho_{j}}+\left(\alpha_{j,M}\right)^{\rho_{j}}\left(p_{l,j}^{M}\right)^{1-\rho_{j}}\right)^{\frac{1}{\rho_{j}-1}}$ is an inverse CES factor cost bundle. However, when $\tau_{l}^{p}=0$ or $\hat{s}_{il,j}^{p}\left(\phi,z\right)<\bar{T}^{p}$ for all p, $\left(1-a_{il,j}\left(\phi,z\right)\right)=1$.

Then, the variety price combines mark-ups, multiregional production frictions, and iceberg trade costs.

$$p_{iln,j}\left(\phi,z\right)=\mathcal{M}_{j}\gamma_{il,j}\mu_{il,j}\left(\phi,z\right)d_{ln,j},$$

where $\mathcal{M}_{j}=\frac{\eta_{j}}{\eta_{j}-1}$.

From the household demand structure (Equation 14), the revenue of this plant can be derived as:

$$\begin{aligned}R_{il,j}\left(\phi,z\right)=&\sum_{n}p_{iln,j}\left(\phi,z\right)q_{iln,j}\left(\phi,z\right)\\=&\sum_{n}\left(\frac{p_{iln,j}\left(\phi,z\right)}{P_{in,j}\left(\phi\right)}\right)^{1-\eta_{j}}\left(\frac{P_{in,j}\left(\phi\right)}{P_{n,j}}\right)^{1-\sigma_{j}}X_{n,j}\end{aligned} \tag{A.7}$$

and the quantity demand of the plant can be derived as:

$$q_{il,j}\left(\phi\right)=\sum_{n}d_{ln,j}\left(\frac{p_{iln,j}\left(\phi,z\right)}{P_{in,j}\left(\phi\right)}\right)^{-\eta_{j}}\left(\frac{P_{in,j}\left(\phi\right)}{P_{n,j}}\right)^{-\sigma_{j}}\frac{X_{n,j}}{P_{n,j}}, \tag{A.8}$$

where $q_{il,j}\left(\phi,z\right)=\sum_{n}d_{ln,j}q_{iln,j}\left(\phi,z\right)$. The corresponding profit is:

$$\pi_{il,j}\left(\phi,z\right)=\frac{R_{il,j}\left(\phi,z\right)}{\eta_{j}}. \tag{A.9}$$

D.2 Power plants

The cost minimization problem is similar to the above, which can be written as:

$$\begin{aligned}\min_{e^{\mathcal{E}}_f,(1-a)} & p_f e^{\mathcal{E}}_f + \sum_{p\in\Lambda_{i,f}(z)} \tau^p_i \left(1-a\right)^{\frac{1}{\alpha^p_f}} \kappa^{\mathcal{E},p}_f e^{\mathcal{E}}_f \\ & s.t. \\ & y_{i,f}\left(z\right) = \left(1-a\right) \min\left\{z e^{\mathcal{E}}_f, k_{i,f}\left(z\right)\right\}.\end{aligned}$$

The first order conditions with respect to $(1-a)$ and $e^{\mathcal{E}}_f$ are:

$$\sum_{p\in\Lambda_{i,f}(z)} \tau^p_i \frac{1}{\alpha^p_f} \left(1-a\right)^{\frac{1}{\alpha^p_f}-1} \kappa^{\mathcal{E},p}_f e^{\mathcal{E}}_f = \nu_{i,f}\left(z\right) z e^{\mathcal{E}}_f,$$

$$p_f + \sum_{p\in\Lambda_{i,f}(z)} \tau^p_i \left(1-a\right)^{\frac{1}{\alpha^p_f}} \kappa^{\mathcal{E},p}_f = \nu_{i,f}\left(z\right) z \left(1-a\right).$$

Using both, when $\tau^p_i > 0$ and $\hat{s}^p_{i,f}\left(z\right) \geq \bar{T}^p_f$ for at least one p, $\left(1-a_{i,f}\left(z\right)\right)$ is a solution to the following equation:

$$\left(1-a\right) = \left(\frac{p_f}{\left(\frac{1}{\alpha^p_f}-1\right)\sum_{p\in\Lambda_{i,f}(z)} \tau^p_i \kappa^{\mathcal{E},p}_f}\right)^{\alpha^p_f}, \tag{A.10}$$

which strictly decreases in τ^p_i. When $\tau^p_i = 0$ or $\hat{s}^p_{i,f}\left(z\right) < \bar{T}^p$ for all p, $\left(1-a_{i,f}\left(z\right)\right) = 1$. Fuel f use is

$$e^{\mathcal{E}}_{i,f}\left(z\right) = \min\left\{\frac{k_{i,f}\left(z\right)}{z}, \frac{y_{i,f}\left(z\right)}{z\left(1-a_{i,f}\left(z\right)\right)}\right\}.$$

Then, the unit power generation cost can be expressed as:

$$\begin{aligned}\nu_{i,f}\left(z\right) =& \frac{p_f + \sum_{p\in\Lambda_{i,f}(z)} \tau^p_i \left(1-a_{i,f}\left(z\right)\right)^{\frac{1}{\alpha^p_f}} \kappa^{\mathcal{E},p}_f}{z\left(1-a_{i,f}\left(z\right)\right)} \\ =& \frac{p_f + \sum_{p\in\Lambda_{i,f}(z)} \tau^p_i \left(\frac{p_f}{\left(\frac{1}{\alpha^p_f}-1\right)\sum_{p\in\Lambda_{i,f}(z)} \tau^p_i \kappa^{\mathcal{E},p}_f}\right)^{1-\alpha^p_f} \kappa^{\mathcal{E},p}_f}{z},\end{aligned} \tag{A.11}$$

which does not depend on $y_{i,f}\left(z\right)$, but locally increases in pollution tax τ^p_i.

The corresponding profit is

$$\pi_{i,f}(z) = (p_e - \nu_{i,f}(z))\, y_{i,f}(z). \tag{A.12}$$

D.3 Aggregation and General equilibrium conditions

The price index of sector j in location n should satisfy the following condition:

$$P_{n,j} = \left(\sum_i M_{i,j} \mathbb{E}_\phi \left[\left(P_{in,j}^{1-\sigma_j}(\phi) \right) \right] \right)^{\frac{1}{1-\sigma_j}},$$

where

$$P_{in,j}(\phi) = \left(\sum_l \mathbb{E}_z \left[p_{iln,j}^{1-\eta_j}(\phi, z) \right] \right)^{\frac{1}{1-\eta_j}}.$$

The labor markets clear in district l:

$$L_l = \sum_{i,j} M_{i,j} \mathbb{E}_{\phi,z} \left[\ell_{il,j}(\phi, z) \right].$$

Using the demand function (Equation A.7), the production function (Equation A.1), and the ratios of the first order conditions (Equation A.2), the labor demand can be expressed as:

$$\ell_{il,j}(\phi, z) = \frac{\sum_n d_{ln,j} \left(\frac{p_{iln,j}(\phi,z)}{P_{in,j}(\phi)} \right)^{-\eta_j} \left(\frac{P_{in,j}(\phi)}{P_{n,j}} \right)^{-\sigma_j} \frac{X_{n,j}}{P_{n,j}}}{\phi z \left(1 - a_{il,j}(\phi, z)\right) \left(G_{il,j}(\phi, z)\right)^{\rho_j} \alpha_{j,L}^{-\rho_j} w_l^{\rho_j}}.$$

The capital market clearing is:

$$\sum_i K_i = \underbrace{\sum_{i,l} \sum_j M_{i,j} \mathbb{E}_{\phi,z} \left[k_{il,j}(\phi, z) \right]}_{\text{Variable inputs (manufacturing)}} + \underbrace{\sum_i \sum_j \frac{M_{i,j}}{Prob\left(\pi_{i,j}(\phi) \geq 0\right)} f_{i,j}^E}_{\text{Entry inputs (manufacturing)}}$$
$$+ \underbrace{\sum_i \sum_f \frac{M_{i,f}}{Prob\left(\pi_{i,f}(z) \geq 0\right)} f_{i,f}^E}_{\text{Entry inputs (power generation)}},$$

where we can derive k similarly:

$$k_{il,j}(\phi, z) = \frac{\sum_n d_{in,j} \left(\frac{p_{iln,j}(\phi,z)}{P_{in,j}(\phi)} \right)^{-\eta_j} \left(\frac{P_{in,j}(\phi)}{P_{n,j}} \right)^{-\sigma_j} \frac{X_{n,j}}{P_{n,j}}}{\phi z \left(1 - a_{il,j}(\phi, z)\right) \left(G_{il,j}(\phi, z)\right)^{\rho_j} \alpha_{j,K}^{-\rho_j} r^{\rho_j}}.$$

The product market clears in each district i and sector j:

$$X_{l,j} = \sum_{k=1}^{J} \gamma_{jk} M_{i,k} \mathbb{E}_{\phi,z} \left[p_{i,k}^{M} m_{il,k} \left(\phi, z \right) \right] + \gamma_j \left(w_l L_l + r K_l \right),$$

where we can derive m similarly:

$$m_{il,j} \left(\phi, z \right) = \frac{\sum_n d_{ln,j} \left(\frac{p_{iln,j}(\phi,z)}{P_{in,j}(\phi)} \right)^{-\eta_j} \left(\frac{P_{in,j}(\phi)}{P_{n,j}} \right)^{-\sigma_j} \frac{X_{n,j}}{P_{n,j}}}{\phi z \left(1 - a_{il,j} \left(\phi, z \right) \right) \left(G_{il,j} \left(\phi, z \right) \right)^{\rho_j} \alpha_{j,M}^{-\rho_j} \left(p_{l,j}^{M} \right)^{\rho_j}}.$$

The total electricity demand sums up industrial electricity demands:

$$D_e = \sum_{i,l} \sum_{j} D_{il,j}, \tag{A.13}$$

where we have

$$D_{il,j} = M_{i,j} \mathbb{E}_{\phi,z} \left[e_{il,j,e} \left(\phi, z \right) \right].$$

Using the fuel demand function (Equation A.3) additionally, we have:

$$e_{il,j,e} \left(\phi, z \right) = \left(\frac{\tilde{p}_{il,j}^{f} \left(\phi, z \right)}{p_{il,j}^{E} \left(\phi, z \right) \alpha_{j,e}} \right)^{-\lambda_j} \frac{\sum_n d_{in,j} \left(\frac{p_{iln,j}(\phi,z)}{P_{in,j}(\phi)} \right)^{-\eta_j} \left(\frac{P_{in,j}(\phi)}{P_{n,j}} \right)^{-\sigma_j} \frac{X_{n,j}}{P_{n,j}}}{\phi z \left(1 - a_{il,j} \left(\phi, z \right) \right) \left(G_{i,j} \left(\phi, z \right) \right)^{\rho_j} \alpha_{j,E}^{-\rho} \left(p_{il,j}^{E} \left(\phi, z \right) \right)^{\rho}}.$$

The emissions of pollutant p from manufacturing plants in district l and sector j, $S_{i,j}^{p}$, can be expressed as:

$$S_{l,j}^{p} = \sum_{i} M_{i,j} \mathbb{E}_{\phi,z} \left[\left(1 - a_{il,j} \left(\phi, z \right) \right)^{\frac{1}{\alpha_j^p}} \left(\kappa_j^p q_{il,j} \left(\phi, z \right) + \sum_{f \in \mathbb{F}} \kappa_f^p e_{il,j,f} \left(\phi, z \right) \right) \right].$$

Also, I can write the emissions of pollutant p from fossil fuel f power plants in district l, $S_{l,f}^{p}$, as:

$$S_{l,f}^{p} = M_{l,f} \mathbb{E}_{z} \left[\left(1 - a_{l,f} \left(z \right) \right)^{\frac{1}{\alpha_f^p}} \kappa_f^{\mathcal{E},p} e_f^{\mathcal{E}} \right].$$

Then, the total emissions are the sum of these sectoral emissions: $S_l^p = \sum_j S_{l,j}^p + \sum_f S_{l,f}^p$.

