Immoral Hazard?
Hazardous Substances And Lack of Chemical Innovation

Extended Abstract, Please Do Not Cite and Circulate

Abstract

We study how patenting in chemical substances changed after Europe's 2007 REACH regulation that required European firms to register their use of hazardous chemical substances. We find that firms with higher baseline pollution levels reduced patent applications by 13-29% following REACH implementation. REACH operated through both extensive margins (firms ceased innovating) and intensive margins (reduced patent output), revealing comprehensive negative innovation responses among the most pollution intensive firms.

Keywords: Green Patents, Innovation, Chemical Emissions, Environmental Policy, REACH regulation

JEL classification: D62; G30; K32; O31

1 Introduction

The nexus between regulatory constraints on firms and their incentives to innovate (Karen, Oates, and Portnery (1995)) has received greater attention in the past decade with the increase in environmental regulation. The general patterns of the increasing regulation and at the same time new green innovation captured by, e.g., patents in green technologies has received criticism of disentangling general time trends and controlling for the growth in production capacity. For example, Bolton, Kacperczyk, and Wiedemann (2024) provide evidence that green innovation activity does not predict emission reductions at the firm level, while Cohen, Gurun, and Nguyen (2022) document that most of the green patents in the United States are filed by energy-producing firms, traditionally seen as lagging in environmental standards.

We study regulation implemented in Europe that introduced requirements to disclose the use of hazardous chemical compounds in firms' production in Europe and relate it to the incentives to innovate. The REACH (Registration, Evaluation, Authorization, and Restriction of Chemicals)[1] regulation provides a unique setting for examining whether the mandatory registration of chemical substances has had any effect on innovation, on emission levels, and on coordination among firms when registering the use of these substances. REACH fundamentally transformed the European chemicals landscape by establishing mandatory reporting requirements for manufacturers and importers to submit comprehensive operational reports about chemical substances and register this data with the European Chemicals Agency (ECHA). Enacted in 2007 under EC Regulation 1907/2006, REACH operates on the principle that chemical substances exceeding one tonne per year per company must undergo mandatory registration with ECHA. This process requires companies to identify risks associated with their chemical substances and demonstrate effective risk management strategies. The registration for each chemical substance needs to be completed once and this registration stays active indefinitely, subject to some exclusions. The regulation, arguably serves as a catalyst for increased innovation as companies seek to transition away from hazardous chemicals to safer alternatives.

[1] Online Appendix provides a more detailed discussion on the institutional background of REACH legislation.

Unlike prior work that focuses on CO_2 emissions, we study the industrial emissions linked to ten specific hazardous chemical substances, including benzene, methane, hydrogen cyanide, and carbon monoxide, providing granular evidence on firm level innovation responses to targeted chemical regulation.[2]

In addition to collecting data on each firm's use of particular hazardous substances from ECHA, we rely on European Pollutant Release and Transfer Register (EPRT) on the comprehensive data on industrial emissions across European facilities, capturing both point source emissions and waste transfers for each substance. Our third source of data is a combined substance-level patent dataset from United States Patent and Trademark Office (USPTO) and the European Patent Office (EPO) that allows to identify patents whose abstracts contain keywords corresponding to each substance. Importantly, we can investigate the mentions of the particular chemical compounds in the patent texts to analyze whether patenting activity linked to those particular chemical compounds changed after regulation for firms that were heavy-users of these substances more than for others.

After matching firms across three datasets using a standard fuzzy-matching methodology, we include firms which have at least one instance of industrial emission data on the EPRT, whether or not that firm has any chemical patents in patents datasets. Our final matched dataset spans the years 2007 to 2023. As we also measure the pollution that comes from the particular compounds, all three components – use of chemical compounds, pollution that comes particularly from them, and patents in them particularly – provide us with a unique granular way of studying environmental externalities, patents, and production processes.

We find that firms with higher baseline pollution levels in 2007 actually decreased their patent applications by 13-29% following the implementation of REACH. This finding shows how regulatory pressure affects innovation decisions among the most affected firms, contradicting theoretical predictions about regulation induced innovation incentives. The analysis reveals that REACH operated through both extensive margin effects (some firms ceased innovating entirely) and intensive margin effects (continuing innovators reduced patent out-

[2]We focus on chemical substances, the names of which are perfectly matched in the EPRT and REACH databases. If the substance names are perfectly matched across these two databases then we can cleanly identify and link emissions and registrations for the same substance. In further work, we are expanding the list of chemicals to include substances which are close matches across the two databases.

put). This finding highlights the comprehensive negative innovation responses among the most pollution-intensive firms.

Our study is the first to demonstrate that regulation of specific chemical substances can produce innovation responses that differ markedly from those observed for broader environmental policies. The focus on non-CO2 chemical emissions reveals important heterogeneity in how firms respond to targeted environmental regulations, with implications for policy design in chemical safety and environmental protection.

2 Data and Sample Construction

2.1 Data

Our analysis combines patent data from the United States Patent and Trademark Office (USPTO) and the European Patent Office (EPO) with emissions data from the European Pollutant Release and Transfer Register (EPRT). EPRT provides comprehensive data on industrial emissions across European facilities, capturing both point source emissions and waste transfers for our target substances.[3] On the other hand, patent data from both the USPTO and EPO allows us to capture innovation activities across major patent jurisdictions, providing a comprehensive view of technological development related to the substances we study in the paper.

Patent data construction follows a keyword-based approach where we identify patents whose abstracts contain references to specific chemical substances of environmental concern. We construct our patent sample by identifying patents whose abstracts contain keywords corresponding to ten specific chemical substances: 1,2-dichloroethane, anthracene, atrazine, benzene, carbon monoxide, ethylene oxide, fluorine, hydrogen cyanide, methane, and naphthalene.[4]

We include all firms from the EPRT database, which may or may not have any patents. This specification captures population-wide innovation effects and allows us to examine

[3]EPRT relate to Scope 1 emissions, also known as "direct" emissions from production processes. In the Online Appendix we discuss why this is compatible with our analysis.

