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Pollution, green innovation, and firms

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Abstract

This thesis comprises three empirical studies centred around the theme of cleaning up production. All essays focus on the producers' side, as their behaviour can have a significant impact not only on labour conditions and overall social welfare but also on the environment and climate change.

The first paper in this thesis identifies and quantifies the main channels for reducing air pollution emissions from the manufacturing sector in Sweden. The results show that the main driver of declining emissions between 2007 and 2017 was improvements in emission intensities, while the composition of output actually shifted towards more pollution-intensive goods.

The second and third papers focus on green innovation and its determinants at the level of individual firms. The second paper presents a set of stylised facts about clean technology innovators in Sweden and their key firm and industry characteristics. The main finding is that patents in clean technologies by Swedish firms tend to be dominated by larger and more established firms compared to other types of patents. A simple model of innovation and firm size, proposed in the paper, suggests a mechanism that helps to explain the patterns observed in the data.

The third paper examines the impact of competition with imports of equipment for renewable energy (e.g., solar PV panels and cells or wind turbines) from China on innovation in the European Union. The results show that firms facing higher competition with imports from China substantially reduced their rate of patenting between 2005 and 2017. The adverse effect was larger for firms that patent more frequently. Furthermore, the growth in Chinese import competition reduced the likelihood of applying for a patent in the renewable energy sector.

Keywords: air pollution, green innovation, patents, import competition, manufacturing, firms.

Pollution, green innovation, and firms

Abstract

Denna avhandling består av tre empiriska studier med ett gemensamt tema – renare produktion och grön omställning. Alla uppsatser fokuserar på producenter, vars verksamhet och beslut kan ha en betydande inverkan inte bara på tillväxten, arbetsmarknaden och den allmänna sociala välfärden utan också på miljön.

Den första uppsatsen identifierar de viktigaste mekanismerna bakom minskade utsläpp av luftföroreningar från den svenska tillverkningsindustrin mellan 2007 och 2017. Resultaten visar att nedgången i utsläppsintensitet var den främsta drivkraften bakom minskade utsläppen, trots en övergång till produktionen av mer utsläppsintensiva varor.

Den andra och tredje uppsatsen studerar grön innovation. Den andra artikeln ger en översikt över de viktigaste företags- och industrispecifika faktorerna för grön innovation i Sverige. Studien finner att patent inom klimatsmart teknik från svenska företag oftast innehas av större och mer etablerade aktörer jämfört med andra typer av patent. En enkel modell för innovation och företagsstorlek föreslås i artikeln för att förklara dessa resultat.

Den tredje uppsatsen undersöker hur import av nyckelkomponenter inom förnybar energi (t.ex. solcellspaneler och -celler, vindturbiner) från Kina påverkar grön innovation i Europeiska unionen mellan 2005 och 2017. Resultaten visar att företag som utsätts för högre importkonkurrens sökte betydligt färre patent i förnybar energi. Den negativa effekten var större för företag som hade fler patent i sin portfölj. Studien visar också att ökningen av kinesisk importkonkurrens minskade sannolikheten för europeiska företag att ansöka om patent inom förnybar energi.

Nyckelord: luftföroreningar, grön innovation, patent, importkonkurrens, tillverkningssektorn, företag

Dedication

To my family.

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List of publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I. Ustyuzhanina, P. (2022). Decomposition of air pollution emissions from Swedish manufacturing. *Environmental Economics and Policy Studies*, 24(2), 195-223.

II. Karpaty, P., Ferguson, S., Norbäck, P.-J., and Persson, L. (2023). Who's doing clean tech innovation? Evidence from Swedish firms. [Manuscript]

III. Karpaty P. (2023). Import competition and environmental innovation: Evidence from the renewable energy sector in the EU. [Manuscript]

Paper I is reproduced with the permission of the publishers.

The contribution of Polina Karpaty to the papers included in this thesis was as follows:

I. I am the sole author of the paper and have contributed to all stages of its development.

II. I was responsible for merging the patent data with the registry data for Swedish firms and preparing the stylised facts. I also contributed to the development of the paper’s idea and reviewed relevant literature. I wrote various sections of the paper and collaborated with co-authors to produce the final draft.

III. I am the sole author of the paper and have contributed to all stages of its development.

1. Introduction

Air pollution and greenhouse gases emitted from industrial sites in Europe are estimated to have cost society between €277 and €433 billion in 2017, exceeding the total annual economic output of many individual Member States (EEA, 2021). However, industry can reduce its environmental impact by adopting sustainable practices and investing in clean technologies. Given that the behaviour of producers can significantly affect labour conditions, social welfare, and the environment and climate change, this doctoral thesis focuses on the challenges and decisions faced by the business sector in cleaning up production.

This thesis consists of three empirical essays sharing a common theme – cleaning up production. In the first paper, I identify and quantify the mechanisms behind the reduction in air pollution emissions from the manufacturing sector in Sweden. The second and third papers focus on green innovation and its determinants at the level of individual firms. I investigate what characteristics of firms are important for success in clean technology inventions and how increased imports of cheaper key components in renewable energy technologies affect innovators in the European Union.

The findings of this thesis have important implications for policymakers and businesses alike. By understanding the mechanisms behind the reduction in air pollution emissions and the determinants of green innovation, policymakers can design regulations more effectively. Businesses, on the other hand, can use the findings to make informed decisions about their investments in clean technologies and sustainable practices.

The remainder of this introductory chapter is organised as follows. Section 2 reviews the main building blocks of the thesis and its contribution to existing literature. A summary of each essay is given in Section 3. Finally, Section 4 concludes by discussing the main policy implications.

2. The three elements

This doctoral thesis is structured around the three pillars emphasized in its title: pollution, green innovation, and firms. These elements serve as the foundation of my doctoral research. In this section, I explore each element in detail, discussing the key concepts and findings of my thesis and highlighting its contributions to the existing literature.

2.1 Pollution

Growth in the manufacturing sector typically leads to increased production and consumption of goods. As a result, this can cause higher emissions of air pollutants such as particulate matter (PM), nitrogen oxides (NOx), sulfur dioxide (SO_2), and volatile organic compounds (VOCs). Larger concentrations of these pollutants in the air we breathe can harm our health and the environment by causing respiratory problems, contributing to smog and acid rain, and affecting productivity (Graff Zivin and Neidell, 2013; WHO, 2018). Outdated production technologies, lack of pollution control measures, or inadequate environmental regulations can further amplify the link between manufacturing sector growth and air pollution emissions. However, the growth in the manufacturing sector does not necessarily mean more smog or acid rain. There are ways to reduce the negative impact on air quality, such as adopting cleaner production technologies and implementing pollution control measures.

In the last two–three decades, manufacturing production in many large economies has become cleaner, despite output growth. This has been documented in studies of the US (Levinson, 2015; Shapiro and Walker, 2018), the EU (Brunel, 2017), Canada (Najjar and Cherniwchan, 2020), China (Cole and Zhang, 2019), Sweden (Ustyuzhanina, 2022), and a larger set of various countries (Grether et al. 2009). One way to understand what drives changes in aggregate pollution emission levels is to decompose them into components reflecting changes in industrial activities within an economy. The approach is based on the idea that changes in total pollution over time might be attributed to three mechanisms: changes in the size of the economy (scale effect), changes in the mix of industries from more pollution-intensive towards less pollution-intensive or vice versa (composition effect), and changes in emission intensities, i.e. emissions per unit of output, of individual industries (technique effect). This method was originally proposed by Grossman and Krueger (1993) and Copeland and Taylor (1994) and later formalised by Levinson (2009).

An important conclusion of previous research is that pollution intensity within manufacturing industries has been decreasing. This means that the decline in pollution from manufacturing is due to the technique effect. Even in cases where the composition effect was positive, such as in China (Cole and Zhang, 2019), the EU (Brunel, 2017), and Sweden (Ustyuzhanina, 2022), and contributed to a pollution increase from the manufacturing sector, the magnitude of the technique effect was large enough to result in an overall decrease in emissions.

The technique effect, which mainly explains the decline in manufacturing emissions of SO_2, NOx, PM_{10} and VOCs in Sweden between 2007 and 2017, is closely linked to the adoption of pollution abatement technologies. Domestic environmental regulation has shown to be an effective instrument for encouraging manufacturers to reduce their release of pollutants into the environment (Shapiro and Walker, 2018). The question remains whether firms adopt existing abatement technologies or develop new ones. Empirical evidence suggests that environmental regulations targeting local pollutants have encouraged the adoption of available techniques and equipment rather than promoting innovation. While existing technologies may become obsolete over time, innovation creates opportunities for further progress and greater reductions in abatement costs. This is particularly important for greenhouse gas emissions, where abatement technologies are not yet mature (Calel, 2020; Greaker and Popp, 2022). What factors are important for innovation in the future-oriented technologies, like renewable energy? Why do some firms innovate more than others? I discuss these and other questions related to green innovation in the remaining part of this introductory chapter.