E Production function estimation

The production function is estimated without any pollution tax prior to the regulation. I drop j for simplicity because the production function is estimated for each sector separately. After the realization of ϕ and z, the sales of a plant with (ϕ, z) headquartered in district i and producing in district l is the sum of revenues across all districts n:

$$\begin{aligned}
R_{il}(\phi,z) =& \sum_n p_{iln}(\phi,z)\, q_{iln}(\phi,z) \\
=& \sum_n Q_n^{\frac{1}{\eta_j}} P_n^{\frac{\sigma_j}{\eta_j}} P_{in}^{\frac{\eta_j-\sigma_j}{\eta_j}}(\phi)\, q_{iln}^{\frac{\eta_j-1}{\eta_j}}(\phi,z) \\
=& q_{il}^{\frac{\eta_j-1}{\eta_j}}(\phi,z) \sum_n Q_n^{\frac{1}{\eta_j}} P_n^{\frac{\sigma_j}{\eta_j}} P_{in}^{\frac{\eta_j-\sigma_j}{\eta_j}}(\phi)\, s_{iln}^{\frac{\eta_j-1}{\eta_j}}(\phi) \\
=& q_{il}^{\frac{\eta_j-1}{\eta_j}}(\phi,z)\, \Gamma_{iln}(\phi),
\end{aligned}$$

where the total quantity manufactured by the plant, $q_{il}(\phi,z) = \sum_n d_{ln} q_{iln}(\phi,z)$, and the plant-level share of output sold in district n relative to total output manufactured, $s_{iln,j}(\phi,z) = \frac{q_{iln,j}(\phi,z)}{q_{il,j}(\phi,z)} = s_{iln}(\phi)$, and $\Gamma_{iln}(\phi) = \sum_n Q_n^{\frac{1}{\eta_j}} P_n^{\frac{\sigma_j}{\eta_j}} P_{in}^{\frac{\eta_j-\sigma_j}{\eta_j}}(\phi)\, s_{iln}^{\frac{\eta_j-1}{\eta_j}}(\phi)$. I use the unit production cost (7), the demand function (14), and the price index (Equation 13). This result shows that the share is independent of z.

Then, the profit maximization of the firm can be written as follows. I further drop ϕ and location subscripts for convenience:

$$\begin{aligned}
\max_{\ell,k,m,e}\Gamma \Bigg(\chi \Bigg(\alpha_L \left(\frac{\ell}{\bar{L}}\right)^{\frac{\rho-1}{\rho}} + \alpha_K \left(\frac{k}{\bar{K}}\right)^{\frac{\rho-1}{\rho}} + \alpha_M \left(\frac{m}{\bar{M}}\right)^{\frac{\rho-1}{\rho}} + \alpha_E \left(\frac{e}{\bar{E}}\right)^{\frac{\rho-1}{\rho}} \Bigg)^{\frac{\rho}{\rho-1}} \Bigg)^{\frac{\eta-1}{\eta}} \\
- \left(w\ell + rk + p^M m + p^E e\right),
\end{aligned}$$

where $\chi = \phi z$. Taking ratios across the first order conditions with respect to ℓ, m, and e, we have the following relationship between factors and factor expenditures:

$$\frac{m}{\bar{M}} = \left(\frac{\alpha_L}{\alpha_M}\frac{p^M m}{w\ell}\right)^{\frac{\rho}{\rho-1}} \frac{\ell}{\bar{L}}, \tag{A.14}$$

$$\frac{e}{\bar{E}} = \left(\frac{\alpha_L}{\alpha_E}\frac{p^E e}{w\ell}\right)^{\frac{\rho}{\rho-1}} \frac{\ell}{\bar{L}}. \tag{A.15}$$

Now unobserved $\frac{e}{\bar{E}}$ can be uniquely recovered once ρ is known because the expenditures for labor, fuels, and material and the number of employment are observed. Thus, I can identify several production parameters by replacing $\frac{e}{\bar{E}}$ and $\frac{m}{\bar{M}}$ with Equations A.15 and A.14 and exploiting the first order conditions to control for the transmission bias from unobserved hicks-neutral productivity χ to observed inputs (Doraszelski et al. (2013); Doraszelski et al. (2018)). From the first order condition with respect to ℓ, productivity χ can be written as:

$$\begin{aligned}\chi^{\frac{\eta-1}{\eta}} =& \frac{\eta}{\eta-1}\frac{1}{\Gamma}\frac{w\left(\frac{\ell}{\bar{L}}\right)}{\alpha^L\left(\frac{\ell}{\bar{L}}\right)^{\frac{\rho-1}{\rho}}} \\ &\times\left(\alpha_L\left(\frac{\ell}{\bar{L}}\right)^{\frac{\rho-1}{\rho}}+\alpha_K\left(\frac{k}{\bar{K}}\right)^{\frac{\rho-1}{\rho}}+\alpha_M\left(\frac{m}{\bar{M}}\right)^{\frac{\rho-1}{\rho}}+\alpha_E\left(\frac{e}{\bar{E}}\right)^{\frac{\rho-1}{\rho}}\right)^{1-\frac{\rho}{\rho-1}\frac{\eta-1}{\eta}}. \end{aligned} \tag{A.16}$$

Plugging this productivity into the revenue with a time-varying shock u_t such that $\mathbb{E}_t[u_t]=0$ and using Equations A.15 and A.14, the revenue can be rewritten with logarithms as:

$$\ln R_t = \ln\frac{\eta}{\eta-1}+\ln\left(w_t\left(\frac{\ell_t}{\bar{L}}\right)\left(1+\frac{\alpha_K}{\alpha_L}\left(\frac{k_t}{\bar{K}}/\frac{\ell_t}{\bar{L}}\right)^{\frac{\rho-1}{\rho}}\right)+p_t^M\left(\frac{m_t}{\bar{M}}\right)+p_t^E\left(\frac{e_t}{\bar{E}}\right)\right)+u_t, \tag{A.17}$$

where I deflate the amount of nominal capital by the corresponding deflator. This is because capital is assumed to be freely mobile, and, hence, has one price. The main parameters of interest are the CES elasticity of substitution in demand, η, and the CES elasticity of substitution in the outer production function, ρ. For the consistency of the estimates, I estimate it with nonlinear least squares (NLLS) (Grieco et al., 2016). I also estimate $\frac{\alpha_K}{\alpha_L}$ and take the geometric mean of Equations A.15 and A.14 and normalize such that $\alpha_K+\alpha_E+\alpha_L+\alpha_M=1$. This is an advantage provided by the geometric mean normalization of the CES function.

The elasticity of substitution in the inner production function λ is also of interest. Since I know all variables and parameters, I can estimate λ with a time-varying shock ε_t such that $\mathbb{E}[\varepsilon_t]=0$ with the following equation:

$$\ln\left(\frac{e_t}{\bar{E}}\right)=\frac{\lambda}{\lambda-1}\ln\left(\sum_{f\in\mathcal{F}}\alpha_f\left(\frac{e_{f,t}}{\bar{e}_f}\right)^{\frac{\lambda-1}{\lambda}}\right)+\varepsilon_t. \tag{A.18}$$

I back out α_f such that $\sum_f \alpha_f = 1$.

F Solution Algorithm

The model has the power sector as an upstream sector of the manufacturing sector. It can be solved in the following way:

1. Fix the capital structure K as the numeraire ($r = 1$).
2. Solve for the power plant emission control measure use $(1 - a_{i,f}(z))$ (Equation A.10), which does not depend on any endogenous macro variables.
3. Guess the numbers of manufacturing firm headquarters $M_{i,j}$.
   (a) Guess an electricity price p_e.
      i. Guess manufacturing wages and prices w_i and $P_{i,j}$.
      ii. Solve for the manufacturing firm optimization problem.
         A. Solve for the manufacturing plant emission control measure use $\left(1 - a^p_{il,j}(\phi, z)\right)$ (Equation A.6).
         B. Calculate marginal production costs $\mu_{il,j}(\phi, z)$ (Equation 7) and plant profits $\pi_{il,j}(\phi, z)$ (Equation A.9).
      iii. Given the solution above, compute the labor demands L_i (Equation 18), manufacturing prices $P_{i,j}$ (Equation 13), and manufacturing expenses $X_{i,j}$ (Equation 19).
      iv. If the labor and product markets clear, move to the next step. Otherwise, go back to to Step 3 (a) i and repeat until they clear.
   (b) Compute the total manufacturing electricity demand D_e (Equation A.13) and solve for the power generation firm optimization problem.
   (c) Calculate marginal power generation costs $\nu_{i,f}(z)$ (Equation A.11).
   (d) According to MOD, dispatch D_e for given the power plant numbers$M_{i,f}$.
      i. Dispatch should be below the capacity $k_{i,f}(z)$.
      ii. Dispatch should be divided according to the capacity if the marginal costs are the same.
      iii. Set p_e by SMP.
   (e) Calculate plant profits $\pi_{i,f}(z)$ (Equation A.12).
   (f) Compute $M_{i,f}$ (Equation 17).
   (g) Iterate the above until we have electricity supply = electricity demand and $M_{i,f}$ stop moving.

(h) If the electricity market clears and the free entry condition holds, stop. Otherwise, go back to to Step 3 (a) and repeat until they do so.

4. Compute $M_{i,j}$ (Equation 16).

5. If the free entry condition holds, stop. Otherwise, go back to to Step 3 and repeat until it holds.

6. Solve the household optimization problem by deriving u_i (Equation 12).

G Additional tables

Table A.1: Policy goal

SCA	Caps		Reduction rates
Pollutant	Initial year (2020)	Final year (2024)	
Total	46,208	36,842	-20%
NO_x	34,105	28,635	-16%
SO_x	11,627	7,814	-33%
TSP	476	393	-17%

CA	Caps		Reduction rates
Pollutant	Initial year (2020)	Final year (2024)	
Total	160,616	108,094	-33%
NO_x	114,678	82,452	-28%
SO_x	43,145	23,611	-45%
TSP	2,793	2,031	-27%

SA	Caps		Reduction rates
Pollutant	Initial year (2020)	Final year (2024)	
Total	87,899	64,985	-26%
NO_x	57,361	41,790	-27%
SO_x	29,847	22,709	-24%
TSP	691	486	-30%

SEA	Caps		Reduction rates
Pollutant	Initial year (2020)	Final year (2024)	
Total	135,629	91,999	-32%
NO_x	90,741	58,956	-35%
SO_x	43,534	32,056	-26%
TSP	1,354	987	-27%

Notes: Caps sum up the emissions allowances (initial allocation (including additional allocation), carryover, and net purchases (purchases − sales)) of all regulated establishments within markets. Total is the sum of NO_x caps, SO_x caps, and TSP caps (ton). Reduction rates are taken between 2020 and 2024 and expressed in percentage. SCA denotes the Seoul Capital Area, CA denotes the Central Area, SA denotes the Southern Area, SEA denotes the South-East Area.
Sources: Ministry of Environment.