[4]To identify these specific chemical substances, we match the names of substances between the European Environmental Agency and REACH. We select the chemical substances with exact name match.

whether environmental regulations spur innovation among previously non-innovative firms. The sample contains around 39,000 observations across 4,062 firms.[5]

The emissions levels we observe are widely distributed across Europe. Figure 1 plots a map of the facilities emitting one of the chemical substances, carbon monoxide, across 31 European countries. The total average emission for this substance are 3,990 million kilograms across all years in analysis. It can be noticed that although the majority of the facilities are heavy emitters, there is heterogeneity for some facilities which report a lower average emission across the years.

Similarly, Figure 2 plots a map of the firms that own granted patents mentioning the substance carbon monoxide. There are 16 firms across 8 European countries that applied (successfully) for patents mentioning carbon monoxide, for a total of 80 patents across all years. The map shows that this specific patenting activity is less geographically dispersed compared to the facilities emitting the same substance.

Table 1 presents descriptive statistics for emissions, facilities, and patenting activity across different substance types, where the total average emission is expressed in million kilograms. Patenting activity is concentrated in our sample for the substances benzene, methane and carbon monoxide. While the substances for which we observe larger levels of emission are carbon monoxide, methane and fluorine.

Figure 3 presents the unconditional relationship between patent counts and emissions pooled by all substances; Figure 4, instead, is disaggregated by substance. The pooled specification shows a slightly negative raw correlation (-0.009), while the substance-level analysis reveals considerable heterogeneity in these unconditional relationships. For benzene and ethylene oxide, the raw correlations are slightly positive, while carbon monoxide and methane show a weakly negative pattern.

Table 2 presents descriptive statistics for emission levels, patenting activity, and number of facilities across European countries. The total average emission represents the aggregate annual emissions across all facilities and all substances tracked in the dataset for each country, expressed in million kilograms. Germany, United Kingdom, Spain, France and Poland are

[5]Online Appendix describes the fuzzy matching algorithm to link companies in the EPRT with patenting companies.

the top emitters for all years and substances in analysis. The highest patenting activity is concentrated in Italy, Netherlands, Germany, France and United Kingdom.

Finally, Table 3 presents the summary statistics of the variables included in the treatment intensity regression presented in the empirical analysis section.

3 Empirical Findings

This section presents a difference-in-differences design with continuous treatment intensity to test whether firms with higher baseline emission levels in 2007 increased their patent applications following the REACH implementation. This design exploits variation in pre-policy pollution intensity across firms and substances to identify differential innovation responses to environmental regulation.

The implementation of REACH regulation on June 1, 2007 represents a plausibly exogenous regulatory shock affecting all European firms handling chemical substances above threshold quantities. The exogeneity of REACH implementation stems from several features. Compliance is mandatory for all firms manufacturing or importing regulated substances above one tonne per year, and the regulatory burden scales directly with firms' substance usage (companies with higher emission levels must register more substances, prepare more extensive safety documentation, and face greater probability of future authorization requirements). This creates differential regulatory exposure based on pre-existing production patterns rather than forward looking strategic choices. We measure baseline emissions in 2007, capturing production processes established before firms could respond to REACH requirements.

Our baseline regression can take the following form:

$$\begin{aligned}\text{patents count}_{i,s,t} = \exp\big(&\beta_1 \cdot \text{policy pollution interaction}_{i,s,t} + \beta_2 \cdot \text{pollution baseline}_{i,s} + \\ &+\beta_3 \cdot \text{policy post2007}_t + \phi_{i,s,t} + \epsilon_{i,s,t}\big)\end{aligned} \tag{1}$$

where i denotes firm, s substance, t year; $\text{patents count}_{i,s,t}$ refers patent applications at the firm-substance-year level; $\text{pollution baseline}_{i,s}$ to 2007 emission level for substance s by

firm i; policy post2007$_t$ to post policy indicator variable taking the value of one for years after and including the year 2007 and zero otherwise to policy pollution interaction$_{i,s,t}$ = (policy post2007$_t$ $\times$ pollution baseline$_{i,s}$): interaction term between the post 2007 policy indicator and firm-substance 2007 pollution baseline, while $\phi_{i,s,t}$ is a flexible fixed effects structure, which varies by specification.

As in our case, the patent data exhibits extreme zero inflation: 99.74% of our observations have zero patents, we employ zero-inflated Poisson (ZIP) models in our analysis. Our baseline specification employs pollution baseline as the primary determinant of zero inflation status. Higher baseline pollution levels increase the probability of being classified as a structural zero (never innovator), while lower pollution levels increase the probability of being a potential innovator. This specification reflects the economic intuition that highly polluting firms may operate in traditional industries with limited innovation focus, making them inherently less likely to engage in patenting activity. The count model estimates the treatment intensity effect among firms capable of innovation, while the zero inflation model identifies the factors that determine innovation capacity itself. This decomposition allows for a more nuanced understanding of how environmental regulation affects different types of firms in the population.

We estimate four specifications to test robustness: (1) baseline ZIP model, (2) policy variables in the zero inflation component, (3) substance fixed effects, and (4) quadratic pollution baseline terms. The results in Table 4 document our main results. The policy pollution interaction variable has a negative and statistically significant coefficients across all specifications. This result demonstrates that firms with higher baseline pollution levels reduced their patent applications more following the 2007 policy implementation.