2.2 Green innovation

Green innovation is the second pillar on which this doctoral thesis is standing. It refers to the development, adoption, and diffusion of new or improved products, processes, technologies, or practices that have positive impacts on the environment or contribute to climate change mitigation (CCM) and adaptation. Innovation is key to sustainable growth as it helps to decouple growth from natural capital exhaustion and contributes to economic development and job creation (OECD, 2011). Green innovation spans various sectors such as energy, transportation, agriculture, and manufacturing. It is widely accepted that accelerating climate change mitigation (CCM) innovation, a subset of green innovation, is essential for meeting the global net-zero emissions targets (IEA, 2020).

One way to measure innovation is to use patents and employ data from large detailed databases as PATSTAT, as in previous studies (e.g., Jaffe et al., 1993). Despite limitations such as not capturing incremental inventions or innovations outside the patent system (Moser, 2013), patents are now a standard metric in environmental innovation literature (e.g., Popp, 2002; Aghion et al., 2016; Calel, 2020). Patent data allows for disaggregation and identification of patents within specific categories and provides access to harmonized data observations over several decades.

CCM patenting has grown rapidly in recent years and outpaced patenting in other technologies. In this thesis's second and third essays, I document a fivefold increase in new CCM patents in Sweden and Europe between 2005 and 2012 followed by a substantial drop. Similar findings have been reported in previous studies (e.g., Popp et al., 2020).

The growing literature on green innovation has identified several factors that can affect innovation and patenting in clean technologies. Regulatory frameworks can shape incentives for innovation through emission standards, tax incentives, and government-supported R&D programs. The shift towards clean technologies depends on the price of energy inputs and market size, as higher prices and demand encourage innovation. Additionally, a stock of accumulated over time knowledge is an important factor (Popp, 2002; Johnstone et al., 2010; Acemoglu et al., 2012; Noailly and Smeets, 2015; Aghion et al., 2016; Calel and Dechezleprêtre, 2016; Hart, 2019). With this doctoral thesis, I contribute to this growing literature in two ways.

First, my co-authors and I explore heterogeneity among firms and identify key characteristics of individual innovators in the clean tech sector compared to other innovators. This is the research objective of the second essay. We find that clean patents are more concentrated in a small number of large established firms than other patents, at least in the case of Sweden. Our theoretical model provides a possible explanation of this finding by showing that larger firms have a greater incentive to research in clean technology as their profits decrease more compared to smaller firms when failing in the invention process.

Second, while the existing literature on the patenting of clean technologies has explored various factors that could influence a firm's decision to patent and its rate of patenting, the impact of the supply of critical components in the energy sector and competition with low-income countries' imports has not been extensively studied. In the third essay of this thesis, I examine the effects of imports from China of core manufacturing products in the renewable energy sector on clean innovation in the EU. The results suggest that European innovators were largely discouraged by Chinese import competition, leading to fewer new innovators entering the market and a decline in patenting rates and patent application probability.

2.3 Firms

The common denominator of all three studies in this thesis is firms and their behaviour. As the primary agents of innovation in any economy, firms play a crucial role in abatement and green innovation. They are key sources of environmental pollution and drivers of technological change. At the same time, firms have a significant impact on the environment and climate change mitigation through their production processes. They have the potential to drive green innovation by investing in the research and development of new, cleaner technologies and adopting more sustainable practices. They are responsible for developing new products, processes, and technologies to reduce environmental impact and promote sustainable development. By studying the actions and behaviour of individual firms, one can gain insights into the specific factors that influence invention processes in clean technologies.

Since much of the innovation that can be commercialised takes place at the level of individual firms, the research object in the second and third essays is individual firms. The studies focus on the factors that affect firms' decisions to innovate in green technologies. Although I collect data on firm-level emissions of air pollutants in the first essay, I do not study firms' behaviour directly but indirectly through changes in emissions and output at the level of narrowly defined manufacturing industries.

Defining firms as the third main element in this doctoral thesis also means using detailed firm-level data in the empirical analysis. Firm-level observations provide me with valuable information on the organisational characteristics that might correlate with the decision to pursue green innovation, such as the size and age of the firm, its corporate structure and sales value, its innovative capacity, and its contribution to the accumulated knowledge stock. As firms differ dramatically along many dimensions, even within narrowly defined industries, understanding and accounting for this heterogeneity in the empirical analysis is important, not least from the methodological perspective. Failure to do so can result in biased estimates and incorrect inference. Finally, the conclusions drawn from the analysis of detailed firm-level observations are also important for informing policymakers. This allows them to tailor policies to meet the needs and challenges of different types of firms.

3. Summary of papers

This section is a summary of the three essays that comprise the thesis.

3.1 Paper 1: Decomposition of air pollution emissions from Swedish manufacturing

Over the past few decades, Swedish manufacturing output has seen a steady increase, while emissions of key air pollutants have decreased. In the opening essay of my thesis, I examine the primary drivers behind this decline in air pollution emissions, focusing on sulfur dioxide (SO_2), nitrogen oxides (NOx), non-methane volatile compounds (VOCs), and particulate matter (PM_{10}) from Swedish manufacturing between 2007 and 2017. As our lives are directly affected by the air we breathe—pollution has serious adverse effects on both human health and productivity and labour supply (Graff Zivin and Neidell 2013; WHO 2018)—understanding the sources of the abatement is crucial to ensure that the reduction in pollution continues in a sustainable manner.

In the opening essay of my doctoral thesis, I study emissions of SO_2, PM_{10}, VOCs and NOx from the manufacturing sector in Sweden. While the sector is a significant driver of the Swedish economy, many manufacturing activities are energy- and pollution-intensive. To name one example, 40% of total SO_2 emissions in Sweden originated from manufacturing processes! Despite this, air pollution emissions fell by more than one-third between 2007 and 2017.

I use a methodology from Levinson (2009, 2015), which builds on Grossman and Krueger (1993) and Copeland and Taylor (1994), to decompose detailed data on manufacturing emissions into three mechanisms: scale, composition, and technique effects. I construct an index of emission intensities for SO_2, NOx, VOCs, and PM_{10}, similar to the Laspeyres and Paasche price indexes, to examine the contributions of these three effects to the emission reductions in Swedish manufacturing in 2007–2017.

The paper's main finding is that the composition of the Swedish manufacturing sector shifted towards pollution-intensive goods during the analysed period. Another important result is that the clean-up of Swedish manufacturing is primarily driven by the technique effect, as is the case elsewhere. However, the brown shift, or the positive composition effect, limited the scale of the clean-up in manufacturing. For instance, a reduction in SO_2 and PM_{10} emissions by 34 percent and 48 percent, respectively, corresponds to a decrease in the emissions intensity by 38 percent and 47 percent. However, if we hold both scale and technique effects constant, SO_2 and PM_{10} emissions would increase by 7 percent and 3 percent, respectively. The largest positive composition effect was for VOCs – 8 percent. A possible explanation for the brown shift might be exogenous (non-policy) reductions in the price of dirty goods, causing substitution towards such goods or income effects if policy pushes consumers towards clean goods (Hart, 2018).

Importantly, identifying the brown shift was made possible through the use of detailed data on emissions and manufacturing production in the analysis. Without this level of detail, it would be difficult to accurately capture the effects of changes in the composition and pollution intensity of manufacturing. I find that the role of the composition and technique effects may vary in terms of magnitude and sign across the most pollution-intensive manufacturing industries and pollutants. Therefore, this paper sheds light on the heterogeneity within the manufacturing sector in Sweden, which is important for policymaking and future research as it underlines the importance of data disaggregation.

3.2 Paper 2: Who's doing clean tech innovation? Evidence from Swedish firms

In the second paper, my co-authors and I utilise historical patent data and rich data on firm-level characteristics to present a set of stylised facts on the relationship between clean technology innovation and firm size, firm age, and industry and ownership characteristics. Despite the implementation of "green innovation" policies by numerous governments, there is a dearth of evidence whether the majority of green innovation is produced by small, young firms – or older, established firms. Understanding the characteristics of innovating firms is important for policymakers to effectively target their efforts towards supporting startups or promoting further innovation among established firms.

This study examines whether clean tech innovating firms in Sweden differ from other innovating firms in terms of their performance and firm-level characteristics. We propose a simple theoretical model to explain our findings.

Following the extensive literature, we use firm patenting as a measure of innovation and combine it with comprehensive firm-level data from Sweden on sales, age, ownership, employment, and industry. Our focus is on clean tech patents, a subset of green technology patents. Clean tech patents cover a wide range of low-carbon technologies aimed at mitigating climate change. Some examples include the use of renewable energy sources in electricity generation and electric energy management in vehicles. The final dataset includes over 5500 Swedish innovating firms that filed more than 70000 patents between 1998 and 2019. Of all innovating firms in the sample, 700 are clean tech innovators.

We find that patents in clean technologies by Swedish firms tend to be dominated by larger and more established firms compared to other patents. We also find that clean tech patents are more concentrated in a small number of firms than other patents.

To explain why clean tech innovation is relatively dependent on a small number of well-established firms, we propose a simple model of innovation and firm size. In the model, firms that produce carbon-intensive goods incur greater losses from a carbon tax than smaller firms. When the government raises the carbon dioxide tax, firms can invest in innovative activities resulting in clean tech inventions. The invention would reduce production-related carbon dioxide emissions and eliminate tax-related costs. We show that the incentive to innovate in clean technologies increases more for larger firms with high absent-invention profits due to the carbon emissions tax. This mechanism explains our main empirical finding that larger and more established firms dominate patenting in clean technologies by Swedish firms compared to other patent types. The incentive for undertaking R&D increases the most for large firms.