Table A.2: Spatial distribution of regulated plants

	Seoul Capital Area	Central Area	Southern Area	South-East Area	Total
Number	453	320	87	399	1,259

Notes: The number of each cell denotes the number of targeted plants in each area in 2020.
Sources: Ministry of Environment.

Table A.3: Emissions factors for production process

Emission Facility	Target Emission Facility	Material, Product, or Fuel	Air Pollutant Emission Coefficient			
			NO_x	SO_x	TSP	Unit
6) Coke (and related products) Storage Facility	Coke Storage Facility	Coke		0.6880	0.6210	kg/Coke Production (ton)
7) Combustion Facility (General Boiler)	SRU Combustion Funance	SRU Byproduct Gas		1.2300	0.0101	kg/Gas Processed (ton)
8) Basic Organic Compound Manufacturing Facility 9) Gas Manufacturing Facility 10) Basic Inorganic Compound Manufacturing Facility 11) Inorganic Pigments and Other Metal Oxide Manufacturing Facility 12) Synthetic Dye, Softeners, and Other Colorant Manufacturing Facility 13) Fertilizer and Nitrogen Compound Manufacturing Facility 14) Medical Substances and Pharmaceutical Manufacturing Facility 15) Other Chemical Product Manufacturing Facility, 16) Carbonization Facility 17) Chemical Fiber Manufacturing Facility	Furnance	Powder (Cosmetics)			1.3359	kg/Powder (Cosmetics) Production (ton)
		High-Density Polyethylene (HDPE)			0.0782	kg/Powder (Cosmetics) Production (ton)
		Vinyl Chloride Monomer (VCM)	0.0210	0.0226		kg/High-Density Polyethylene Production (ton)
		Hydrochloric Acid	0.0710	0.1056		kg/Vinyl Chloride Production (ton)
	(Combustion) Funance	Calcium Phosphate Fuel		0.4700		kg/Hydrochloric Acid Production (ton)
		Carbon Black Process Gas (0.05%)		0.5830		kg/Fuel Consumption (ton)
	Drying Facilities	Benzoil Peroxide			0.4925	kg/Benzoil Peroxide Production (ton)
		Hydrogen Peroxide			0.0014	kg/Hydrogen Peroxide Production (ton)
		Zirconium Silicate Semi-Finished Product			0.3043	kg/Semi-Finished Product Production (ton)
		Compound Fertilizer			0.1943	kg/Compound Fertilizer Production (ton)
		Herbal Powder			25.3125	kg/Herbal Powder Production (ton)
		Powdered Detergent			3.0200	kg/Powdered Detergent Production (ton)
		Iron Oxide (For Audio)			0.4063	kg/Iron Oxide Production (ton)
		Hydrochloric Acid			0.0490	kg/Hydrochloric Acid Production (ton)
		Vinyl Chloride Monomer (VCM)			0.0212	kg/Vinyl Chloride Production (ton)
		Paint (Oil-Based/Water-Based) Products			0.0053	kg/Paint Production (ton)
		Adhesive Tape	0.0005		0.0001	kg/Adhesive Tape Production (ton)

Table A.4: Emissions factors for production process

Emission Facility	Target Emission Facility	Material, Product, or Fuel	Air Pollutant Emission Coefficient			
			NO_x	SO_x	TSP	Unit
8) Basic Organic Compound Manufacturing Facility 9) Gas Manufacturing Facility 10) Basic Inorganic Compound Manufacturing Facility 11) Inorganic Pigments and Other Metal Oxide Manufacturing Facility 12) Synthetic Dye, Softeners, and Other Colorant Manufacturing Facility 13) Fertilizer and Nitrogen Compound Manufacturing Facility 14) Medical Substances and Pharmaceutical Manufacturing Facility 15) Other Chemical Product Manufacturing Facility 16) Carbonization Facility	Drying Facility	Titanium Dioxide Ore			0.3000	kg/Titanium Dioxide Production (ton)
		Carbon Black			0.1910	kg/Carbon Black Production (ton)
		Tire Cord Fabric			0.2466	kg/Tire Cord Fabric Production (ton)
		Polyester Filament			0.0679	kg/Polyester Filament Production (ton)
		Antibiotics	22.750		16.860	kg/Antibiotics Production (ton)
		PVC Resin			0.7740	kg/PVC Resin Production (ton)
		Salt/Diethyl Glycol			0.0432	kg/Salt, Diethyl Glycol Recovery (ton)
	Calcination Facility	Titanium Dioxide		5.3600	1.8125	kg/Titanium Dioxide Production (ton)
		Calcium Phosphate			0.5447	kg/Calcium Phosphate Production (ton)
		Iron Oxide (For Audio)			0.0260	kg/Iron Oxide Production (ton)
	Melting/Dissolution Facility	Polyester Filament			0.0498	kg/Polyester Filament Production (ton)
		Sulfur		0.0419	0.0051	kg/LAS Production (ton)
17) Chemical Fiber Manufacturing Facility 21) Non-Metallic Mineral Product Manufacturing Facility	Calcination Facility	Lime	0.3400	0.1730	0.2975	kg/Lime Production (ton)
		Barium Carbonate		2.3550	1.1000	kg/Barium Carbonate Production (ton)
		Strontium Carbonate		4.9500	1.6920	kg/Strontium Carbonate Production (ton)
	Melting/Dissolution Facility	Slaked Lime			0.0047	kg/Slaked Lime Usage (ton)
	Integrated Facility for Drying, Sorting, Weighing, Mixing, and Shipping	Asphalt	0.0313	0.0557	10.9742	kg/Asphalt Production (ton)

Table A.5: Emissions factors for production process

Emission Facility	Target Emission Facility	Material, Product, or Fuel	Air Pollutant Emission Coefficient			
			NO_x	SO_x	TSP	Unit
22) Primary Steel Manufacturing Facility	Melting/Dissolution Facility	Aluminum			6.1200	kg/Aluminum Usage (ton)
23) Primary Non-Ferrous Metal Manufacturing Facility	Crucible	Cast Steel			17.625	kg/Cast Steel Product Production (ton)
24) Metal Products, Machinery, Equipment,	Sintering Furnace	Sintered Ore	0.4730	0.8230	0.3620	kg/Sintered Ore Production (ton)
30) Wastewater, Waste, and Waste Gas Incineration Facility, Among Facility (including Incineration Boilers)	Drying Facility	Hot Metal Shot			0.2360	kg/Hot Metal Shot Production (ton)
	Incineration Facility	Lime	1.3290	0.4450		Amount of Waste Incinerated (ton)
		Barium Carbonate	5.2440		1.1000	Amount of Waste Incinerated (ton)
		Strontium Carbonate	1.8170	4.6086	1.6920	Amount of Waste Incinerated (ton)
		Slaked Lime	3.3220	4.6086	0.0047	Amount of Waste Incinerated (ton)

Table A.6: Emissions factors for production process

Emission Facility	Target Emission Facility	Material, Product, or Fuel	Air Pollutant Emission Coefficient			
			NO_x	SO_x	TSP	Unit
3) Pulp, Paper, and Paperboard Manufacturing Facility 5) Printing/ Recording Media Manufacturing (Replicating) Facility	Grinding Facility	Pulp			2.1647	kg/Product Production (ton)
6) Coke (and related product) Storage Facility	Solid Particulate Matter Storage Facility	Slag Forming Agent			0.0260	kg/Slag Forming Agent Production (ton)
	Grinding Facility	Coke (Calcinated Petroleum Ccoke)			0.4400	kg/Coke Production (ton)
		Slag Forming Agent			0.0714	kg/Slag Forming Agent Production (ton)
8) Basic Organic Compound Manufacturing Facility 9) Gas Manufacturing Facility 10) Basic Inorganic Compound Manufacturing Facility 11) Inorganic Pigment and Other Metal Oxide Manufacturing Facility 12) Synthetic Dyes, Plasticizers, and Other Colorant Manufacturing Facility 13) Fertilizer and Nitrogen Compound Manufacturing Facility 14) Pharmaceutical and Medical Substance Manufacturing Facility 15) Other Chemical Product Manufacturing Facility 16) Carbonization Facility 17) Chemical Fiber Manufacturing Facility	Solid Particulate Matter Storage Facility	Pesticide (Wettable Powder)			0.3413	kg/Powder (Cosmetics) Production (ton)
		Anhydrous Gypsum			0.0091	kg/Powder (Cosmetics) Production (ton)
		Soda Ash	0.0210	0.0226	0.7556	kg/High-Density Polyethylene Production (ton)
		Slaked Lime	0.0710	0.1056	0.1110	kg/Vinyl Chloride Production (ton)
		Paint Intermediate Products		0.4700	0.1027	kg/Hydrochloric Acid Production (ton)
		Paint (Oil-based/Water-based) Materials		0.5830	0.0260	kg/Fuel Consumption (ton)
		Polyethylene			0.0755	kg/Benzoil Peroxide Production (ton)
		Polypropylene			0.0636	kg/Hydrogen Peroxide Production (ton)
		Talc (CaF2)			0.0133	kg/Semi-Finished Product Production (ton)
		Ethylene Vinyl Acetate (EVA)			0.5310	kg/Compound Fertilizer Production (ton)
		PVC Resin			0.2100	kg/Herbal Powder Production (ton)
		Surfactants			0.0163	kg/Powdered Detergent Production (ton)

Table A.7: Emissions factors for production process

Emission Facility	Target Emission Facility	Material, Product, or Fuel	Air Pollutant Emission Coefficient			
			NO_x	SO_x	TSP	Unit
8) Basic Organic Compound Manufacturing Facility	Solid Particulate Matter Storage Facility	Solid Phase Anhydrous Phthalic Acid			0.4620	kg/Solid Phase Anhydrous Phthalic Acid Input (ton)
9) Gas Manufacturing Facility		Pesticide (Wettable Powder)	0.0210	0.0226	1.8015	kg/Product Production (ton)
10) Basic Inorganic Compound Manufacturing Facility		Pesticide (Granular Form)	0.0710	0.1056	0.2158	kg/Product Production (ton)
11) Inorganic Pigment and Other Metal Oxide Manufacturing Facility		Modified Polyolefin		0.4700	6.5600	kg/Modified Polyolefin Production (ton)
12) Synthetic Dyes, Plasticizers, and Other Colorant Manufacturing Facility		Compound Fertilizer		0.5830	0.0377	kg/Product Production (ton)
13) Fertilizer and Nitrogen Compound Manufacturing Facility		Powder Coating			2.3250	kg/Paint Production (ton)
14) Pharmaceutical and Medical Substance Manufacturing Facility		Iron Oxide (Video)			0.1026	kg/Iron Oxide Production (ton)
15) Other Chemical Product Manufacturing Facility		Iron Oxide (Audio)			0.0833	kg/Iron Oxide Production (ton)
16) Carbonization Facility		Titanium Dioxide			0.0338	kg/Titanium Dioxide Production (ton)
17) Chemical Fiber Manufacturing Facility		Calcium Phosphate			0.0320	kg/Calcium Phosphate Production (ton)
		Zirconium Silicate			0.1882	kg/Product Production (ton)
		Sodium Bisulfite			0.0376	kg/Sodium Bisulfite Production (ton)
		Capsules			6.7860	kg/Capsule Production (ton)
		Low-Density Polyethylene			0.1404	kg/Low-Density Polyethylene Production (ton)
		Polypropylene			0.1120	kg/Polypropylene Production (ton)
		PVC Resin			0.0385	kg/PVC Resin Production (ton)
	Concentration Facility	LBR (Butadiene Rubber)			0.6090	kg/LBR Production (ton)
		Salt/Diethyl Glycol			0.0223	kg/Salt, Diethyl Glycol Recovery (ton)
		SBR (Styrene-Butadiene Block Copolymer)			1.0163	kg/SBR Production (ton)
		SSBR (Solution SBR)			0.1805	kg/SSBR Production (ton)
		Hexogen (RDX) -Cyclotrimethylene Trinitramine	1.4490	0.3636		kg/RDX Production (ton)
		Emulsion Explosives (EMX) Manufacturing	0.0247			kg/EMX Production (ton)