The baseline specification reveals that among firms classified as potentially innovative, the 2007 REACH policy reduced patent applications by 16.4%. This substantial effect indicates that highly polluting firms cut innovation significantly more than low polluting firms after REACH implementation, directly contradicting the expected treatment intensity response where more affected firms should increase innovation efforts. We account for the possibility that the policy caused some firms to stop innovating entirely by including policy variables in the zero-inflation component and report the results in column (2). The coefficient of in-

terest is negative suggesting that the reduction in patents among remaining innovative firms strengthens to 16.8%. This slightly larger effect suggests that REACH operated through both extensive margin effects (some firms ceased innovating completely) and intensive margin effects (continuing innovators reduced their patent output). The dual channel impact highlights the comprehensive nature of the policy's negative innovation effects. We control for differences across chemical types through substance fixed effects in column (3), recognizing that some chemicals may present more tractable innovation opportunities than others. The main result remains statistically significant. While the magnitude decreases compared to the baseline specification, this suggests that part of the main result was driven by chemical specific factors. The quadratic pollution baseline specification, which allows for non-linear relationships between pollution intensity and innovation responses, yields a similar result.

4 Conclusions

Concluding, our research studies innovation in chemical substances and emissions responses to Europe's 2007 REACH regulation. Unlike CO2 focused studies, we examine ten specific hazardous chemicals including benzene, methane, and hydrogen cyanide using patent and emissions data from 4,168 European firms spanning 2007-2023. We find firms with higher baseline pollution levels decreased patent applications by 13-29% following REACH implementation, contrary to Porter Hypothesis predictions. REACH operated through both extensive margins (firms ceased innovating) and intensive margins (reduced patent output), revealing comprehensive negative innovation responses among the most pollution intensive firms that theory predicts should innovate most.

We are further extending this analysis in a few directions. First, we examine whether chemical innovation can translate into environmental improvements by testing the relationship between patent activity and emission reductions. Second, we investigate how REACH's mandatory disclosure and coordination requirements affect firm behavior, with particular attention to whether high-polluting firms engage in strategic avoidance of regulatory compliance.

References

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Cohen, L., U. T. Gurun, and Q. Nguyen (2022): "The ESG-innovation disconnect: Evidence from green patenting," *Working Paper Harvard Business School*.

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Tables

Table 1: Substances, emission levels and patenting activity

Substance name	Num. facilities	Num. facilities with patents	Num. countries	Total avg. emission	Total patents
Carbon monoxide	1,068	16	31	3,990.99	80
Methane	2,455	15	32	1,828.16	87
Fluorine	596	4	27	12.67	8
Benzene	632	11	31	5.88	112
1,2-dichloroethane	148	0	21	1.00	0
Hydrogen cyanide	152	0	21	0.60	0
Naphthalene	304	1	24	0.41	1
Ethylene oxide	29	1	11	0.13	9
Anthracene	129	0	17	0.03	0
Atrazine	45	0	14	0.00	0

This table presents descriptive statistics for emissions, facilities, and patenting activity across different substance types. The total average emission is expressed in million kilograms. Patents are counted if they contain the keyword related to the substance in the abstract of the patent.

Table 2: Emission levels and patenting activity by country

Country name	Total avg. emission	Total patents	Num. facilities
Germany	1,099.87	56	525
United Kingdom	705.37	23	461
Spain	615.28	0	642
France	470.02	52	398
Poland	445.39	0	172
Italy	416.47	78	487
Belgium	303.10	7	86
Bulgaria	256.68	0	98
Romania	193.33	0	143
Finland	163.92	5	85
Netherlands	163.25	65	146
Czech Republic	156.96	0	114
Slovakia	143.05	0	51
Austria	107.83	0	53
Portugal	93.69	0	105
Sweden	63.71	0	60
Iceland	58.80	0	11
Greece	52.25	0	32
Hungary	49.60	0	70
Denmark	44.79	1	111
Ireland	43.17	0	96
Estonia	42.55	0	22
Norway	39.14	6	64
Slovenia	34.52	0	55
Lithuania	24.22	0	36
Switzerland	14.31	4	32
Serbia	14.04	0	33
Croatia	7.52	0	6
Luxembourg	5.84	0	10
Cyprus	5.20	0	13
Latvia	3.57	0	12
Malta	2.43	0	2
Total	**5,763.86**	**297**	**4,431**

This table presents descriptive statistics for emission levels, patenting activity, and number of facilities across European countries. The total average emission represents the aggregate annual emissions across all facilities and all substances tracked in the dataset for each country, expressed in million kilograms (e.g., Germany's 1,099.87 million kg equals approximately 1.1 million metric tons of average annual emission).

Table 3: Summary statistics of the variables included in the treatment intensity regression

Variables	(1) count	(2) mean	(3) std. dev.	(4) min	(5) p25	(6) p50	(7) p75	(8) max
total pollutant quantity 2007	39,165	2,529	12,308	0.01	14.3	270	1,181	227,000
patents count	39,165	0.01	0.16	-	-	-	-	17
pollution baseline	39,165	5	3	0	3	6	7	12
policy pollution interaction	39,165	3	3	-	-	1	6	12
policy post2007	39,165	1	1	-	-	1	1	1

This table presents summary statistics for the variables included in the treatment intensity regressions (Table 5). Total pollutant quantity is expressed in thousands of kilograms. Patents count is the count of patents related to each substance. Pollution baseline = log((total pollutant quantity Kg 2007/1000) + 1). Policy pollution interaction = policy post2007 × pollution baseline. Policy post2007 is a dummy variable equal to 1 if year ≥ 2007. Dashes (-) indicate zero minimum values.