Figure 1 visualises the model's predictions in a case where both marginal benefits and marginal costs are linear. An increase in the carbon tax, from t

to $\hat{t}$, corresponds to a shift of the marginal benefit's curve upward (from MB_A to MB_C through MB_B) such that the optimal probability of success, ρ^*, increases. For large firms with $\hat{\varsigma} > \varsigma$, marginal benefits ($\text{MB}_\text{C}$) will be higher than for smaller firms (MB_B). And hence, the incentives to undertake clean tech research will be higher for larger firms than for smaller firms.

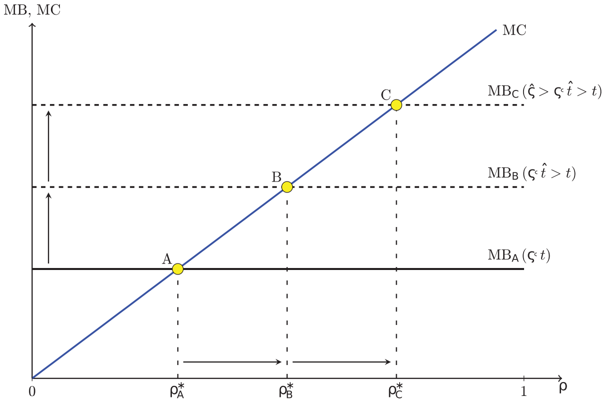

Figure 1. Visual representation of the model

In this essay, we argue that clean tech innovation occurs under very different circumstances than other innovation types, and these circumstances are well documented in the literature. These factors include a smaller accumulated knowledge stock in clean tech (Calel, 2020; Greaker and Popp, 2022) and a longer time horizon between the initial idea and commercialisation (Popp, 2016; Popp et al., 2020). These particular circumstances favour larger firms. The advantages of innovation that accrue to larger firms in the context of clean tech are arguably less pronounced for other types of innovation in general.

3.3 Paper 3: Import competition and environmental innovation: Evidence from the renewable energy sector in the EU

Between 2005 and 2017, patenting in the renewable energy (RE) sectors, such as hydropower, geothermal, solar PV, solar thermal, and wind power, grew more than ten times faster than in manufacturing within the European Union (EU). At the same time, China has become a net exporter of the core equipment for RE technology (e.g., wind and hydraulic turbines, solar PV panels and cells) and the world's largest player in the RE market. China's exports directly used in the RE sector in the EU in 2011-2012 were worth about USD 23 million, accounting for about 10% of the trade surplus, compared to only 0.5% in 2005.[1]

In the final paper of my thesis, I examine how China's rapid expansion as a leading RE manufacturer affected innovation in the EU between 2005 and 2017. The paper answers two research questions: 1) how did import competition affect the entry of new RE innovators in the EU?, and 2) what was the impact of import competition on the volume of RE innovation in the EU? The focus on the role of China is motivated by the country's dominant position in the international market for RE equipment.

Similar to the second essay, I use patents to measure innovation, but the focus is on five RE technologies: hydro, geothermal, solar PV, solar thermal, and wind power. I match data on patenting for individual innovators in all EU countries from PATSTAT 2021 with trade data from the BACI database. During this period, 4544 unique EU innovators filed more than 17000 RE patents at the European Patent Office, along with 301000 other patents.

To address potential endogeneity issues, I use the approach from Autor et al. (2013; 2020) and instrument imports of RE-related equipment from China into a technology-EU country pair with imports from China into the United States within the same RE technology.

Table 1 summarises the main findings. The impact of competition with imports from China (*CN share*) on all three outcome variables – entry rate, firm-level annual patent counts, and probability of patenting – is negative. At the technology-country level (column 1), higher competition with imports from China has prevented new innovators from entering the RE innovation market in the EU. A one standard deviation increase of the mean value of *CN share,* i.e. from 0.10 to 0.10 + 0.14, corresponds to a 14 percent decrease in the entry rate. At the level of individual innovators, an increase of the share of China in total imports of RE-related products of the same magnitude leads to a 12 percent decrease in the number of patents per year for an average firm, or by almost one patent over the five years (column 2). The likelihood of a positive decision to apply for an RE patent decreases by about 2 percent (column 3). Additionally, I find that the negative effect on the volume of patenting is larger for firms that innovate more frequently.

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[1] Source: BACI database, own calculations.

Table 1. Summary of the main results

	Entry rate	**Patent counts**	**Probability of patenting**
	IV	PPML & control function	Linear probability & instrument
	(1)	(2)	(3)
CN share	-24.802*	-1.931*	-0.256**
	(14.133)	(1.124)	(0.121)
Country-technology controls	YES	YES	YES
Firm-level controls	NO	YES	YES
Country-level controls	YES	NO	NO
Technology dummy	YES	YES	YES
Country#Year FE	YES	YES	YES
SE	clusters	bootstrap	clusters
F	14	28	28
N	995	14735	14735

I show that in the renewable energy sector, where China’s global share has increased dramatically since 2005, EU firms have suffered large reductions in the rate of technological entry and the level of patenting. This result emerges once I allow for a dynamic response to Chinese import competition to take into account that research and patenting takes time and control for technology and firm-level characteristics. The negative effect on patenting highlights the need to rethink policies in the EU's RE sector, which I discuss in more detail in Section 4.

4. Policy considerations

This doctoral thesis presents empirical evidence on how production processes can be made cleaner and less emission-intensive. The three essays in applied economics have important policy implications.

The first study's results show that while manufacturing producers can reduce the emissions intensity of existing products, they may also shift to producing more dirty goods. Therefore, policymakers need to consider the strengths of composition and technique effects to minimize the risk of countervailing changes in the industry and goods mix. Either the technique effect needs to be stronger to achieve emission reductions, or compositional changes towards dirty goods must be prevented. However, further research is needed to identify the sources of the brown shift and pollution-decreasing technique effect. If the supply side drives the brown shift, stricter regulations on firms and their emissions are necessary. On the other hand, if the pollution-decreasing technique effect is due to firms switching to another type of fuel, its size might be limited as firms may not adopt new technologies.

The historical pattern of patenting and regression analysis from the second paper suggests that firm size matters more in innovation in clean tech patents than in other innovation types. It is an open question whether policymakers should target large, established firms as they already have resources for R&D in clean technologies. In contrast, smaller firms may require more targeted policy support, such as tax incentives or subsidies, to facilitate clean tech innovation.

The third essay's findings indicate that import competition with China negatively affects renewable energy innovation in the EU. If domestic firms cannot compete with products imported from China, the returns to R&D in clean technology relative to dirty technology would fall, making research in dirty technology relatively more profitable. To achieve the net-zero emission goals, policymakers should directly tackle the primary market failure by providing R&D subsidies to improve energy- and cost-efficiency in essential products. Alternatively, policies that indirectly target research in the green sector, such as subsidies for local manufacturing of key components, may be effective. Additionally, diversifying supply chains and improving the manufacturing of products relevant to RE technologies may be useful if access to affordable inputs through imports from low-income countries is slowing down technology development.

The literature on green innovation maintains a consensus that this type of innovation differs fundamentally from others since it is potentially subject to environmental and innovation market failures. As innovators often cannot entirely appropriate knowledge and internalize all the benefits from their research due to spillovers across other firms, their expected future payoffs are lower than social returns. This appropriability problem may be more severe in clean energy technologies than in other technologies because the accumulated knowledge stock in future-oriented research is relatively small compared to mature sectors (Greaker, 2022). If private returns on clean innovation decrease relative to returns on dirty innovation (e.g., electricity generation with solar energy vs more energy-efficient coal-fired electricity generation), due to factors such as import competition with cheap equipment from China, it could worsen the problem by making clean innovation relatively less profitable and result in less innovation in clean technologies worldwide.

My hope is that this doctoral thesis will encourage further research into the areas of environmental policy, pollution abatement, and determinants of green innovation performed by individual firms, deepening our understanding of these domains and enabling policymakers to make informed decisions that foster a cleaner and more sustainable future for all.

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Popular science summary

This doctoral thesis has three main building blocks: pollution, green innovation, and firms. The first essay examines why air pollution from Sweden's manufacturing sector declined so rapidly. In the second and third essays, I focus on green innovation and what makes firms want to apply for patents in clean technologies. Finally, the third building block is firms. They are the common denominator for all three papers in the thesis. The reason for that is simple. Firms – or, taken broadly, the producer side of the economy – are the key sources of pollution and the primary agents of innovation. The business sector plays a key role in the green transition – for example, through its production processes and research in clean technologies.

I find that technological improvements played a key role in reducing emissions, even as the Swedish manufacturing sector shifted towards producing more polluting goods between 2007 and 2017.

Regarding green innovation, I show that the size of firms matters. Larger and more established firms lead the way in developing clean technologies. A simple model, outlined in the second essay, suggests a possible mechanism: when firms must pay tax on their carbon emissions, larger firms would have more incentives to invest in clean technology inventions than smaller firms because larger firms would have more profit to lose.

Finally, competition from cheaper inputs like solar PV panels and cells imported from China to the EU also matters. During the years when China started becoming a key supplier of several key components in the renewable energy sector globally, European firms' patenting shrank significantly.