Table A.8: Emissions factors for production process

Emission Facility	Target Emission Facility	Material, Product, or Fuel	Air Pollutant Emission Coefficient			
			NO_x	SO_x	TSP	Unit
8) Basic Organic Compound Manufacturing Facility 9) Gas Manufacturing Facility 10) Basic Inorganic Compound Manufacturing Facility 11) Inorganic Pigment and Other Metal Oxide Manufacturing Facility 12) Synthetic Dyes, Plasticizers, and Other Colorant Manufacturing Facility 13) Fertilizer and Nitrogen Compound Manufacturing Facility 14) Pharmaceutical and Medical Substance Manufacturing Facility 15) Other Chemical Product Manufacturing Facility 16) Carbonization Facility 17) Chemical Fiber Manufacturing Facility	Reaction Facility	Surfactant (AOS)		0.1745	0.1795	kg/AOS Production (ton)
		Surfactant (LAS)			0.3508	kg/LAS Production (ton)
		Nylon Chips			0.0453	kg/Nylon Chips Production (ton)
		Magnesium Silicate (MgSiO2)			2.1600	kg/Magnesium Silicate Usage (ton)
		Hemihydrate and Dihydrate Gypsum			0.0697	kg/Phosphate Production (ton)
		Titanium Dioxide		0.5600	0.2266	kg/Titanium Dioxide Production (ton)
		Refined Phosphate			0.0313	kg/Product Production (ton)
		Precipitate			0.1480	kg/Precipitate Production (ton)
		Waste Caustic Soda		0.0208	0.0208	kg/Waste Caustic Soda Treatment (ton)
		Polyester Chips			0.0084	kg/Polyester Chips Production (ton)
		Polyethylene			0.0057	kg/Polyethylene Production (ton)
		Sulfuric Acid		0.8988		kg/Phthalocyanine Pigment Material (Blue Derivative) Production (ton)
		Sulfur		0.3735		kg/Sulfuric Acid Production (ton)
		Sodium Bisulfite		0.0768		kg/Sodium Bisulfite Production (ton)
		Nitro Toluene (DNT+MNT) Products	0.0688			kg/Nitrotoluene Production (ton)
		Dynamite Products	0.0028			kg/Dynamite Production (ton)
		Hexogen(RDX)-Cyclotrimethylene Trinitramine Products	0.7982			kg/RDX Production (ton)
		Toluidine Products	0.0150			kg/Toluidine Production (ton)
		Diazonitrophenol (DDNP) Raw Materials	1.0000			kg/DDNP Production (ton)
	Reaction Facility (Oxidation-Reduction)	Iron Oxide for Magnetic Tape			0.0677	kg/Iron Oxide Production (ton)
	Reaction Facility (Coupling Reaction)	Azo Pigment (Soluble)			0.1168	kg/Azo Pigment Production (ton)

Table A.9: Emissions factors for production process

Emission Facility	Target Emission Facility	Material, Product, or Fuel	Air Pollutant Emission Coefficient			
			NO_x	SO_x	TSP	Unit
8) Basic Organic Compound Manufacturing Facility 9) Gas Manufacturing Facility 10) Basic Inorganic Compound Manufacturing Facility 11) Inorganic Pigment and Other Metal Oxide Manufacturing Facility 12) Synthetic Dyes, Plasticizers, and Other Colorant Manufacturing Facility 13) Fertilizer and Nitrogen Compound Manufacturing Facility 14) Pharmaceutical and Medical Substance Manufacturing Facility 15) Other Chemical Product Manufacturing Facility 16) Carbonization Facility 17) Chemical Fiber Manufacturing Facility	Reaction Facility (Diazo Reaction)	Azo Pigment (Soluble)			0.0187	kg/Azo Pigment Production (ton)
	Calcination Facility	Titanium Dioxide	1.1350			kg/Titanium Dioxide Production (ton)
	Condensation Facility	Nitric Acid	0.0008			kg/Nitric Acid Production (ton)
		Hexogen (RDX) - Cyclotrimethylene Trinitramine	0.5709			kg/RDX Production (ton)
	Radiation Facility	Polyester Filament			0.0498	kg/Polyester Filament Production (ton)
	Grinding Facility	Copper Pigment (Beta Type)			0.9650	kg/Copper Phthalocyanine Pigment (Blue) - β-Type Production (ton)
		Copper Pigment (Alpha Type)			4.2270	kg/Copper Phthalocyanine Pigment (Blue) - α-Type Production (ton)
		Pesticide (Granular Form)			0.1988	kg/Product Production (ton)
		Compound Fertilizer			0.1573	kg/Product Production (ton)
		Powder Detergent			0.0913	kg/Powder Detergent Production (ton)
		Powder Coating			1.9210	kg/Product Paint Production (ton)
		Copper Phthalocyanine Pigment			0.3205	kg/Halogenated Copper Phthalocyanine Pigment (Green) Production (ton)
		Azo Pigment (Soluble)			7.6130	kg/Azo Pigment Production (ton)
		Caprolactam			0.0194	kg/Nylon Chip Production (ton)
		Trimethylolpropane			0.0023	kg/Trimethylolpropane Production (ton)
		Epoxy Resin	0.0688		0.0040	kg/Product Paint Production (ton)
		Salt/Diethyl Glycol	0.0028		0.0423	kg/Salt, Diethyl Glycol Recovery (ton)
		Calcium Phosphate (Semi-Finished Product)	0.7982		0.0539	kg/Calcium Phosphate Production (ton)
		Titanium Dioxide (Finished Product)	0.0150		0.1138	kg/Titanium Dioxide Production (ton)
		Titanium Ore	1.0000		0.4500	kg/Titanium Dioxide Production (ton)
		Calcium Phosphate (Raw Material)			0.0522	kg/Calcium Phosphate Production (ton)
	Grinding Facility (Fusion Compounding)	Paint (EMC Coating)			0.2778	kg/Product Paint Production (ton)

Table A.10: Emissions factors for production process

Emission Facility	Target Emission Facility	Material, Product, or Fuel	Air Pollutant Emission Coefficient			
			NO_x	SO_x	TSP	Unit
8) Basic Organic Compound Manufacturing Facility 9) Gas Manufacturing Facility 10) Basic Inorganic Compound Manufacturing Facility 11) Inorganic Pigment and Other Metal Oxide Manufacturing Facility 12) Synthetic Dyes, Plasticizers, and Other Colorant Manufacturing Facility 13) Fertilizer and Nitrogen Compound Manufacturing Facility 14) Pharmaceutical and Medical Substance Manufacturing Facility 15) Other Chemical Product Manufacturing Facility 16) Carbonization Facility 17) Chemical Fiber Manufacturing Facility	Grinding Facility (Raw Materials)	Paint (EMC Coating)			0.0139	kg/Product Paint Production (ton)
	Grinding Facility (Packaging)	Trimethylolpropane			0.0466	kg/Trimethylolpropane Production (ton)
	Sorting Facility	Pesticide (Hydrate Form)			1.5220	kg/Product Production (ton)
		Pesticide (Granular Form)			0.0300	kg/Product Production (ton)
		Powder Detergent			0.0468	kg/Powder Detergent Production (ton)
		Calcium Phosphate			0.2042	kg/Calcium Phosphate Production (ton)
		Refined Products			7.8875	kg/Refined Products Production (ton)
		Capsules			1.2260	kg/Capsule Production (ton)
		Powder (Color Cosmetics)			1.4900	kg/Color Cosmetic (Powder) Production (ton)
		Compound Fertilizer			0.3431	kg/Product Production (ton)
	Refining Facility	Hydrogen Peroxide			0.0038	kg/Hydrogen Peroxide Production (ton)
		Toluidine	0.0300			kg/Toluidine Production (ton)
	Mixing Facility	High-Density Polyethylene			0.0008	kg/High-Density Polyethylene Production (ton)
		Granules			34.7250	kg/Granule Production (ton)
		Benzoil Peroxide			0.5637	kg/Benzoil Peroxide Production (ton)
		Copper Pigment (Beta Type)			0.0867	kg/Copper Phthalocyanine Pigment (Blue) - β-Type Production (ton)
		Pesticide (Hydrate Form)			1.9560	kg/Product Production (ton)
		Pesticide (Granular Form)	0.0974	0.0652	1.0058	kg/Product Production (ton)
		Dynamite			0.0352	kg/Dynamite Production (ton)
		Drinks			0.9893	kg/Drink Production (ton)
		Trace Mineral Additive (Additive)			0.2506	kg/Trace Mineral Additive Production (ton)
		Powder Detergent			0.5186	kg/Powder Detergent Production (ton)

Table A.11: Emissions factors for production process

Emission Facility	Target Emission Facility	Material, Product, or Fuel	Air Pollutant Emission Coefficient			
			NO_x	SO_x	TSP	Unit
8) Basic Organic Compound Manufacturing Facility 9) Gas Manufacturing Facility 10) Basic Inorganic Compound Manufacturing Facility 11) Inorganic Pigment and Other Metal Oxide Manufacturing Facility 12) Synthetic Dyes, Plasticizers, and Other Colorant Manufacturing Facility 13) Fertilizer and Nitrogen Compound Manufacturing Facility 14) Pharmaceutical and Medical Substance Manufacturing Facility 15) Other Chemical Product Manufacturing Facility 16) Carbonization Facility 17) Chemical Fiber Manufacturing Facility	Mixing Facility	Pesticide (Powder Form)			0.1311	kg/Product Production (ton)
		Fabric Softener (Including Liquid Detergent)			0.0078	kg/Fabric Softener and Liquid Detergent Production (ton)
		Laundry Soap			0.0493	kg/Laundry Soap Production (ton)
		Salt (Crude)			0.0527	kg/Copper Phthalocyanine Pigment (Blue) - β-Type Production (ton)
		Salt (Crude), DEG Volatile			0.0351	kg/Copper Phthalocyanine Pigment (Blue) - β-Type Production (ton)
		Pigments/Solvents /Additives			0.0138	kg/Paint Production (ton)
		Adhesive Tape			0.0001	kg/Adhesive Tape Production (m^2)
		Titanium Dioxide			0.0113	kg/Titanium Dioxide Production (ton)
		Magnetic Paint			0.0661	kg/Magnetic Paint Production (ton)
		Toothpaste			0.0364	kg/Toothpaste Production (ton)
		Capsules			28.3300	kg/Capsules Production (ton)
		Tire Cord			0.0169	kg/Tire Cord Production (ton)
		Powder (Color Cosmetics)			20.0900	kg/Powder (Color Cosmetics) Production (ton)
		Solid Raw Materials for Paint			0.0005	kg/Paint Production (ton)
		Polyester Chips			0.0009	kg/Polyester Chips Production (ton)
		Polyethylene			0.0214	kg/Polyethylene Production (ton)
		Polypropylene Glycol (PPG)			0.0053	kg/Polypropylene Glycol Production (ton)
		Synthetic Rubber Adhesive			0.3818	kg/Product Production (ton)
		Antibiotics			1.3820	kg/Antibiotics Production (ton)
		Sulfuric Acid		0.8416		kg/Copper Phthalocyanine Pigment (Blue) - α-Type Production (ton)
		Paint (Powder Coating)			0.1324	kg/Paint Production (ton)
		Paint (Water-Based)			3.6640	kg/Paint Production (ton)
		Resin			0.1974	kg/Resin Production (ton)