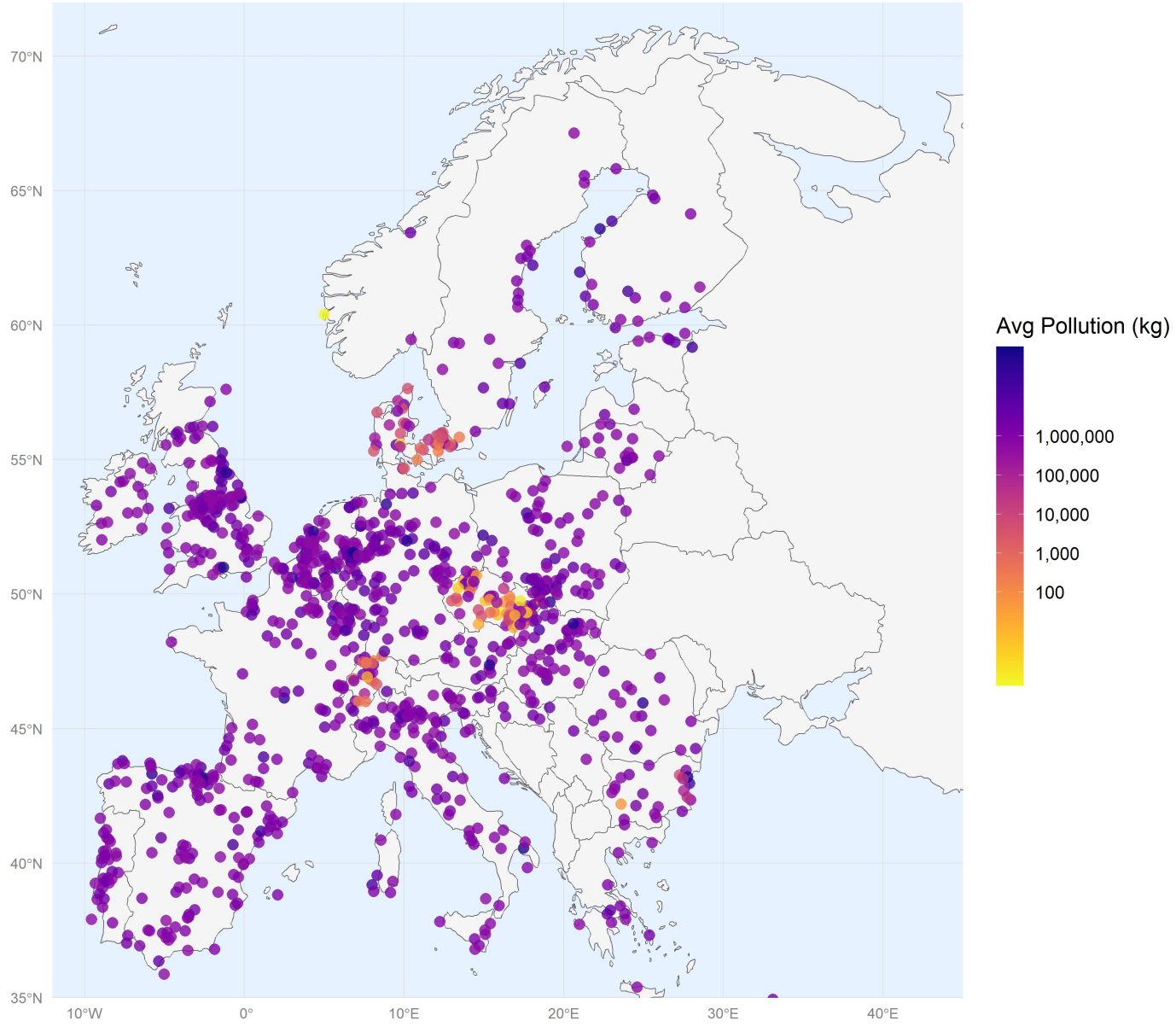
Table 4: Main Results

Dep. var.	Patents count (1)	Patents count (2)	Patents count (3)	Patents count (4)
Variables	Baseline ZIP	Policy in Zero-Inflation	Substance FE	Quadratic Pollution Baseline
policy pollution interaction	-0.179**	-0.184**	-0.154*	-0.129*
	(0.068)	(0.068)	(0.061)	(0.059)
pollution baseline	0.212***	0.215***	0.583***	-0.594***
	(0.037)	(0.037)	(0.089)	(0.122)
policy post2007	0.222	0.299	0.315	0.229
	(0.413)	(0.446)	(0.381)	(0.371)
Substance Fixed Effects	No	No	Yes	No
Zero-Inflation: Policy	No	Yes	No	No
Pollution Baseline Quadratic	No	No	No	Yes
Observations	39,165	39,165	39,165	39,165
AIC	1734.1	1735.9	1619.6	1692.8

This table presents the results from Zero-Inflated Poisson (ZIP) regression models examining the treatment intensity effect. The dependent variable is patent applications (count). Panel A shows results for the full sample (39,165 observations), while Panel B shows results for the matched sample (2,190 observations). Column (1) presents the baseline ZIP model, column (2) includes policy variables in the zero inflation component, column (3) adds substance fixed effects, and column (4) includes quadratic pollution baseline terms. All models include a zero inflation component with pollution baseline as the primary predictor. The policy implementation date is June 1, 2007. Treatment effects represent the interaction between policy post 2007 and pollution baseline. ***, **, and * denote significance at the 0.001, 0.01, and 0.05 levels respectively.