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I dedicate this thesis to my family. Without them, I would not be where I am today. Even from afar, their support and encouragement have been a constant source of strength throughout the whole journey. My deepest appreciation goes to them.

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RESEARCH ARTICLE

Decomposition of air pollution emissions from Swedish manufacturing

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Abstract

Starting from the ’90s, Swedish manufacturing output has been constantly growing, while emissions of some major air pollutants have been declining. This paper decomposes manufacturing pollution emissions to identify the forces associated with the abatement. It uses a newly available dataset on actual annual emissions from Swedish manufacturing and creates an index of emission intensities for the major local air pollutants to directly estimate the technique effect for the period 2007–2017. The results suggest that the main driver of the clean-up was improvements in emission intensities, while the composition of output actually moved towards more pollution-intensive goods. In the absence of changes in scale and technique, manufacturing pollution emissions would have increased in a range between 3 (particulate matter) and 20% (non-methane volatile compounds) between 2007 and 2017.

Keywords Environmental policy · Pollution decomposition · Technique effect · Composition effect · Manufacturing

JEL Classification Q53 · Q56

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1 Introduction

Emissions of air pollutants such as sulphur dioxide (SO_2), nitrogen oxides (NO_x), non-methane volatile compounds (VOCs), and particulate matter (PM_{10}) from manufacturing have fallen steeply in North America and Western and Northern Europe over recent decades (Levinson 2009; Brunel 2017; Shapiro and Walker 2018; Najjar and Cherniwchan 2020). As our lives are directly affected by the air we breathe—pollution has serious negative effects on both human health and productivity and labour supply (Graff Zivin and Neidell 2013; WHO 2018)—understanding the sources of the abatement is crucial to ensure that a pollution decline would continue in a sustainable way. While the sources of the abatement might be due to trade liberalization or increasing demand for cleaner goods, there is a wealth of evidence that the primary driver of these emission reductions in industrialised economies has been technique effects, i.e. production processes have become cleaner, which overwhelms the positive scale effect of increasing overall economic activity. However, there is much less clarity about the role of the composition effect, i.e. the effect of changes in the range of goods produced. Hitherto, evidence on composition effects has been mixed and inconclusive. For environmental policy targeting such ambitious goals as 50% share of renewable energy sources in inland energy consumption by 2020, 50% decrease in energy intensity by 2030 compared to the year 2005, or zero net greenhouse gas emissions by 2045[1], it is important to be aware of the strengths of both composition and technique effects and the underlying mechanisms. For instance, research subsidies leading to energy-efficiency improvements and lower emissions may lower prices of energy-intensive goods, which risks leading to a countervailing composition effect.

The goal of this study is to examine the main drivers of a decline in air pollution emissions from Swedish manufacturing between the years 2007 and 2017. For this, I use detailed data on manufacturing emissions to air and decompose them into three mechanisms: scale, composition, and technique effects. Taking Grossman and Krueger (1993) and Copeland and Taylor (1994) as the starting point and following the decomposition approach as in Levinson (2009, 2015), I create an index of emissions intensities for SO_2, NO_x, VOCs and PM_{10}—analogous to a Laspeyres and Paasche price indexes—to explore the contribution of these three effects to the emission reductions in Swedish manufacturing during the period 2007–2017.

The focus on manufacturing is due to several reasons. Historically, the sector has been an important driver of the Swedish economy. In the recent decade, almost one-third of total sales and one-fourth of gross value-added came solely from manufacturing production. At the same time, many manufacturing activities are energy- and pollution-intensive. Between 2007 and 2017, the sector alone accounted for almost 40% of total SO_2 emissions in Sweden on average. Although the contribution

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[1] All targets are set for Sweden. Sources: Sweden's Climate Act and Climate Policy Framework, https://www.swedishepa.se/Environmental-objectives-and-cooperation/Swedish-environmental-work/Work-areas/Climate/Climate-Act-and-Climate-policy-framework-/; Sweden's energy and climate goals, https://www.energimyndigheten.se/klimat--miljo/sveriges-energi--och-klimatmal/.

of NO_x, VOCs and PM_{10} from manufacturing to the aggregate emissions is modest (14% on average during the studied period), the reductions in emissions were remarkably high—30% on average, larger than for agriculture or other industrial sectors. Being pollution-intensive, the manufacturing sector is directly targeted by environmental policies that aim at improving energy efficiency, increasing the share of renewables in energy consumption and reducing industrial emissions, where among the most important are the EU legislation on industrial emissions[2] and the Swedish Environmental code. In a small open economy as Sweden, manufacturers, which are often exporters of both final and intermediate goods and owned by multinational corporations, are largely exposed to competition in the world market and sensitive to unexpected price changes (Tillväxtverket 2018). Manufacturing producers should both comply with stringent environmental regulations and be competitive. By quantifying the scale, composition and technique effects, one can better understand how the manufacturing sector as a whole responded to these different forces.

The study relates to two strands of literature. First, the paper contributes to a growing empirical literature examining the sources of the emission reductions, mainly in the manufacturing sector, with the method of statistical decomposition (Grether et al. 2009; Levinson 2009, 2015; Brunel 2017; Shapiro and Walker 2018; Cole and Zhang 2019; Najjar and Cherniwchan 2020). I contribute to the literature by applying and adapting the state-of-the-art methodology and very recent data disaggregated at the four-digit level to a small open economy, Sweden. Regarding the methodology, for my measure of manufacturing output, I use data on the value of manufacturing production, which excludes costs for goods that were bought and resold without being adjusted. A more common approach in this literature—to use sales as a measure of output (Levinson 2009, 2015; Cole and Zhang 2019; Najjar and Cherniwchan 2020)—would leave out the importance of trade for a small open economy such as Sweden. Regarding data, I study actual annual emissions for Swedish manufacturing during a very recent period, 2007–2017. It allows me to estimate the technique effect directly, as opposed to early studies (Levinson 2009; Brunel 2017) where it is calculated as a residual. Finally, I complement the literature with additional evidence on the presence of a brown shift—a persistent shift towards more dirty production, which offsets a clean-up of manufacturing.

Second, the paper relates to a large empirical literature examining the relationship between environmental policies of different character and industry- or firm-level environmental outcomes (e.g., Greenstone 2003; Millock and Nauges 2006; Gamper-Rabindran 2009; Gibson 2019; Najjar and Cherniwchan 2020), and to few papers examining some particular policy instruments in Sweden (Sterner and Turnheim 2009; Åström et al. 2017). While these papers focus on evaluating specific policies, often establishing a causal link between a change in regulation and environmental performance, the goal of my paper is to examine how the manufacturing

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[2] EU Directive 2010/75/EU and its precursor Directive 2008/1/EC. Following the regulation, plants performing certain industrial activities are required to obtain a production permit that is based on the use of best available techniques. Producers that fail to comply will be subject to penalties.

sector in Sweden evolved—in terms of production and air pollution emissions—during the very recent period, 2007–2017, when various regulations were in place.[3]

The main finding of the paper is that the composition of the Swedish manufacturing sector switched towards pollution-intensive goods between the years 2007 and 2017. I show that holding both scale and technique effect constant, emissions of SO_2 and VOCs would increase by 7 and 20%, respectively. At the same time, the results indicate that, as expected, the clean-up of Swedish manufacturing appears to be primarily driven as elsewhere by the technique effect. For example, a fall in SO_2 and PM_{10} emissions by 34 and 48 per cent corresponds to a decrease in the emissions intensity by 39 and 25%, respectively. Also, the findings suggest that the role of the composition and technique effects might differ in terms of sign and magnitude both across the most pollution-intensive manufacturing industries and pollutants.

The rest of this paper proceeds as follows. Section 2 describes the relevant literature and discusses the possible sources of the brown shift. In Sect. 3, I describe the data sources and the decomposition method. The results of the decomposition analysis are in Sect. 4. Section 5 discusses the robustness of the findings, and Sect. 6 concludes.

2 Literature review and motivation

In this section, I review two strands of the existing literature to which I contribute in this paper. First, I discuss the relevant empirical studies examining the relationship between various environmental policies and industry- or firm-level environmental outcomes. Mainly, for the manufacturing sector. Second, I review the literature that employs the same decomposition method as in this paper. Also, I discuss the importance of the higher data disaggregation and possible mechanisms that might explain positive (i.e., pollution-increasing) compositional changes that were found in some recent studies.

2.1 Environmental policies and environmental outcomes

As the paper examines changes in manufacturing emissions during the period when several regulations that target industrial emissions to the air have been implemented or were already in place, it is important to understand the potential of environmental policies with a similar design to reduce both emissions and emission intensities and how industries at the aggregate level or firms might react to such regulations.