Table A.12: Emissions factors for production process

Emission Facility	Target Emission Facility	Material, Product, or Fuel	Air Pollutant Emission Coefficient			
			NO_x	SO_x	TSP	Unit
8) Basic Organic Compound Manufacturing Facility 9) Gas Manufacturing Facility 10) Basic Inorganic Compound Manufacturing Facility 11) Inorganic Pigment and Other Metal Oxide Manufacturing Facility 12) Synthetic Dyes, Plasticizers, and Other Colorant Manufacturing Facility 13) Fertilizer and Nitrogen Compound Manufacturing Facility 14) Pharmaceutical and Medical Substance Manufacturing Facility 15) Other Chemical Product Manufacturing Facility 16) Carbonization Facility 17) Chemical Fiber Manufacturing Facility	Mixing Facility	Refining (Raw Materials)			6.4300	kg/Refined Products Production (ton)
		Refining (Finished)			9.6850	kg/Refined Products Production (ton)
		Paint (Oil-Based)			2.0873	kg/Paint Production (ton)
	Mixing Facility (Primary)	Paint (EMC Coating)			0.1944	kg/Paint Production (ton)
	Mixing Facility (Secondary)	Paint (EMC Coating)			0.7847	kg/Paint Production (ton)
	Mixing Facility (Drying Process)	Refining			13.6400	kg/Refined Products Production (ton)
	Mixing Facility (Storage)	Pesticide (Hydrate Form)			1.4196	kg/Product Production (ton)
	Mixing Facility (Filling)	Granules			1.7660	kg/Granules Production (ton)
		Capsules			9.3620	kg/Capsules Production (ton)
	Recovery Facility	Nylon Chips			0.0750	kg/Nylon Chips Production (ton)
		Chlorine	0.0007	0.0013	0.0005	kg/Chlorine Production (ton)
		Salt/Diethyl Glycol			0.0488	kg/Salt, Diethyl Glycol Recovery (ton)
		Phthalic Anhydride		0.0549		kg/Phthalic Anhydride Production (ton)
	Absorption Facility	Tire Cord			0.0095	kg/Tire Cord Production (ton)
		Nitric Acid	0.3866			kg/Nitric Acid (65%) Production (ton)
21) Non-Metallic Mineral Product Manufacturing Facility	Solid Particulate Matter Storage Facility	Phosphate Rock			0.0929	kg/Phosphate Rock Storage (ton)
		Refined Phosphate			0.3752	kg/Product Production (ton)
		Barium Carbonate			0.2950	kg/Barium Carbonate Production (ton)
		Strontium Carbonate			0.3660	kg/Strontium Carbonate Production (ton)
	Grinding Facility	Phosphate Rock			0.0276	kg/Phosphate Production (ton)

Table A.13: Emissions factors for production process

Emission Facility	Target Emission Facility	Material, Product, or Fuel	Air Pollutant Emission Coefficient			
			NO_x	SO_x	TSP	Unit
21) Non-Metallic Mineral Product Manufacturing Facility	Sorting Facility	Phosphate Rock			0.0062	kg/Phosphate Production (ton)
	Mixing Facility	Barium Carbonate			1.0300	kg/Barium Carbonate Production (ton)
		Strontium Carbonate			1.0800	kg/Strontium Carbonate Production (ton)
22) Primary Steel Manufacturing Facility 23) Primary Non-Ferrous Metal Manufacturing Facility 24) Metal Products, Machinery, Equipment, Devices, Transport Equipment, Furniture Manufacturing Facility 25) Automobile Parts Manufacturing Facility	Solid Particulate Matter Storage Facility	Manganese Alloy Steel			0.3830	kg/Manganese Alloy Steel Production (ton)
	Electric Arc Furnace	Manganese Alloy Steel		2.4480	3.9735	kg/Manganese Alloy Steel Production (ton)
		Scrap Metal			1.3000	kg/Scrap Metal Usage (ton)
		Aluminum			1.5500	kg/Aluminum Usage (ton)
	Inductotherm	Cast Steel Shot			0.1870	kg/Cast Steel Shot Production (ton)
	Crushing Facility	Cast Steel Grit			0.6980	kg/Cast Steel Grit Production (ton)
		Manganese Alloy Steel			0.3961	kg/Manganese Alloy Steel Production (ton)
		Slag			0.0013	kg/Slag Production (ton)
	Coating Facility	Cylinder Head (Aluminum Alloy Cast Steel)			3.4000	kg/Product Production (ton)
	De-dusting Facility	Cylinder Head (Aluminum Alloy Cast Steel)			0.8050	kg/Product Production (ton)

Notes: Different production processes have different emissions factors in manufacturing and power generation, respectively.
Sources: Ministry of Environment.

Table A.14: Emissions factors for fuel use

Fuel type	NO_x		SO_x		TSP	
	Industry	Power	Industry	Power	Industry	Power
Kerosene (sulfur content 0.001%)	2.16	2.16	17.0S	17.0S	0.05	0.05
Kerosene (sulfur content 0.01%)	2.40	2.40, 14.7 (1)	17.0S	17.0S	0.24	0.24, 0.07 (1)
Diesel (sulfur content 0.1, 0.05%)	2.40	2.40, 53.4 (2)	17.0S	17.0S	0.24	0.24, 1.67 (2)
Bunker-A oil	5.99	5.99	5.28	5.28	0.84	0.84
Bunker-B oil	2.47	2.47	14.3S	14.3S	1.20	1.20
Bunker-C oil (sulfur content 0.3~4.0%)	6.64	6.64	14.3S	14.3S	1.1S+0.39	1.1S+0.39
Anthracite coal	5.83	9.00	19.5S	19.5S	5.0A	5.0A
Bituminous coal	5.55	7.50	19.0S	19.0S	5.0A	5.0A
LNG	3.70	6.04, 42.9 (2)	0.01	0.01	0.03	0.03
LPG	2.28	2.28	0.01	0.01	0.07	0.07

Notes: Different fossil fuels have different emissions factors in manufacturing and power generation, respectively.
1. A (ash content): The ash content values of anthracite coal (40%) and bituminous coal (10%) are 40 and 10, respectively.
2. S (sulfur content): The sulfur content values of kerosene (0.1%), Bunker-A oil (1.5%), Bunker-B oil (1.2%), anthracite coal (0.7%), and bituminous coal (0.5%) are 0.1, 1.5, 1.2, 0.7, and 0.5, respectively.
3. Unit of emission factors: Oil (g/ℓ), Coal (g/kg), LNG (g/m^3), LPG (g/kg).
4. Conversion factors: LNG (1 kg = 1.238 m^3), LPG (1 kg = 1.97 ℓ = 0.529 m^3).
5. Footnote (1): Gas turbine. Footnote (2): Internal combustion engine.
For fuels or energy sources other than those specified above, as well as for processes, the emission factors of air pollutants shall be prescribed and announced by the President of the National Institute of Environmental Research (NIER). This is very rare—around 100 establishment per year—and beyond the scope of this paper.
Sources: Ministry of Environment.

Table A.15: Policy effect: plant

	Manufacturing		*Power generation*
	Regulated	Unregulated affiliated	Regulated
ln Measure use	0.22*	-0.01	-0.03
$(s.e.)$	0.09	0.10	0.05
ln Electricity use	0.92***	0.01	
$(s.e.)$	0.11	0.15	
ln Electricity share	0.12*	0.10	
$(s.e.)$	0.06	0.06	
ln Sales	0.05	0.11	0.49**
$(s.e.)$	0.04	0.06	0.15
N	7,848	3,825	2,150

Notes: * denotes p<0.05, ** denotes p<0.01, and *** denotes p<0.001.

Table A.16: Policy effect: district-industry

	Manufacturing	*Power generation*
ln NO_x emissions	-0.52***	1.69
$(s.e.)$	0.05	1.90
ln SO_x emissions	-0.54***	1.39
$(s.e.)$	0.06	1.94
ln TSP emissions	-0.43***	1.96
$(s.e.)$	0.05	2.06
ln Sales	-0.10***	1.84*
$(s.e.)$	0.04	1.10
N	105,278	782

Notes: * denotes p<0.05, ** denotes p<0.01, and *** denotes p<0.001.

Table A.17: Policy effect: geographic leakage

	Manufacturing	*Power generation*
ln NO_x emissions	0.35	0.82
$(s.e.)$	0.19	0.58
ln SO_x emissions	1.52***	2.25**
$(s.e.)$	0.31	0.83
ln TSP emissions	0.41*	1.12**
$(s.e.)$	0.25	0.47
ln Sales	0.09	1.12
$(s.e.)$	0.19	0.75
N	4,529	149

Notes: * denotes p<0.05, ** denotes p<0.01, and *** denotes p<0.001.

Table A.18: Robustness check: regulated manufacturing plant

	Mining/quarrying	Food/beverages/tobacco	Textiles/apparel/leather	Wood/paper/printing/media	Petro/chem/pharma/rubber/plastics
ln Measure use	0.00	0.19	-0.09	0.39	0.13
(*s.e.*)	0.00	0.30	0.09	0.36	0.14
ln Electricity use	0.27	0.76***	0.29	1.62***	0.40
(*s.e.*)	0.82	0.16	0.49	0.33	0.26
ln Electricity share	-0.14	0.31**	0.01	0.03	-0.19
(*s.e.*)	0.28	0.11	0.25	0.14	0.13
ln Sales	-0.24	0.04	-0.04	-0.05	0.00
(*s.e.*)	0.39	0.09	0.12	0.09	0.09
N	41	983	412	612	1,454
	Non-metallic minerals	Basic/fabricated metals	Electronics/instruments/electrical	Machinery/transport (incl. auto)	Furniture/misc./repair
ln Measure use	0.08	1.17	0.15	1.09	0.00
(*s.e.*)	0.12	0.64	0.44	0.58	0.00
ln Electricity use	0.35	1.28	0.38	0.38	1.32*
(*s.e.*)	0.29	0.76	0.33	0.35	0.53
ln Electricity share	0.06	0.52	-0.03	-0.10	1.35
(*s.e.*)	0.18	0.38	0.12	0.08	0.95
ln Sales	-0.16*	0.40	-0.03	0.04	0.28
(*s.e.*)	0.07	0.36	0.13	0.12	0.31
N	1,349	1,467	752	451	70

Notes: This sample keeps the plants of each corresponding sector. If plants change their sectors over time, they can be in different samples. * denotes p<0.05, ** denotes p<0.01, and *** denotes p<0.001.