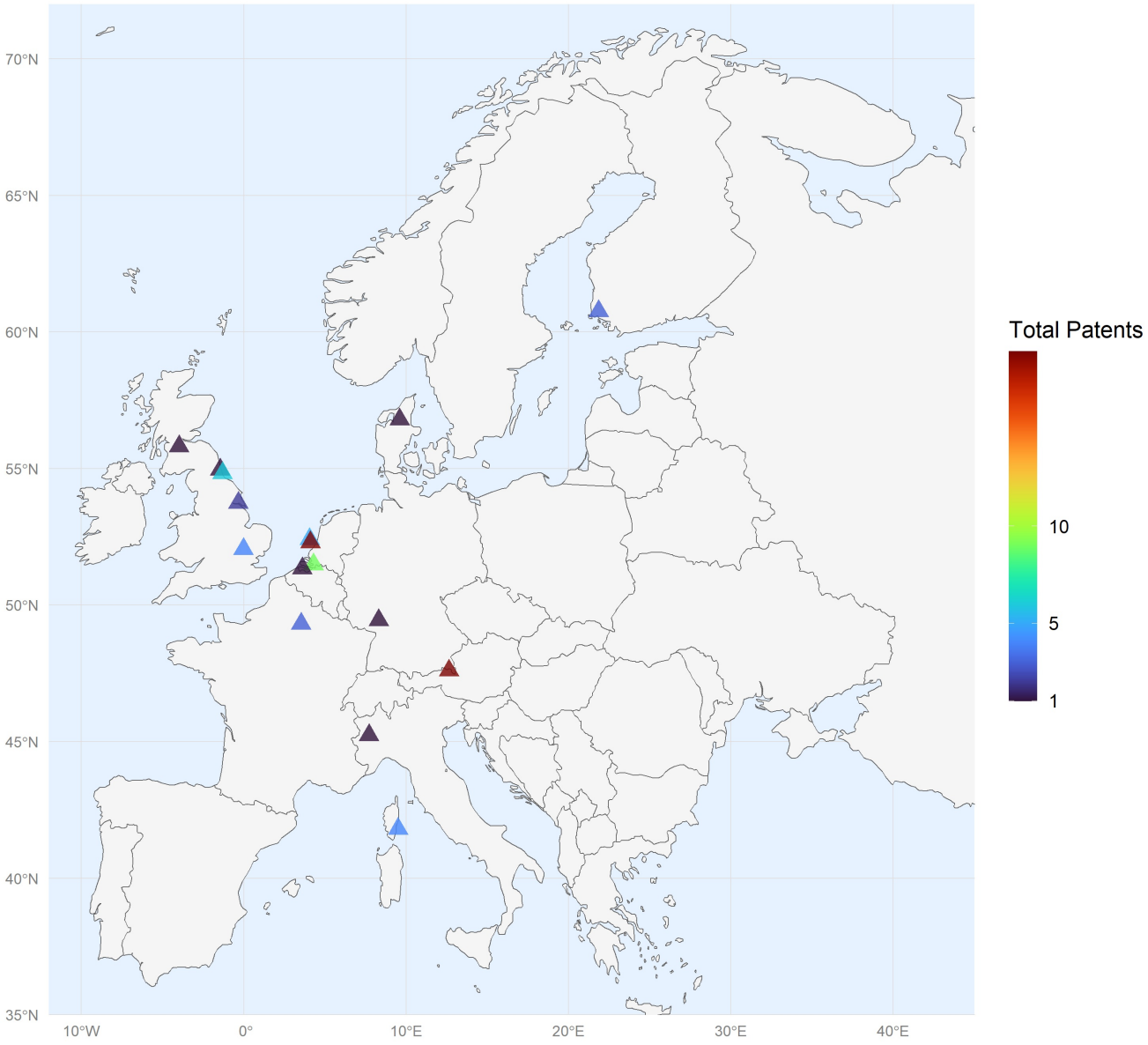
Figures

Figure 1: European polluters (carbon monoxide)



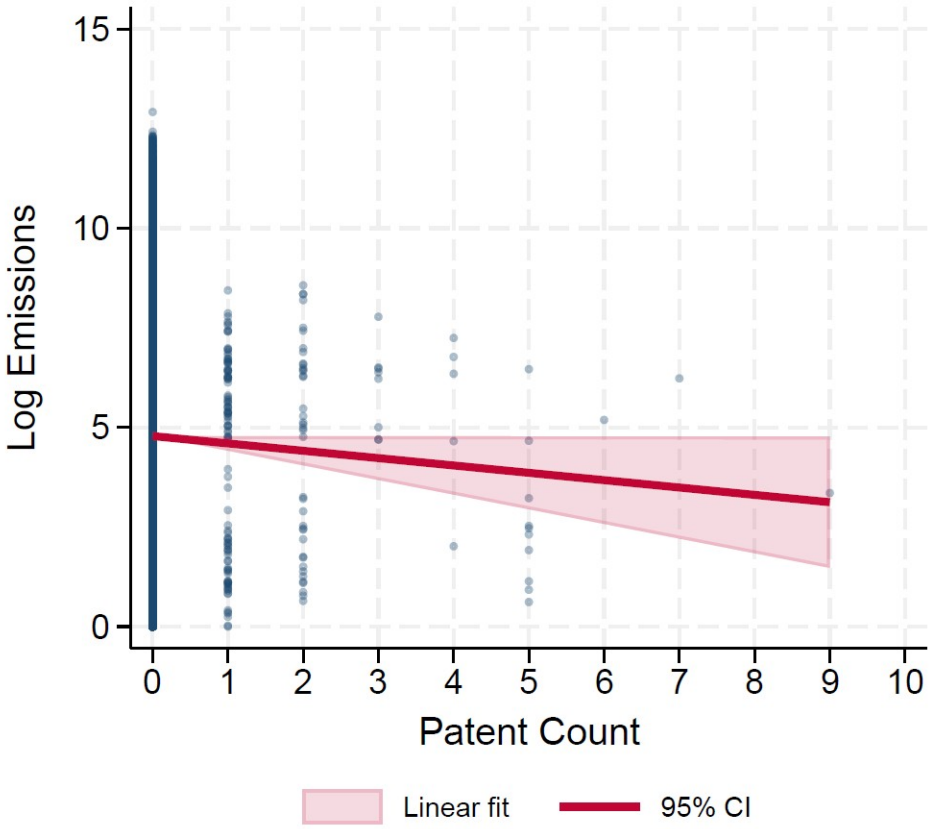
This map represents the 1,068 facilities polluting carbon monoxide across 31 European countries. Total average emissions: 3,990.99 million kg. Locations are geocoded from city names, colour represents average pollution levels across all years (log scale).