There is a wealth of evidence that regulations setting emissions standards for the major air pollutants leads to lower emissions. For instance, it has been shown that the US Clean Air Act (CAA), which is probably one of the most studied

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[3] Apart from the aforementioned legislation on industrial emissions, the EU directives on national ceilings to reduce air pollution, the EU Emissions Trading System (ETS), the Swedish SO_2 tax and NO_x charge are some other important environmental regulations and instruments that were in place between 2007 and 2017. See also Sect. A.4 in the Appendix.

environmental policies, is a powerful tool in reductions of Ozone, SO_2 and PM_{10} emissions (e.g., Henderson 1996; Greenstone 2003; Gamper-Rabindran 2009; Gibson 2019). To mention some examples, Gamper-Rabindran (2009) shows that emissions of VOCs from the chemical industry decreased by 21% in 1988-2001; Gibson (2019) finds that PM_{10} from manufacturing plants fell by between 33 and 38% relative to non-regulated plants between 1992 and 2014. However, the adaptation to a more stringent environmental regulation does not necessarily go through adopting cleaner technologies. Instead, an environmental policy can encourage manufacturing producers to reallocate dirty production to less regulated territories or to substitute air emissions with water emissions. In the case of the CAA, almost one-fourth of reductions in PM_{10} was eliminated by such leakage. Another possible mechanism that might explain the reduction in aggregate emissions—a decline in manufacturing output and exit of dirty producers. A policy might lead to overall improvements in emission intensities, while at the same time forcing producers to decrease production, rather than encouraging them to adopt "green" technologies. Najjar and Cherniwchan (2020) find that a decline in manufacturing $PM_{2.5}$ emissions, caused by a comprehensive air pollution regulation in Canada in 2004–2010, was primarily due to a decrease in production, rather than technological improvements.[4]

Another policy instrument that might have a positive effect on both reduction in emissions and emission intensities is an environmental tax. Two such taxes have been in place in Sweden for almost three decades now: SO_2 tax, which is based on the sulphur content of fuels during combustion, and NO_x charge combined with refund payments, applied to all boilers that produce energy above a certain annual threshold. Surprisingly, very few papers look at the role of such instruments in encouraging manufacturers to pollute less and abate more. Sterner and Turnheim (2009) show that the Swedish NO_x tax with refund system pushes plants to abate but they do not provide any evidence on the effect on emissions. Åström et al. (2017) look jointly at multiple SO_2 policy instruments between 1990 and 2012 and find that limiting the sulphur content in fuel was associated with lower SO_2 emissions but the paper does not provide a direct estimate of the tax's effectiveness. In general, a shift to fuels with lower sulphur content has been considered as a major driver in SO_2 reductions in the industrial processes in Sweden (Naturvårdsverket 2015).[5] In the French context, the tax on air pollutants (SO_2 and VOCs are among them) was associated with lower pollution levels in the chemical, coke and iron and steel industries between 1990 and 1998 (Millock and Nauges 2006) but the particular mechanisms of these reductions are not evaluated.

I add to this large heterogeneous literature by providing descriptive evidence of how the manufacturing sector taking as a whole developed—in terms of its

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[4] The evaluation of this policy is of particular interest as its design is very similar to the EU's policies on industrial emissions that were in place during the studied period in my paper.

[5] Several papers find that under the EU ETS firms switched to a "greener" type of fuel, for example, from coal and oil to gas (Ellerman and McGuinness 2008; Wagner et al. 2014). Although the EU ETS targets CO_2 emissions and these studies do not provide evidence for emissions of local pollutants, there might be spillover effects. For example, shifting to another type of fuel to cut on CO_2 emissions might also reduce emissions of SO_2 or VOCs.

production and air pollution emissions—when multiple environmental policies were in place.

2.2 Sources of emission reductions in manufacturing

My paper contributes to a growing empirical literature examining the sources of the emission reductions in the manufacturing sector. In particular, it complements the literature employing a statistical decomposition method to examine changes in air emissions and emission intensities. This strand of literature has as its starting point the idea that changes in pollution emissions over time can be decomposed into three channels: scale, composition, or technique effects (Grossman and Krueger 1993; Copeland and Taylor 1994). That is, a decline in emissions can be due to a decrease in production (scale), changes in the production structure towards cleaner goods (composition), or improvements in emission intensities (technique). In the last decade, the Levinson approach (Levinson 2009, 2015) that relies on creating an index of emission intensities similar to the Laspeyres or Paasche index has been widely implemented in the environment-related context in empirical studies with industrial data at different levels of aggregation. Overall, the main conclusion is that manufacturing production becomes clear, despite output growth. In the United States, manufacturing emissions of major regulated air pollutants—SO_2, NO_x, VOCs, and PM—fell by more than 50% during the period 1990–2008 (Levinson 2015; Shapiro and Walker 2018). Within the EU, manufacturing emissions of SO_2 decreased by almost 60 percent and NO_2 and VOCs emissions—by approximately 25 percent between 1995 and 2008 (Brunel 2017). In Canada, NO_x, CO, VOCs and $PM_{2.5}$ emission intensities from manufacturing fell by between 41 and 70% during the period 1992–2005 (Najjar and Cherniwchan 2020). A similar pattern has been observed even outside of North America and the EU. Grether et al. (2009) find that aggregate emissions of SO_2 from manufacturing in more than 60 countries fell by 10% in the ’90s, despite an increase in production.[6] In China, SO_2 emissions from manufacturing increased by 51 percent, while the sector grew by more than 600 percent between 2003 and 2015 (Cole and Zhang 2019). I add to this literature by providing empirical evidence for such a small open economy as Sweden where the manufacturing sector is exposed to competition in the world market, sensitive to unexpected price changes and should comply with various environmental regulations.

In recent years, the methodology has also been applied to greenhouse gas emissions (LaPlue and Erickson 2020; Rottner and von Graevenitz 2021; Brunel and Levinson 2021). Overall, they find that the technique effect plays a major role in the reductions of carbon emissions.[7]

As recognized in this literature, the level of sectoral disaggregation in data is crucial. A higher level of aggregation would assign within-industry changes in

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[6] Grether et al. (2009) use a slightly different decomposition method.

[7] Löfgren and Muller (2010) do an accounting exercise for Swedish CO_2 emissions for the period 1993-2006 but use another methodology. They find that fuel substitution was an important driver in reducing aggregate carbon emissions for the industrial and business sectors.

composition to the technique effect. When more aggregated data is used composition effects are likely to be missed. In the extreme case, when there is only one large manufacturing sector it would not be possible to pin down any changes in the compositional mix at all. Thus, to quantify both composition and technique effects most accurately, it is important to build the analysis on the data that takes into account heterogeneity in emission intensities across smaller sub-industries within larger industries.[8] Environment-related data at lower levels of aggregation are scarce as it is often not collected or monitored directly, but estimated and reported at the national or sectoral levels (Naturvårdsverket 2015). For these reasons, for example, Levinson (2009) and Brunel (2017) use US emission intensities for one single year, 1987, and calculate the technique effect as a residual. Because I use detailed data on actual emission intensities, in addition to taking us closer to the "true" values of the composition and technique effects, it allows estimating the technique effect directly.

2.3 Why can the brown shift occur?

In a partial-equilibrium framework, Copeland and Taylor (2005) showed that if pollution reductions are policy-driven, then the more stringent environmental policy would affect emissions not only through cleaner techniques but also through a compositional shift towards cleaner goods, i.e., both effects are negative. However, from the aforementioned studies à la Levinson (2009), the results regarding technique and composition effects for air pollutants are contrasting: technique effects are large and negative, whereas composition effects are generally small. In some cases, composition moves towards less polluting goods, but only to a limited extent (see, e.g., Grether et al. 2009; Shapiro and Walker 2018; Najjar and Cherniwchan 2020). In other cases, composition effects are found to increase emissions (see, e.g., Brunel 2017; Cole and Zhang 2019). A positive composition effect—or a brown shift, a shift towards more dirty production—might be present in CO_2 emissions, too. Barrows and Ollivier (2018) find that Indian manufacturers moved towards more dirty products between 1991 and 2010: firms became dirtier overall, even though the technique effect at the industry level was negative.

What are the mechanisms that might explain the brown shift? Regarding the technique effect, it is more and more clear that this is driven by improved technology rather than, for instance, offshoring of pollution. The pollution haven (or pollution offshoring) hypothesis links decisions made by firms in pollution-intensive industries to trade with countries that have weaker environmental regulations (or to outsource dirty intermediate inputs from such countries) due to trade liberalization. However, empirical investigations have delivered little or no support for this idea (Grossman and Krueger 1993; Kahn 2003; Levinson and Taylor 2008; Cave and Blomquist 2008; Brunel 2017; see also Cherniwchan et al. (2017) for an overview). My analysis adds to this evidence by showing that the share of the

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[8] Recently, several authors have developed and applied pollution decomposition at the firm-, plant, and product-level. See Martin (2011), Cherniwchan et al. (2017), Barrows and Ollivier (2018), Shapiro and Walker (2018).

pollution-intensive industries in the total value of manufacturing output increased over time and, therefore, pollution offshoring was unlikely to be a problem for the Swedish manufacturing sector between 2007 and 2017.

A possible explanation for the brown shift is the presence of strategic environmental policies, i.e., countries may deliberately skew environmental policy to favour certain pollution-intensive industries (Barrett 1994; Ulph and Ulph 1996; Greaker 2003). That might be the case for some protectionistic policy decisions in the European Union (e.g., Miravete et al. (2018)) but there is no reason to expect systematic changes in one specific direction. If policy pushes consumers towards clean goods, the brown shift might be driven either by exogenous (non-policy) reductions in the price of dirty goods causing substitution towards such goods, or by income effects, i.e. that household demand shifts towards pollution-intensive goods such as large and powerful cars and passenger air travel as incomes increase, as suggested by Hart (2018). More evidence on this question could be found if we studied changes in the relative prices of dirty and clean goods, as well as quantities.