Table A.19: Robustness check: unregulated affiliated manufacturing plant

	Mining/quarrying	Food/beverages/tobacco	Textiles/apparel/leather	Wood/paper/printing/media	Petro/chem/pharma/rubber/plastics
ln Measure use	0.00	-0.29	0.00	0.00	0.08
(*s.e.*)	0.00	0.18	0.00	0.00	0.24
ln Electricity use	1.80	-0.24	-1.02	-0.17	-0.16
(*s.e.*)	0.00	0.27	1.82	0.47	0.32
ln Electricity share	0.23	0.05	1.35	-0.35	0.10
(*s.e.*)	0.00	0.09	0.67	0.21	0.15
ln Sales	-0.15	0.03	0.55	-0.30	-0.07
(*s.e.*)	0.00	0.12	0.45	0.20	0.13
N	9	916	36	140	748
	Non-metallic minerals	Basic/fabricated metals	Electronics/instruments/electrical	Machinery/transport (incl. auto)	Furniture/misc./repair
ln Measure use	0.05	-0.01	-0.37	-0.22	7.74
(*s.e.*)	0.07	0.38	0.27	0.40	0.00
ln Electricity use	-0.26	0.52	0.59	0.17	-0.87
(*s.e.*)	0.45	0.36	0.57	0.45	0.00
ln Electricity share	0.18	-0.01	0.11	0.25	0.04
(*s.e.*)	0.14	0.14	0.17	0.27	0.00
ln Sales	0.15	0.10	0.13	0.34	-0.42
(*s.e.*)	0.11	0.19	0.27	0.19	0.00
N	696	618	272	346	15

Notes: This sample keeps the plants of each corresponding sector. If plants change their sectors over time, they can be in different samples. The empty cells above are where either the number of observations or the variation is small. * denotes p<0.05, ** denotes p<0.01, and *** denotes p<0.001.

Table A.20: Robustness check: plant

	Manufacturing		*Power generation*
	Regulated	Unregulated affiliated	Regulated
ln Measure use	0.20*	0.04	-0.10
(*s.e.*)	0.09	0.13	0.10
ln Electricity use	0.70***	0.24	
(*s.e.*)	0.13	0.19	
ln Electricity share	0.17**	0.14	
(*s.e.*)	0.06	0.07	
ln Sales	-0.08*	0.12	0.33
(*s.e.*)	0.04	0.07	0.22
N	5,797	2,434	1,141

Notes: This sample drops plants in the Seoul Capital Area. * denotes p<0.05, ** denotes p<0.01, and *** denotes p<0.001.

Table A.21: Robustness check: plant

	Manufacturing		*Power generation*
	Regulated	Unregulated affiliated	Regulated
ln Measure use	0.47**	-0.12	-0.04
(*s.e.*)	0.16	0.12	0.05
ln Electricity use	1.27***	-0.08	
(*s.e.*)	0.15	0.19	
ln Electricity share	0.24**	0.01	
(*s.e.*)	0.08	0.06	
ln Sales	0.03	0.08	0.21
(*s.e.*)	0.06	0.09	0.15
N	4,684	2,362	1,606

Notes: This sample keeps plants regulated by the greenhouse gas trading at least once. Since the policy monitored the whole firms, there are no unregulated affiliated plants in manufacturing. * denotes p<0.05, ** denotes p<0.01, and *** denotes p<0.001.

Table A.22: Robustness check: plant

	Manufacturing		*Power generation*
	Regulated	Unregulated affiliated	Regulated
ln Measure use	0.43**	-0.05	0.004
(*s.e.*)	0.14	0.12	0.04
ln Electricity use	1.25***	-0.10	
(*s.e.*)	0.14	0.16	
ln Electricity share	0.22**	0.06	
(*s.e.*)	0.07	0.06	
ln Sales	0.05	0.13	0.35*
(*s.e.*)	0.05	0.07	0.17
N	5,417	3,010	1,672

Notes: This sample keeps plants regulated by the greenhouse gas trading or the pilot program at least once. Since the policy monitored the whole firms, there are no unregulated affiliated plants in manufacturing. * denotes p<0.05, ** denotes p<0.01, and *** denotes p<0.001.

Table A.23: Robustness check: plant

	Manufacturing		*Power generation*
	Regulated	Unregulated affiliated	Regulated
ln Measure use	0.19	0.01	-0.08
(*s.e.*)	0.10	0.10	0.07
ln Electricity use	0.78***	0.05	
(*s.e.*)	0.11	0.15	
ln Electricity share	0.17**	0.10	
(*s.e.*)	0.06	0.06	
ln Sales	0.02	0.10	0.38*
(*s.e.*)	0.05	0.06	0.16
N	6,198	3,795	1,639

Notes: This sample imposes an additional exact match on regulated areas. * denotes p<0.05, ** denotes p<0.01, and *** denotes p<0.001.

Table A.24: Robustness check: plant

	Manufacturing
	Regulated
ln Measure use	0.17
$(s.e.)$	0.10
ln Electricity use	0.88***
$(s.e.)$	0.14
ln Electricity share	0.12
$(s.e.)$	0.08
ln Sales	0.07
$(s.e.)$	0.05
N	4,657

Notes: This sample keeps regulated manufacturing plants without any unregulated affiliated plants in the same 3-digit KSICs. I do not consider a counterpart for power plants because within-firm leakage is unlikely to arise. * denotes p<0.05, ** denotes p<0.01, and *** denotes p<0.001.

Table A.25: Robustness check: plant

	Manufacturing		*Power generation*
	Regulated	Unregulated affiliated	Regulated
ln Measure use	0.22*	-0.01	-0.03
$(s.e.)$	0.09	0.10	0.05
ln Electricity use	0.94***	0.02	
$(s.e.)$	0.11	0.15	
ln Electricity share	0.12*	0.09	
$(s.e.)$	0.06	0.06	
ln Sales	0.05	0.11	0.50**
$(s.e.)$	0.04	0.06	0.15
N	7,851	3,826	2,149

Notes: These results use propensity score matching on the same variables. * denotes p<0.05, ** denotes p<0.01, and *** denotes p<0.001.

Table A.26: Robustness check: plant

	Manufacturing		*Power generation*
	Regulated	Unregulated affiliated	Regulated
ln Measure use	0.33***	-0.002	-0.03
(*s.e.*)	0.10	0.11	0.06
ln Electricity use	1.12***	0.03	
(*s.e.*)	0.13	0.15	
ln Electricity share	0.22**	0.09	
(*s.e.*)	0.07	0.06	
ln Sales	0.05	0.11	0.50**
(*s.e.*)	0.04	0.06	0.15
N	7,125	3,640	2,047

Notes: This sample drops plants that were regulated but became exempt from the policy later. * denotes p<0.05, ** denotes p<0.01, and *** denotes p<0.001.

Table A.27: Robustness check: district-industry

	Mining/quarrying	Food/beverages/tobacco	Textiles/apparel/leather	Wood/paper/printing/media	Petro/chem/pharma/rubber/plastics
ln NO_x emissions	-0.56	-0.68***	-0.53***	-0.79***	-0.85***
(*s.e.*)	0.33	0.13	0.16	0.15	0.14
ln SO_x emissions	-0.75	-0.21	-0.68**	-0.90***	-1.30***
(*s.e.*)	0.55	0.15	0.21	0.17	0.21
ln TSP emissions	-0.52	-0.25	-0.48**	-0.85***	-0.90***
(*s.e.*)	0.41	0.14	0.18	0.19	0.16
ln Sales	0.18	-0.17	-0.09	-0.14	-0.11
(*s.e.*)	0.23	0.10	0.12	0.12	0.10
N	1,805	16,310	13,232	10,058	10,743
	Non-metallic minerals	Basic/fabricated metals	Electronics/instruments/electrical	Machinery/transport (incl. auto)	Furniture/misc./repair
ln NO_x emissions	-0.36*	-0.40*	-0.21	-0.47**	-0.19
(*s.e.*)	0.16	0.16	0.13	0.15	0.14
ln SO_x emissions	-0.24	-0.40*	-0.20	-0.67***	-0.50*
(*s.e.*)	0.23	0.19	0.14	0.17	0.20
ln TSP emissions	-0.39	-0.11	-0.19	-0.49**	-0.27
(*s.e.*)	0.22	0.20	0.13	0.15	0.15
ln Sales	-0.10	-0.03	0.04	-0.27*	-0.12
(*s.e.*)	0.12	0.12	0.11	0.13	0.12
N	7,079	7,793	18,464	10,453	9,332

Notes: This sample keeps the industries of each corresponding sector. * denotes p<0.05, ** denotes p<0.01, and *** denotes p<0.001.

Table A.28: Robustness check: geographic leakage

	Mining/quarrying	Food/beverages/tobacco	Textiles/apparel/leather	Wood/paper/printing/media	Petro/chem/pharma/rubber/plastics
ln NO_x emissions	-0.13	-0.25	-0.70	1.50*	-0.09
(*s.e.*)	0.86	0.42	1.57	0.59	0.93
ln SO_x emissions	1.07	1.18**	-3.30	1.89**	0.91
(*s.e.*)	0.77	0.44	2.40	0.59	1.61
ln TSP emissions	0.80	-0.32	-2.00	2.09*	-0.12
(*s.e.*)	0.89	0.41	1.89	0.87	1.05
ln Sales	-0.45	-0.05	-0.72	-0.14	-0.31
(*s.e.*)	0.62	0.37	0.97	0.55	0.54
N	204	1,251	276	382	393
	Non-metallic minerals	Basic/fabricated metals	Electronics/instruments/electrical	Machinery/transport (incl. auto)	Furniture/misc./repair
ln NO_x emissions	0.33	2.33	0.47	3.60**	0.04
(*s.e.*)	0.46	1.32	1.04	1.35	0.40
ln SO_x emissions	2.45**	2.95*	0.47	8.38***	1.41*
(*s.e.*)	0.88	1.42	1.04	2.40	0.59
ln TSP emissions	0.91	2.48	0.44	6.14***	0.43
(*s.e.*)	0.56	1.58	1.03	1.70	0.45
ln Sales	0.75*	0.13	-0.24	1.73	0.13
(*s.e.*)	0.36	0.55	0.93	1.36	0.36
N	592	240	332	230	629

Notes: This sample keeps the industries of each corresponding sector. * denotes p<0.05, ** denotes p<0.01, and *** denotes p<0.001.

Table A.29: Policy effect: district-industry

	Manufacturing	*Power generation*
ln NO_x emissions	-0.50***	-0.06*
$(s.e.)$	0.05	0.03
ln SO_x emissions	-0.52***	0.16
$(s.e.)$	0.07	0.10
ln TSP emissions	-0.38***	-0.20***
$(s.e.)$	0.06	0.02
ln Sales	-0.07*	-0.75
$(s.e.)$	0.04	0.58
N	65,249	440

Notes: This sample drops the observations of the Seoul Capital Area from the sample. * denotes p<0.05, ** denotes p<0.01, and *** denotes p<0.001.