Figure 2: Green innovation in Europe (carbon monoxide)



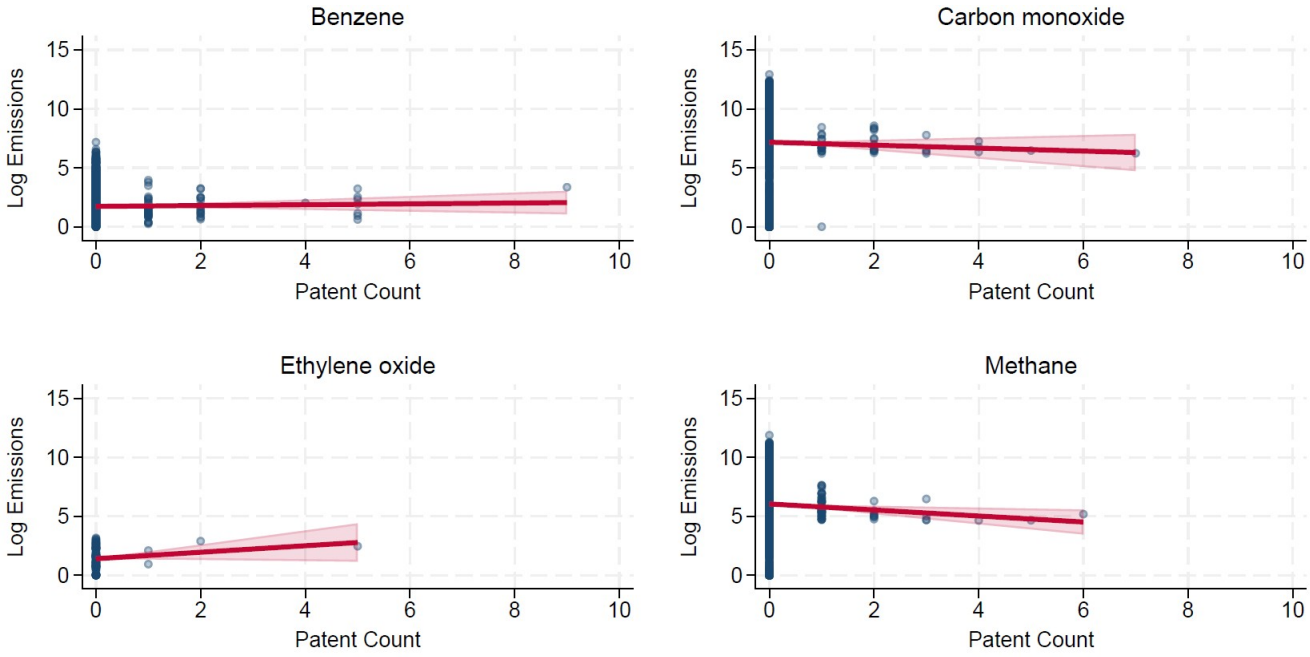
This map represents the 16 firms with patents mentioning carbon monoxide across 8 European countries. Total patents: 80. Locations are geocoded from city names, colour represents total patents count across all years. Only firms with at least one patent are shown.

Figure 3: Emissions-patents relationship with 95% CI



This figure presents the unconditional relationship between patent counts and emissions, pooled by all substances. Sample: firm-substance-year observations, 2007-2023.

Figure 4: Emissions-patents relationship by substance



This figure presents the unconditional relationship between patent counts and emissions, disaggregated by the TOP4 substances. Linear fit with 95% CI shown in red. Sample: firm-substance-year observations, 2007-2023.

Online appendix - not for publication

The Online Appendix presents in greater detail the substances used in this paper and provides examples of their presence in final products and/or production processes.

OA.1 REACH Regulation

OA.1.1 Background

The regulation on the registration, evaluation, authorisation and restriction of chemicals (REACH) represents the cornerstone of European Union legislation designed to protect human health and the environment from chemical risks. Enacted in 2007 under EC Regulation 1907/2006, REACH operates on the principle that chemical substances exceeding one tonne per year per company must undergo mandatory registration with ECHA. This process requires companies to identify risks associated with their chemical substances and demonstrate effective risk management strategies. The regulation's scope extends far beyond industrial applications, encompassing chemicals used in everyday consumer products including cleaning supplies, paints, clothing, furniture, and electrical appliances, thereby affecting most companies operating within the European Union.

The regulatory framework places the burden of proof squarely on companies, requiring them to demonstrate safe usage protocols and communicate risk management measures to end users. REACH establishes distinct roles and responsibilities based on company activities: manufacturers who produce chemicals for internal use or supply to others, importers who purchase materials from outside the EU/EEA, and downstream users who handle chemicals in their industrial or professional operations. Notably, companies established outside the EU are not directly bound by REACH obligations, with compliance responsibility falling to EU-based importers or designated representatives.