To sum up, the findings from the empirical literature on the effects of environmental regulations imposing air quality standards suggest that such policies might lead to lower aggregate emissions but not necessarily to lower emission intensities at the firm- or plant-level. They might also encourage abatement—for instance, to switch to another type of fuel. At the industry level, a clean-up in manufacturing emissions is often driven by improvements in emission intensities but the role of compositional changes is ambiguous. Importantly, the estimated magnitude of both technique and composition effects depends on the level of disaggregation in data—the more detailed data takes us closer to the "true" values of both technique and composition effects.

3 Methods and data

To decompose manufacturing emissions and study the potential sources of the manufacturing abatement, I take as my starting point Grossman and Krueger (1993) and Copeland and Taylor (1994) and follow Levinson (2009, 2015). In this section, I briefly describe the methodology, data sources and the main issues that might arise.

3.1 Decomposition of pollution emissions

The approach is based on the idea that changes in total pollution might be assigned to three mechanisms: changes in the overall size of the economy (scale effect), changes in the mix of sectors—-from towards less pollution-intensive industries (composition effect), and changes in emission intensities of individual industries created by changes in the technologies used in production and abatement (technique effect). Put formally, the total amount of pollution from manufacturing, denoted by P, can be written as

$$P = \sum_i p_i = V \sum_i \frac{v_i}{V}\frac{p_i}{v_i} = V \sum_i \theta_i z_i \tag{1}$$

where $i = 1, \dots, n$ indexes manufacturing industries, V is the total manufacturing output, θ_i is each industry's share in total output ($\theta_i = v_i/V$), and z_i is each industry's emissions coefficient measured as the amount of pollution per monetary value of output in industry i ($z_i = p_i/v_i$). That is, total manufacturing pollution, P, equals the sum of pollution from each manufacturing industry, p_i. Alternatively, manufacturing pollution can be written as the total value of produced manufacturing output, multiplied by the sum of a product of each industry's share in total output, θ_i, and its emission intensity, z_i.

In vector notation, Eq. (1) takes form

$$P = V\boldsymbol{\theta}'\boldsymbol{z} \tag{2}$$

where $\boldsymbol{\theta}$ and $\boldsymbol{z}$ are $n \times 1$ vectors containing the output shares of each of n industries and their emissions intensities, respectively.

Totally differentiate equation (2) to obtain

$$dP = \boldsymbol{\theta}'\boldsymbol{z}dV + V\boldsymbol{z}'d\boldsymbol{\theta} + V\boldsymbol{\theta}'d\boldsymbol{z}. \tag{3}$$

When the total pollution is decomposed as given in (3), the three terms on the right-hand side have a nice interpretation as three main channels, or effects, that determine the change in the total pollution over time (dP): scale, composition and technique effects.

3.2 Data

To estimate how much of change in the total pollution over time can be attributed to each of the effects in (3), I need four time series: (1) data on manufacturing emissions for one or several air pollutants, P; (2) gross value of output from manufacturing, V; (3) each industry's contribution to output, θ_i; (4) each industry's emission intensities, z_i.

I rely on two main data sources. First, data on each four-digit industry's contribution to the total manufacturing output is taken from Statistics Sweden. As a measure of output, I use the variable "Production value", which is a sum of net sales, other operating income and changes in inventory, excluding costs for goods that are bought and sold without being processed. I adjust for inflation using the sector-specific producer price index (PPI) from Statistics Sweden. Second, to calculate each industry's emission intensities and the total emissions of SO_2, NO_x, PM_{10} and non-methane VOCs[9], I use data on actual annual emissions from the newly-available Swedish Pollutant Release and Transfer Register (PRTR). Originally, the data is reported at the plant-level which I aggregate to the four-digit level to combine with

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[9] In the Appendix, there are also results for CO_2 available, although emissions of greenhouse gases are outside of the scope of this paper.

data on manufacturing output. The study covers the period from 2007 to 2017 and includes the whole manufacturing sector.

To my knowledge, data from the Swedish PRTR has not previously been used in economic studies. The facilities listed in the Swedish PRTR are those that perform activities that (1) require environmental permits under the Ordinance (1998:899) concerning Environmentally Hazardous Activities and Protection of Public Health, or (2) covered by the EU Regulation 166/2006 on the European PRTR.[10] The Swedish PRTR includes emissions both to air and water and applies to more than 70 chemicals. Currently, there are more than 7 000 facilities that have to report their emissions to the PRTR. The reporting thresholds for the pollutants included in this study are given in Table A.5. The data on pollution emissions at the four-digit level is aggregated from emissions reported by 431 manufacturing plants. Although the register includes only a small share of Swedish firms, the reporting thresholds were set in such a way that the register would cover at least 90% of the total mass emissions for each specific pollutant (Skårman et al. 2019). The reporting threshold is an important limitation of the data: it allows calculating emission intensities for the most pollution-intensive four-digit industries but those industries that are relatively clean are represented poorly in the PRTR. To evaluate PRTR accuracy, I compare it to data on air pollution emissions from manufacturing at the two-digit level. The data is obtained from the Air Environmental Accounts (AEA) and administrated by Statistics Sweden. Air pollution data in the AEA is a combination of collected and estimated emissions, and it is reported at the national and sectoral levels (Naturvårdsverket 2015). Although these two datasets do differ in values of aggregate emissions, the correlation between them, estimated as regression of log emissions from the PRTR on log emissions from the AEA controlling for year fixed effects, is close to unity for SO_2, NO_x and VOCs.[11] Thus, the results for separate two-digits industries should be interpreted keeping this limitation in mind as those manufacturers that emit relatively little are underrepresented in the sample employed in this study. Another concern with the PRTR data is the fact that it is self-reported, and, therefore, there is a possibility for a measurement error. It is, however, unlikely that the error is systematic as (1) an obligation to report emission is unaffected by reported emissions, and (2) the reported emissions should be reviewed by the permitting authority. For descriptive statistics and details on data collection and data management, see the Appendix (Table 7).

Table 1 lists five most pollution-intensive four-digit industries for two of four pollutants—SO_2 and NO_x. There is large heterogeneity in emission intensities not only across two-digit manufacturing industries but, most importantly, within each of them. For two other pollutants, VOCs and PM_{10}, the picture is very much alike. For instance, there is a large difference between SO_2 and NO_x emission intensities

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[10] In fact, the Swedish thresholds for NO_x and PM_{10} are even lower than the thresholds in the European PRTR.

[11] The estimated coefficient for $\log(SO_2)$ is 1.609 (t-statistic = 9.57), for $\log(NO_x)$—1.586 (5.80), for $\log(PM_{10})$—2.381 (3.76) and for log(VOCs)—0.961 (6.75). The coefficients are estimated with OLS with year fixed effects and standard errors clustered at the two-digit industry level.

Table 1 Top-5 pollution-intensive industries, SO_2 and NO_x

	SO_2		NO_x	
	(1)	(2)	(3)	(4)
	Industry	Intensity	Industry	Intensity
1	Pulp, 17.11	107.20	Cement, lime, plaster, 23.51-23.52	634.47
2	Abrasive products, 23.91-23.99	44.92	Pulp, 17.11	222.54
3	Paper, 17.12	33.95	Paper, 17.12	119.25
4	Glass, 23.11-23.13	31.43	Glass, 23.11-23.13	58.93
5	Iron, steel, ferro-alloys, 24.10	29.55	Abrasive products, 23.91-23.99	40.84

Table reports average emission intensities for SO_2 and NO_x in tons per bln SEK (columns 2 and 4) in descending order. The industry codes in columns 2 and 4 are given under the SNI2007 classification: “Manufacture of pulp”—17.11, “Manufacture of paper”—17.12, “Manufacture of glass” - 23.11-23.13, “Manufacture of cement, lime and plaster”—23.51-23.52, “Manufacture of abrasive products and non-metallic mineral products”—23.91-23.99, “Manufacture of iron, steel, ferro-alloys”—24.10

of “Manufacture of pulp” and “Manufacture of paper”, although both industries are parts of the same two-digit industry “Manufacture of pulp, paper and paperboard”. The numbers in Table 1 highlight the importance of employing data on emissions intensities at the most disaggregated level possible to account for heterogeneity and estimate the changes in techniques and compositions more precise.

3.3 Index issues: Laspeyres and Paasche

Most decomposition analyses of pollution and energy use falls into two categories: index and structural decomposition analysis (IDA and SDA, respectively). While the former relies on country- or industry-level data, the latter combines it with data from input–output tables (see, e.g., Hoekstra and Van den Bergh (2003) or de Boer and Rodrigues (2020) for an overview). In this study, I employ on the IDA and use the analogues of the additive Laspeyres and Paasche indexes in the environment-related context. Both of them leave a residual term, which tends to be larger when the more aggregated data are used. Another possible decomposition approach is to use the log-mean Divisia index (LMDI).[12] It is based on the concept of logarithmic change over time, while both the Laspeyres’- or Paasche’s-type index measures the percentage change over time, using weights based on values in a base year. Compared to the Laspeyres’- and Paasche’s-type index, the LMD index does not leave a residual term. However, the caveat of the method is its sensitivity to a substantially large number of zeroes in the data. Because I use actual emissions reported by manufacturing plants that emit above the thresholds and aggregate it the level of four-digit manufacturing sub-industries, the number of zeroes in the dataset is indeed large. It

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[12] See, for example, Ang (2004) for a methodological overview; and González et al. (2014)—for (one of many) empirical applications.

makes the LMDI method less suitable for this study. As a robustness test, I do the same analysis with the LMD index and more aggregated data and find very similar qualitatively results.