Table A.30: Robustness check: geographic leakage

	Manufacturing	*Power generation*
ln NO_x emissions	0.39	0.85
$(s.e.)$	0.20	0.60
ln SO_x emissions	1.39***	2.28*
$(s.e.)$	0.28	0.83
ln TSP emissions	0.53*	1.16*
$(s.e.)$	0.22	0.47
ln Sales	0.17	1.12
$(s.e.)$	0.16	0.75
N	5,299	159

Notes: This sample drops the observations of the Seoul Capital Area from the sample. The key difference is the sample and exposure differences because now distance is measures after dropping the Seoul Capital Area. * denotes p<0.05, ** denotes p<0.01, and *** denotes p<0.001.

Table A.31: Policy effect: district-industry

	Manufacturing	*Power generation*
ln NO_x emissions	-0.23***	1.91
$(s.e.)$	0.05	1.89
ln SO_x emissions	-0.14*	1.65
$(s.e.)$	0.06	1.88
ln TSP emissions	-0.15**	2.02
$(s.e.)$	0.05	2.09
ln Sales	0.07	2.35
$(s.e.)$	0.04	1.21
N	101,231	716

Notes: These results are conditional on the pre-regulation levels. * denotes p<0.05, ** denotes p<0.01, and *** denotes p<0.001.

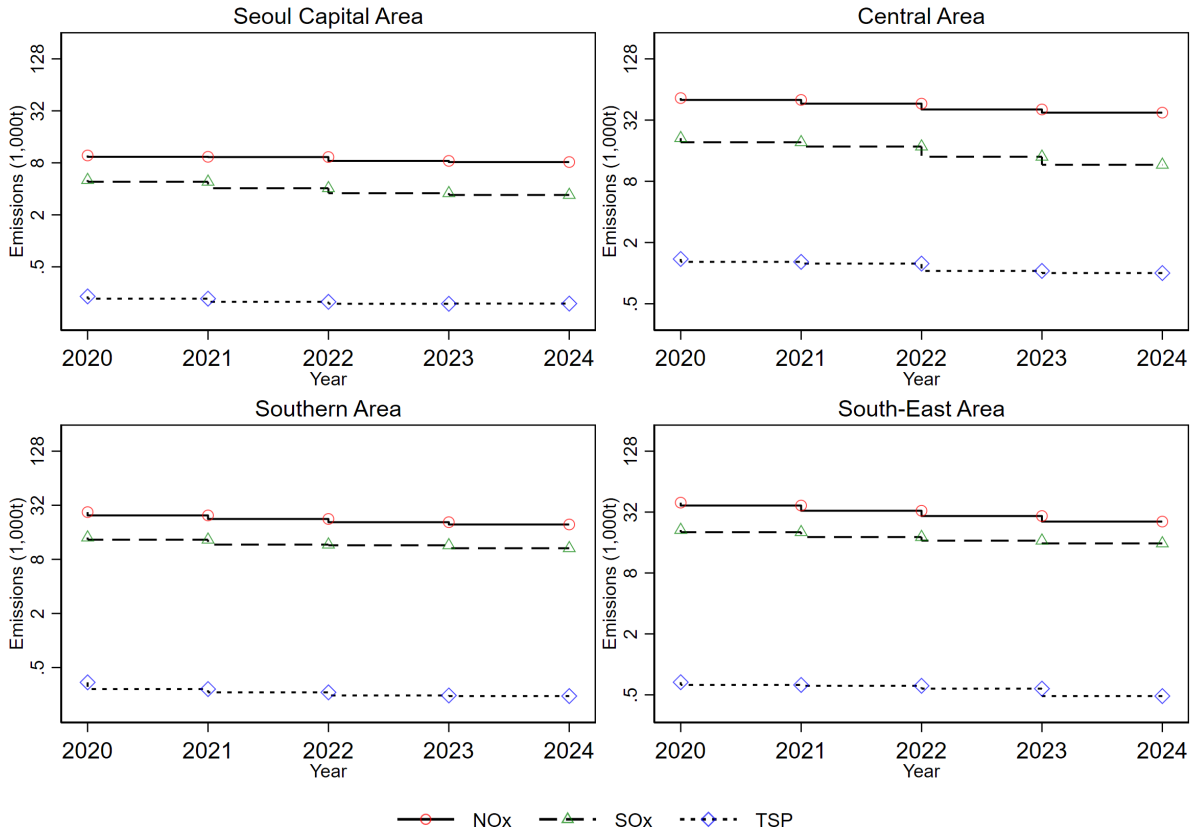
Table A.32: Robustness check: geographic leakage

	Manufacturing	*Power generation*
ln NO_x emissions	0.01	0.92
$(s.e.)$	0.23	1.13
ln SO_x emissions	0.97**	3.94
$(s.e.)$	0.32	2.21
ln TSP emissions	0.09	2.13
$(s.e.)$	0.26	1.32
ln Sales	-0.09	1.14
$(s.e.)$	0.18	0.76
N	4,072	136

Notes: These results are conditional on the pre-regulation levels. * denotes p<0.05, ** denotes p<0.01, and *** denotes p<0.001.

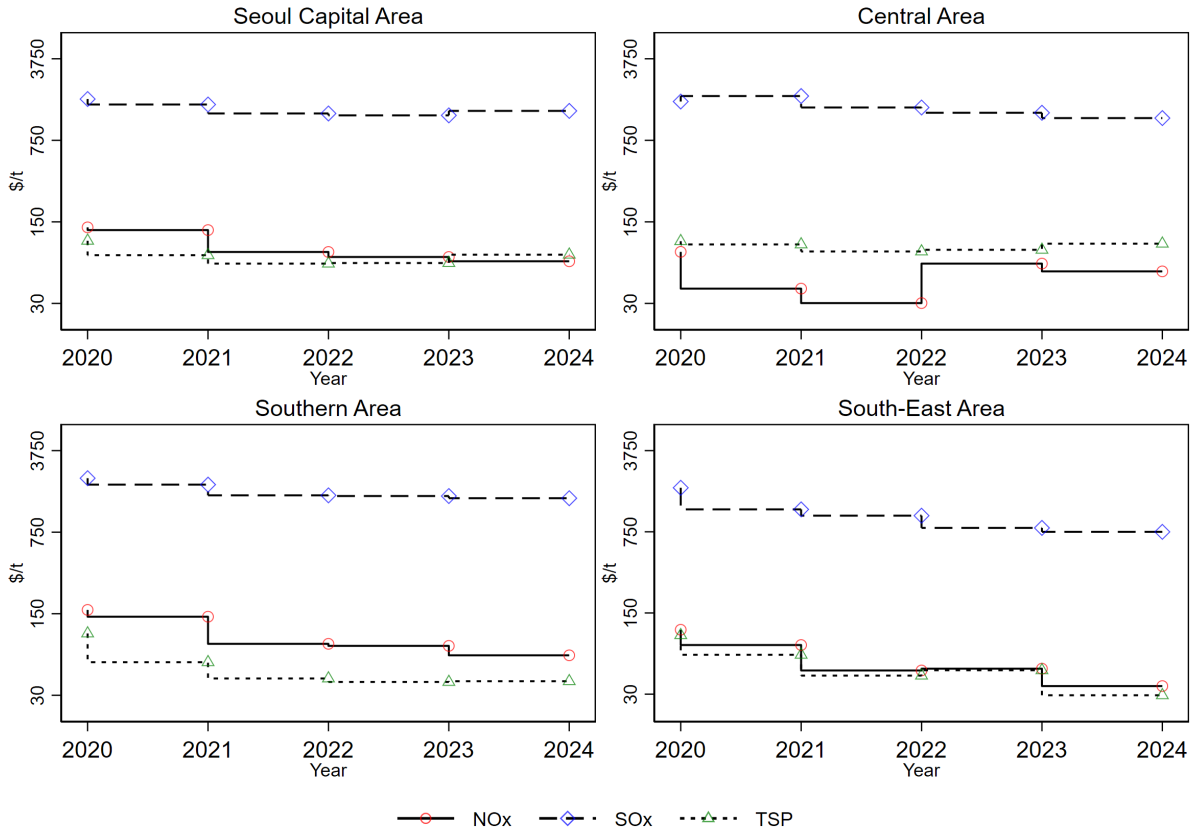
H Additional figures

Figure A.1: Emissions allowances by pollutant



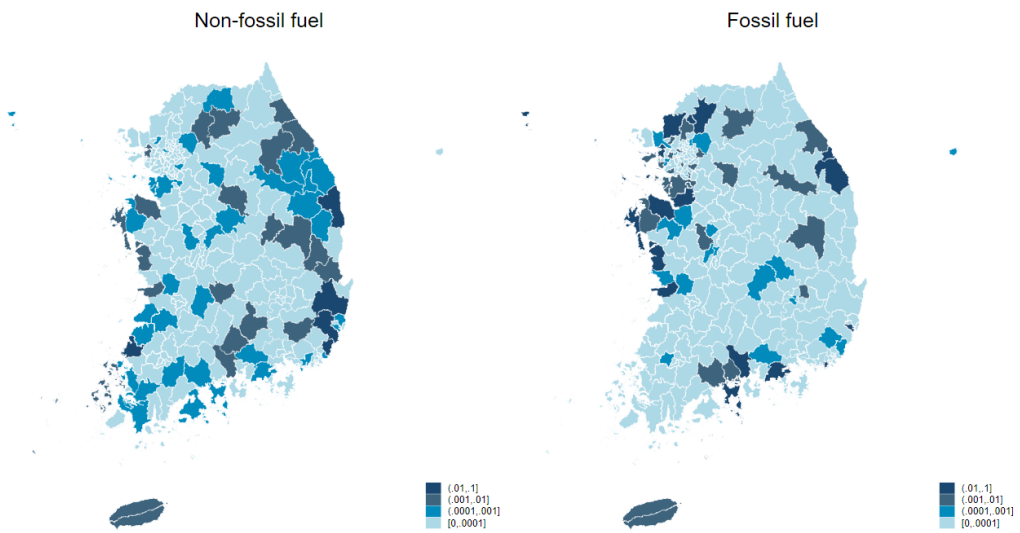
Notes: Here caps are readjusted using past emissions. Each point is connected with a step to capture a time trend clearly.
Sources: Ministry of Environment.

Figure A.2: Emissions allowance prices by pollutant



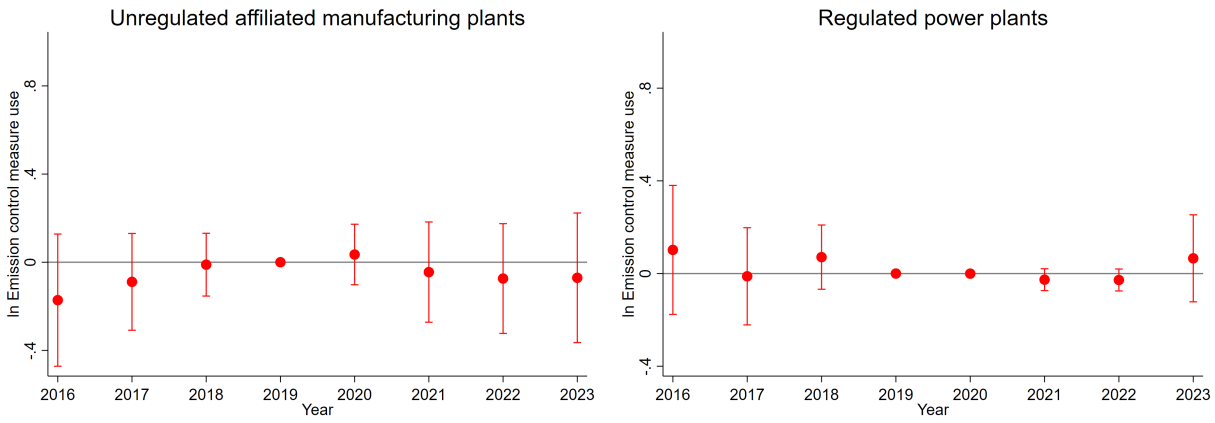
Notes: The average transaction unit price is disclosed as the annual transaction amount divided by the annual transaction volume (excluding free transactions) in each area. Here I use annual average spot exchange rates to change the unit from Korean won to US dollar. There is no explicit price-stabilizing mechanism. Each point is connected with a step to capture a time trend clearly.
Sources: Ministry of Environment, Federal Serve Bank of St. Louis.