A critical component of REACH involves the authorisation process for substances of very high concern (SVHCs), which aims to ensure the progressive replacement of dangerous substances with safer alternatives where technically and economically feasible options exist. This mechanism has proven remarkably effective, with the EU banning approximately 2,000 hazardous chemicals over a thirteen-year period following REACH implementation, surpassing the regulatory efforts of any other global region. The European Environmental Bureau estimates that current regulatory roadmaps will result in the prohibition of 5,000 to 7,000 additional chemicals by 2030.

The implementation of REACH raises important questions about corporate adaptation strategies and innovation responses. The regulation potentially serves as a catalyst for increased research and development investments as companies seek to transition away from hazardous chemicals or develop safer alternatives. This regulatory pressure may force firms to innovate or substitute existing inputs with more expensive alternatives, fundamentally altering production processes and cost structures. The registration database, containing detailed information about substances ranging from tartaric acid to ethanol, provides a unique opportunity to examine how regulatory compliance affects corporate innovation.

The mandatory reporting requirements under Article 117 of REACH, which requires Member States to submit comprehensive operational reports to the Commission every five

years, ensure ongoing monitoring and evaluation of the regulation's effectiveness. This systematic documentation, beginning with the first report submitted in June 2010, creates a robust framework for assessing both regulatory compliance and unintended consequences of chemical restrictions on industrial innovation and competitiveness.

OA.2 Variable Definitions

Variables included in the regressions:

- $\ln(\text{emissions}_{i,s,t}) = \ln\left(\frac{\text{emissions}_{i,s,t}}{1000} + 1\right)$ for firm i, substance s, in year t
- $\text{patents count}_{i,s,t-j}$: patent count for firm i, substance s, in year $t-j$ (lagged j years)
- $\text{policy pollution interaction}_{i,s,t} = (\text{policy post2007}_t \times \text{pollution baseline}_{i,s})$: interaction term between the post-2007 policy dummy and firm-substance-specific 2007 pollution baseline, capturing treatment intensity effects
- $\text{pollution baseline}_{i,s}$: 2007 pollution level serving as our measure of treatment intensity, varying by firm-substance combination
- policy post2007_t: post-policy dummy variable equal to 1 for years 2007–2014, capturing the general policy effect

OA.2.1 Fuzzy Matching

We employ a fuzzy matching algorithm to link companies in the EPRT with patenting companies. Our matching procedure processes 4,168 EPRT companies against 1,466 patent companies across 24 European countries. The algorithm achieves a match rate of approximately 5-8%, yielding between 200-350 high quality matches. We implement a minimum similarity score threshold of 0.8 to ensure match quality and employ country by country processing for computational efficiency. The similarity score classification is considered: *(i)* excellent (scores between 0.9-1.0) for exact matches or substring matches; *(ii)* very good (scores between 0.85-0.89) for first two words identical, or *(iii)* good (scores between 0.8-0.84) for first word identical (with additional filtering).

We convert all text to lowercase, remove accents and special characters, and standardize spacing by collapsing multiple spaces. To improve matching accuracy, we systematically remove common legal forms and business terms that do not contribute to company identification.[6]

Finally, as quality control measures, we remove single character words that provide no discriminatory value, we trim whitespace to ensure consistent formatting, we handle missing or placeholder entries (such as "-" symbols) and we preserve distinctive company specific terms

[6]Legal and business terms: gmbh, se, ag, ltd, limited, inc, corp, corporation, spa, srl, bv, nv, sa, ab, oy, as, kg, plc, ss, snc, gie, sprl, internat, enskild, firma, spółka, z, company, group, holding, international, intl, technologies, tech, solutions, systems, services, europe, european, industry, industrial, manufacturing. Connectors: co, &, and, the, a, an, and others.

that aid identification. This comprehensive matching approach ensures high quality linkages between pollution and patent databases while maintaining computational tractability across our large scale European dataset.

OA.3 Toxic Substances

- **1,2-Dichloroethane**: a chlorinated hydrocarbon that's a colorless liquid with a chloroform-like odor. It's primarily used as an intermediate in producing vinyl chloride for PVC plastic. It's toxic, flammable, and classified as a probable human carcinogen. Exposure can occur through inhalation, ingestion, or skin contact. *Products using it:* PVC pipes, vinyl siding, and other plastic products (though the compound itself is consumed during manufacturing and not present in the final product). *Production processes:* used as an intermediate in vinyl chloride production for making PVC plastics; also used as a solvent in rubber and plastic processing.

- **Anthracene**: a polycyclic aromatic hydrocarbon (PAH) consisting of three fused benzene rings. It appears as colorless to pale yellow crystals and is found in coal tar. It's used in the production of dyes, plastics, and pesticides. It can cause skin photosensitization and is a potential environmental contaminant. *Products using it:* dyes and pigments, particularly alizarin dyes used in textiles; wood preservatives; insecticides. *Production processes:* extracted from coal tar distillation; used as a precursor in manufacturing anthraquinone for dye production.

- **Atrazine**: a widely-used herbicide that inhibits photosynthesis in broadleaf weeds and grasses. It's particularly common in corn cultivation. Atrazine is controversial due to its persistence in groundwater and potential endocrine-disrupting effects in wildlife and possible human health impacts. It's been banned in the EU but remains approved in the US. *Products using it:* agricultural herbicides for corn, sorghum, and sugarcane crops; also used for weed control on golf courses and residential lawns. *Production processes*: applied directly to crops as a pre-emergent and post-emergent herbicide to control broadleaf and grassy weeds.

- **Benzene**: a simple aromatic hydrocarbon that's a colorless, highly flammable liquid with a sweet odor. It's a fundamental building block in petrochemicals and is used to make plastics, resins, synthetic fibers, and rubber. Benzene is a known human carcinogen, particularly linked to leukemia, and exposure primarily occurs through inhalation. *Products using it:* gasoline (contains small amounts); plastics like polystyrene; synthetic rubber; nylon and polyester fibers; detergents; pesticides. *Production processes:* used as a chemical feedstock to produce styrene (for plastics), cumene (for phenol and acetone), and cyclohexane (for nylon production); historically used as an industrial solvent.