The data I use allow me to directly assess the technique effect rather than indirectly project each industry's emission using fixed industry-specific values of pollution intensities as in the early studies (Levinson 2009; Brunel 2017). That is, the paper estimates the changes in emission intensities for each manufacturing industry directly on a year-by-year basis, holding its composition constant. For each pollutant, I calculate an index of emission intensity similar to a Laspeyres'- and Paasche's-type index with the individual industries' emissions instead of prices (I_L and I_P, respectively) as follows:

$$I_L = \frac{\sum_{i=1}^{n} z_i^{(t)} v_i^{(0)}}{\sum_{i=1}^{n} z_i^{(0)} v_i^{(0)}} \times 100 \tag{4}$$

$$I_P = \frac{\sum_{i=1}^{n} z_i^{(t)} v_i^{(t)}}{\sum_{i=1}^{n} z_i^{(0)} v_i^{(t)}} \times 100, \tag{5}$$

where $z_i^{(t)}$ is emission intensity for industry i in year t, $z_i^{(0)}$ and $v_i^{(0)}$ are emission intensity and output for industry i, respectively, in the first year.

In its traditional context with prices and quantities, the Laspeyres index is upward-biased and tends to overstate inflation, whereas the Paasche index tends to understate inflation because it uses current-period quantity weights that already reflects changes in consumption due to price changes. Similarly, in the pollution context, the Laspeyres index might overstate the technique effect, while the Paasche index might understate it due to composition changes over the period. By calculating both the Laspeyres'- and Paasche's-type index, I put bounds on the degree to which the technique effect might be over- or underestimated.

4 Results

I take Eqs. 4 and 5 directly to the data and present the results in this section. I find a clear brown shift for the manufacturing sector as a whole but I also show that there is vast heterogeneity across manufacturing industries.

4.1 Results for the manufacturing sector

Table 2 shows the Laspeyres and Paasche indexes of emission intensity for each air pollutant for the period between 2007 and 2017. These are the direct estimates of the technique effect for the Swedish manufacturing sector. The emission intensity of PM_{10} decreased the most compared to other pollutants. It fell to 0.527 (−47.3%) of its value in the year 2007 by the Laspeyeres index or to 0.488 (−51.2%) by the

Table 2 Indexes of emission intensities, 2007-2017

Pollutant	Laspeyres	Paasche
NO_x	0.906	0.842
PM_{10}	0.527	0.488
SO_2	0.625	0.577
VOCs	0.789	0.662

Paasche index. The indexes for SO_2 and VOCs fell within a similar range, while the NO_x emission intensity experienced the smallest decline among all other pollutants—it decreased to 0.906 by the Laspeyres index and 0.842 by the Paasche index.

The reductions of SO_2 and PM_{10} emission intensities appear to be the largest. The results of the decomposition into the scale, composition and technique effects are in Table 3. Figure 1 plots the decomposition for all four pollutants with the Laspeyres-type index over time (similar graphs for the Paasche index are in the Appendix).

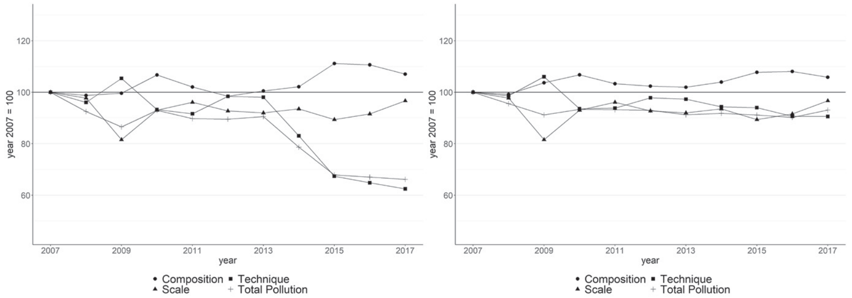
Aggregate emissions of SO_2 and PM_{10} decreased by 34 and 48%, respectively, between 2007 and 2017, while a decline in VOCs and NO_x was more modest—less than 10%. As the period in the analysis includes the global financial crisis and the Great Recession, the growth in the manufacturing (inflation-adjusted) production was just below zero, −3%. For all pollutants except for VOCs, the line that depicts the technique effect declines almost as much as actual pollution towards the end of the period. In fact, for PM_{10} emissions, the pollution reduction is almost entirely attributed to the changes in emission intensity. For VOCs and SO_2 emissions, for a large part of the studied period, the line depicting the technique effect is below the line depicting the change in aggregate pollution, indicating that, in the absence of any other effect, the overall reduction in these two air pollutants would be even larger. For instance, for SO_2, it would be 37% over the period.

The most striking finding is a positive composition effect: the line that illustrates changes in composition is above the scale effect line for all four pollutants during

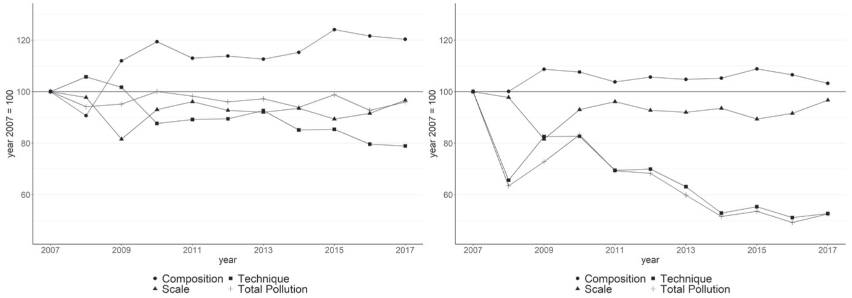
Table 3 Decomposition of Swedish manufacturing emissions, 2007–2017

	Δ Total pollution	Scale	Laspeyres		Paasche	
			Composition	Technique	Composition	Technique
	(1)	(2)	(3)	(4)	(5)	(6)
NO_x	−0.069	−0.033	0.058	−0.094	0.122	−0.158
PM_{10}	−0.475	−0.033	0.032	−0.473	0.070	−0.512
SO_2	−0.338	−0.033	0.070	−0.375	0.118	−0.423
VOCs	−0.041	−0.033	0.203	−0.211	0.331	−0.338

Table reports estimates from a decomposition of the change in air pollution intensity of the Swedish manufacturing sector between 2007 and 2017. The industries are defined as four-digit codes under the NACE Rev. 2 classification. Column 1 reports the percentage change in aggregate emissions from the manufacturing sector compared to the year 2007. The aggregate pollution is decomposed into the scale (column 2), composition and technique effects using the Laspeyres'-type index (columns 3 and 4) and the Paasche's-type index (columns 5 and 6). Each row reports estimates for a different air pollutant



(a) SO_2 **(b)** NO_x



(c) VOCs **(d)** PM_{10}

Fig. 1 Decomposition of air pollution emissions from Swedish manufacturing, 2007-2017. *Notes:* The technique effect is calculated by taking the percentage change in a Laspeyres'-type index as in equation (4). The composition effect is calculated as the difference between the change in the aggregate pollution, the scale effect and the technique effect. Values are normalized to 100 in 2007

almost the entire period. The interpretation is simple, although unexpected: the mix of four-digit industries within the whole manufacturing sector changed in such a way that it moved towards pollution-intensive goods. Holding both scale and technique effects constant, the changes in composition alone would increase SO_2, PM_{10} and NO_x emissions in a range between 3 and 7%. The largest pollution-increasing composition effect is for VOCs: in the absence of any other effect, emissions of this group of pollutants would rise by 20% compared to the level of the year 2007. As shown in Table 3, both the Laspeyres and Paasche indexes captured the brown shift for all four pollutants.

The decomposition analysis per se does not allow for causal inference: it cannot answer what particular policy determined the changes in technique and composition of manufacturing. But with regard to the brown shift, some points are worth mentioning. First, to adjust for price fluctuations, I deflated the data using the sector-specific PPI. The positive composition effect is, therefore, not a result of price changes. Second, the results might be driven by one or several pollution-intensive industries. But the combination of a positive composition effect and negative technique effect persists even when I remove the most pollution-intensive industries (see Table 9 in the Appendix). Another concern is that I use the production value measured in monetary terms, which might over- or underestimate the real growth in produced quantity in a particular manufacturing industry. It is especially relevant for “Manufacture of coke and refined petroleum products”. Its share doubled between 2007 and 2017.[13] In fact, the increase in the volume produced in this industry was slightly volatile but modest during the period.[14] However, when I drop this industry from the sample it does not affect the results qualitatively: for SO_2 emissions, the technique effect is −0.347 and the composition effect is +0.061, computed with the Laspeyres index.