Figure A.3: Power generation in Space



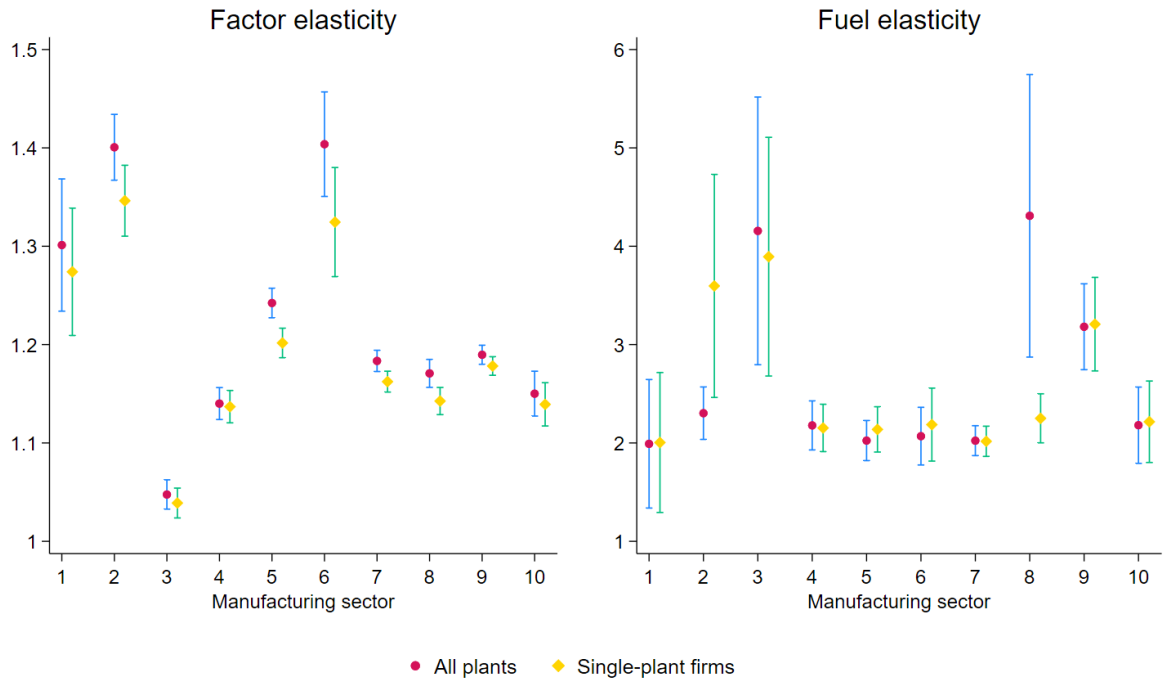
Notes: Fossil fuel power generation includes coal, gas, and oil as its energy source. Non-fossil fuel power generation includes the rest as its energy source. The unit is Gigawatt. The sample in 2016 is used. The geographic concentration (or dispersion) of power plants is common across countries. Hanson (2023) documents a similar pattern in the U.S.

Figure A.4: Event dynamics: plants



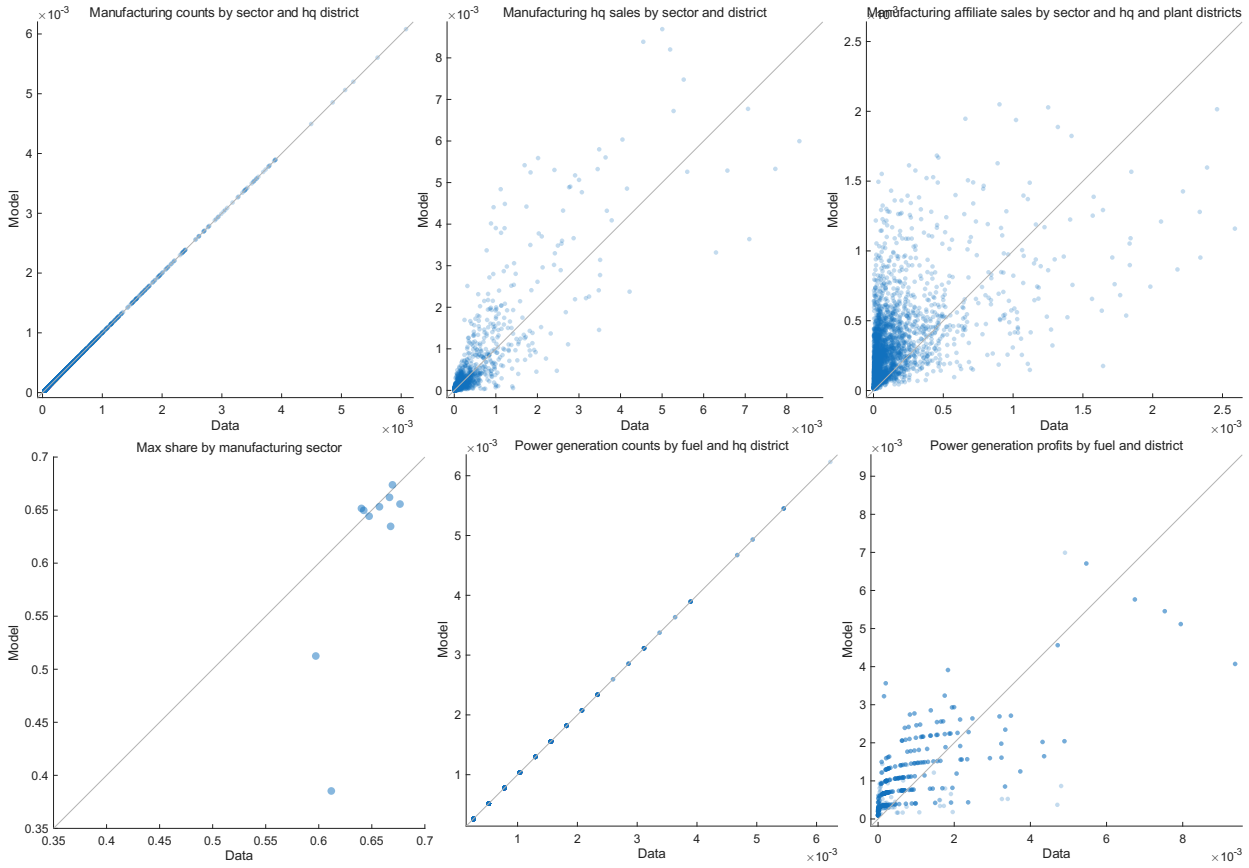
Notes: The 95% confidence intervals are shown jointly with the point estimates.

Figure A.5: Parameters from production function estimation



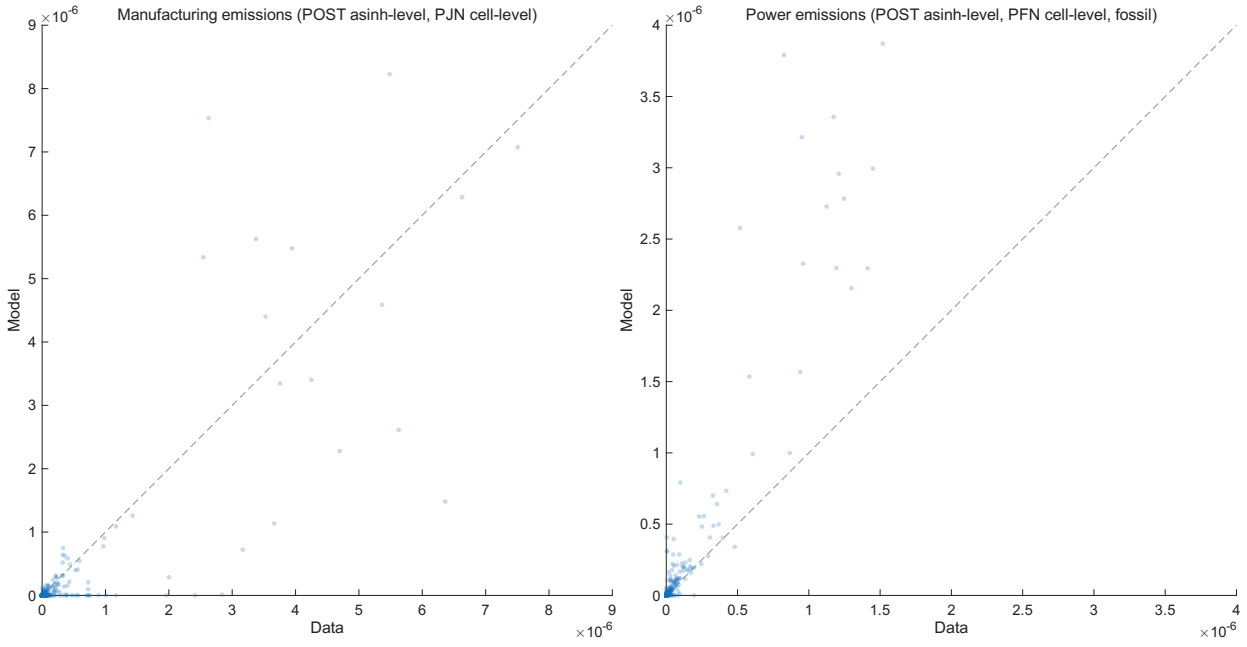
Notes: All plants include plants that have many affiliated plants while single-plant firms remove those from the sample.

Figure A.6: Model fit: pre-regulation moments



Notes: The panel compares manufacturing and power generation moments under no regulation that are targeted for calibration. The normalized values are plotted. The numbers of firms are used as weights except for themselves and max sales. The inverse hyperbolic sine transformation has been used to address zeros. The 45-degree line indicates a perfect fit between the model and the data. Profits are variables profits. There are 10 manufacturing sectors, 250 districts, and 4 power generation fuels. All moments are pooled into one dimension. For example, the number of manufacturing firms is pooled over sectors and districts.

Figure A.7: Model fit: post-regulation moments



Notes: The panel compares manufacturing and power generation moments under regulation that are untargeted. The normalized values are plotted. The inverse hyperbolic sine transformation has been used to address zeros. The 45-degree line indicates a perfect fit between the model and the data. The power generation emissions only come from fossil fuel use. There are 3 pollutants, 10 manufacturing sectors, 250 districts, and 3 power generation fuels. All moments are pooled into one dimension. For example, manufacturing emissions are pooled over pollutants, sectors, and districts.