- **Carbon Monoxide**: a colorless, odorless, tasteless gas (CO) produced by incomplete combustion of carbon-containing materials. It's highly toxic because it binds to hemoglobin more readily than oxygen, preventing oxygen delivery to tissues. Sources

include vehicle exhaust, faulty heating systems, and fires. It can cause headaches, dizziness, confusion, and death at high concentrations. *Products using it:* not intentionally used in consumer products, but present in cigarette smoke and vehicle exhaust. *Production processes:* used in metallurgy for reducing iron ore to iron in blast furnaces; used in synthesis gas production for making methanol and other chemicals.

- **Ethylene Oxide**: a colorless gas at room temperature with a sweet, ether-like odor. It's used extensively to sterilize medical equipment and as a chemical intermediate in producing other compounds like antifreeze. It's highly flammable and explosive, and is classified as a human carcinogen. Exposure can cause respiratory irritation and neurological effects. *Products using it:* sterilized medical devices (surgical instruments, implants, pharmaceuticals); antifreeze and polyester products made from ethylene glycol. *Production processes:* used for sterilizing heat-sensitive medical equipment and supplies; used as a chemical intermediate in producing ethylene glycol (antifreeze), polyester fibers, and detergents.

- **Fluorine and Inorganic Compounds (as HF)**: fluorine is an extremely reactive, pale yellow gas, the most electronegative element. Its inorganic compounds, particularly hydrogen fluoride (HF), are highly corrosive and toxic. HF is used in industrial processes like aluminum production, petroleum refining, and glass etching. Exposure can cause severe burns and systemic toxicity, with fluoride ions interfering with calcium metabolism. *Products using it:* aluminum products (uses cryolite flux); Teflon and other fluoropolymers; refrigerants; toothpaste and water fluoridation (controlled amounts of fluoride compounds). *Production processes:* used in aluminum smelting; petroleum refining (alkylation process); uranium enrichment; etching glass and semiconductors; producing fluorocarbons for refrigerants and propellants.

- **Hydrogen Cyanide**: a highly toxic, colorless gas or liquid with a faint almond-like odor (though not everyone can smell it). It interferes with cellular respiration by inhibiting cytochrome oxidase. It's used in industrial processes like producing plastics and pesticides. Exposure can cause rapid onset of symptoms including headache, confusion, seizures, and death. It's released during combustion of certain materials. *Products using it:* some plastics (acrylics, nylon); pesticides and fumigants; certain specialty chemicals. *Production processes:* used in producing adiponitrile (for nylon 6,6 production); making acrylic plastics and fibers; gold and silver mining (extracting precious metals from ore); fumigation of ships and buildings.

- **Methane**: the simplest hydrocarbon, a colorless, odorless gas that's the primary component of natural gas. It's produced naturally through decomposition of organic matter in anaerobic conditions and is also released from livestock, wetlands, and fossil fuel extraction. Methane is highly flammable and is a potent greenhouse gas, roughly 28-36 times more effective at trapping heat than CO2 over a 100-year period. *Products using it:* natural gas for heating and cooking; compressed natural gas (CNG) vehicle fuel; feedstock for producing hydrogen, ammonia, and methanol. *Production processes:* used as fuel in power generation; feedstock in steam reforming to produce hydrogen

and synthesis gas; raw material for producing ammonia (fertilizers), methanol, and various chemicals.

- **Naphthalene**: a polycyclic aromatic hydrocarbon consisting of two fused benzene rings. It appears as white crystalline solids with a distinctive mothball odor, in fact, it's the traditional active ingredient in mothballs. Found in coal tar and petroleum, it's used to make plastics, resins, and other chemicals. It can cause hemolytic anemia and is classified as a possible human carcinogen. *Products using it:* mothballs and deodorizer blocks; phthalic anhydride (used in plastics); dyes; synthetic resins and tanning agents. *Production processes:* sed in producing phthalic anhydride for manufacturing plasticizers, resins, and dyes; used as a chemical intermediate in making carbaryl insecticide and various surfactants.

OA.4 Discussion on Scope 1 vs Scope 3 emissions

The EPRT measure of pollution used in this paper, comes from reported releases of pollutants for a facility, so it relates to Scope 1 emissions (also known as "direct" emissions from production processes only, excluding those from electricity use). Scope 1 emissions are direct greenhouse gas emissions from sources that are owned or controlled by a company. Differently, Scope 3 emissions are indirect emissions that occur in a company's value chain, both upstream and downstream. These are emissions the company doesn't directly control but are a consequence of its activities.

In our context, it is important to acknowledge that Scope 1 emissions are generated by production processes, while Scope 3 emissions are generated by the inclusion of the substances in the final products. For example, if a firm manufacture products containing benzene, the emissions from this substance when the product is used or disposed of would be part of the Scope 3 inventory. For this reason, we have identified which are the substances among those that we are studying in this paper, that could be involved in Scope 1 emissions only or that could be part of the Scope 3 emissions also (i.e. included in the list of substances of the final product). To make this distinction between substances, we reviewed papers from the field of Industrial Ecology.

These are the substances whose levels of pollution refer to Scope 1 only. They cannot be present in the final product, therefore their pollution levels are generated during production processes only: 1,2-Dichloroethane, anthracene, atrazine, benzene, carbon monoxide, ethylene oxide, fluorine and inorganic compounds (as HF), and methane. The two substances that can also be potentially included in Scope 3 emissions are: hydrogen cyanide and naphthalene (representing 10% of the observations on patents in our sample).