4.2 Heterogeneity within Swedish manufacturing

The results of the decomposition summarized in Table 3 delivers an important message: the reductions of manufacturing pollution emissions were due to the pollution-decreasing technique effect but the pollution-increasing composition effect limited the clean-up of the sector as a whole. But within the manufacturing sector, there is large heterogeneity, both in terms of the contribution of each sub-industry to the gross emissions and the sectoral output. In fact, in 2017, the share of the most pollution-intensive industries in the gross manufacturing emissions was more than 80% for all four pollutants and above 90% for SO_2 and VOCs.[15] But taking together, they contribute to approximately 40% of the gross manufacturing output (in 2017).

As the pollution-intensive industries contribute the most to the gross manufacturing emissions, it is worth looking closer at their technique and composition effects. These are listed in Table 4. Clearly, these industries evolved differently between 2007 and 2017—the calculated changes in emission intensities vary both in sign and in magnitude. They also differ from the technique effects calculated for the whole manufacturing sector. For instance, the technique effects for “Manufacture of paper and paper products” (NACE code 17) for SO_2 and PM_{10} are very similar to the values from Table 3 but for NO_x—the technique effect is much larger in magnitude. Furthermore, it appears that the technique effect for VOCs was positive, i.e., emission intensities of VOCs increased over time and contributed to more pollution. Similarly for “Manufacture of basic metals” (NACE code 24)—the technique effect calculated for PM_{10} emissions indicates no presence of technological improvements in this manufacturing industry. For SO_2 and NO_x, it has the negative sign but the magnitude is very different: it is lower for the former and much larger for the latter. The role of the composition effect differs, too.

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[13] The share of the group of industries from 19.10 to 20.17 under the NACE Rev. 2 classification in the total deflated value of production increased from 0.0463 to 0.105 over the period.

[14] Own calculations based on the Industrial Production Index for the sector “Manufacture of coke and refined petroleum products” from Statistics Sweden.

[15] The most pollution-intensive two-digit industries are different for different pollutants. For SO_2, PM_{10} and NO_x, these are “Manufacture of paper and paper products” and “Printing and reproduction of recorded media” (NACE codes 17–18), “Manufacture of other non-metallic mineral products” (NACE code 23), “Manufacture of basic metals” (NACE code 24), “Manufacture of coke and refined petroleum products”, “Manufacture of chemicals and chemical products” and “Manufacture of basic pharmaceutical products and pharmaceutical preparations” (NACE codes 19–21). For VOCs, it is also “Manufacture of rubber and plastic products” (NACE code 22) and “Manufacture of motor vehicles, trailers and semi-trailers” (NACE code 29).

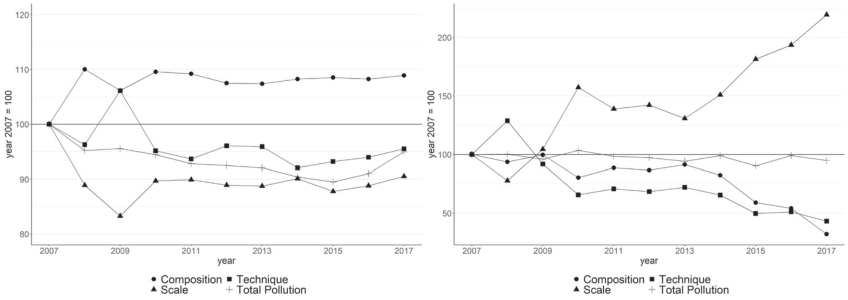
Table 4 Composition and technique effects for the most pollution-intensive industries, 2007-2017

	SO2					NOx			
	Laspeyres		Paasche			Laspeyres		Paasche	
Industry	CE	TE	CE	TE	Industry	CE	TE	CE	TE
17	0.096	−0.360	0.092	−0.356	17	0.089	−0.045	0.087	−0.043
19–21	0.009	−0.570	0.009	−0.570	19–21	0.003	−0.559	0.008	−0.564
23	−0.241	−0.578	−0.051	−0.768	23	−0.245	0.292	−0.083	0.130
24	0.044	−0.265	0.036	−0.257	24	0.009	−0.226	0.006	−0.223
	VOCs					PM10			
	Laspeyres		Paasche			Laspeyres		Paasche	
Industry	CE	TE	CE	TE	Industry	CE	TE	CE	TE
17	0.080	0.049	0.081	0.049	17	0.092	−0.479	0.090	−0.477
19–21	−0.052	−0.584	−0.040	−0.596	19–21	0.009	−0.925	−0.414	−0.925
22	−0.229	0.648	0.041	0.378	23	0.257	−0.471	0.285	−0.498
29	−0.004	−0.150	−0.004	−0.150	24	−0.073	0.211	−0.070	0.209

Table reports estimates of the composition effect (CE) and technique effect (TE) for the most pollution-intensive industries. The estimates are for the period 2007–2017. The industries are defined as two-digit codes under the NACE Rev. 2 classification. The industries are included based on the average pollution intensity over the period 2007–2017

For instance, while it was pollution-increasing for all pollutants, the negative sign prevails for VOCs emissions from the dirties two-digit industries.

The results for the year-by-year decomposition for two-digit industries are also ambiguous and differ both across pollutants and in comparison to the findings for the whole manufacturing sector. For sake of brevity, I focus on only one pollutant, NO_x, and two large groups of two-digit industries—the paper and pulp industry (NACE code 17) and petroleum, chemical and pharmaceutical industries (NACE codes 19–21). Unfortunately, the values of output at the four-digit level are reported by Statistics Sweden in a way that does not allow looking at time series for industries 19, 20 and 21 separately. All three effects are calculated as in Eqs. 3–5 but evaluated within a particular two-digit industry (or group of industries) rather than for the whole manufacturing sector. The decomposition of NO_x emissions from these two large groups of industries are plotted in Fig. 2. While the whole manufacturing sector showed a slightly negative growth between 2007 and 2017 and production in the paper and pulp industry fell by 10% (panel (a)), the scale effect for the petroleum, chemical and pharmaceutical industries (panel (b)) was very large and positive. Holding changes in techniques and compositions constant, NO_x emissions would have increased by almost 50% compared to the year 2007. The growth was mainly in the petroleum industry when the value of output more than doubled over the studied period. Two other effects have also completely different patterns. Similar to the whole sector, these industries became cleaner, and the technique effect contributed to the clean-up. But the role of the reductions in emissions to the overall decline in NO_x emission intensities was very different. For the paper and pulp industry, both the technique and scale effects were pollution-decreasing but the



(a) Paper and pulp industry **(b)** Petroleum and chemical industries

Fig. 2 Decomposition of NO_x emissions for two-digit industries, 2007-2017. *Notes:* Panel (a) shows the decomposition for the industry 17 under the NACE Rev. 2 classification. Panel (b) shows the decomposition for the group of two-digit industries 19–21 under the NACE Rev. 2 classification. The technique effect is calculated by taking the percentage change in a Laspeyres'-type index as in equation (4). The composition effect is calculated as the difference between the change in the aggregate pollution, the scale effect and the technique effect. Values are normalized to 100 in 2007

negative output growth played a more important role. Furthermore, their contribution to NO_x reductions was offset by changes in the mix of four-digit sub-industries towards more dirty production. There was a constant brown shift starting after the global financial crisis. In the absence of the scale and technique effects, NO_x emissions would have increased by 9%. For the chemical and pharmaceutical industries, changes in the mix of sub-industries were less important but changes in NO_x emissions from increasing due to substantial output growth.

There might be various sources of variation across two-digit industries. Among others, these industries use very different production technologies and, hence, might not necessarily react in the same way to the same policy. Identifying particular policy mechanisms is outside the scope of this paper. The goal of this exercise is to emphasize that heterogeneity within the manufacturing sector is substantial. Despite a tendency to raise the costs of dirty industries to push producers towards cleaner technologies within both Sweden and the EU, the results for the technique effect for the most pollution-intensive industries are ambiguous and differ across pollutants. While for the sector as a whole the technique effect was the major driver of the reductions in emissions, its role seems to be less important in the clean-up of some specific two-digit industries. The same applies to the brown shift. Also, this exercise highlights the importance of using the most detailed data available to improve the precision of the estimates of changes in compositions and techniques.

5 Robustness and discussion

Although the methodology this study uses has been widely implemented in other environment-related economic studies, it is not without limitations. I discuss its drawbacks in the section below and do several robustness checks to test the sensitivity of the results.

The method I use does not account for the fact that each four-digit industry consists of smaller heterogeneous sub-industries and each of them consists of even more heterogeneous firms and plants. Over time, the composition at a higher level of disaggregation may change, and there may be some new entries or exits. In the framework used in this study, these changes are assigned to the technique effect, which is an important limitation of the analysis.

The analysis suggests that decomposition based on the more aggregated data may leave out a large proportion of compositional changes. Table 5 shows the results of the same decomposition analysis but using data on both pollution emissions and (real) output aggregated at the two-digit level: a higher level of aggregation tends to assign within-industry changes in composition to the technique effect and a bigger share of changes in composition is likely to be missed. Therefore, a higher level of disaggregation should take us closer to the "true" technique and composition effects. However, there is no reason to expect any particular direction—a pollution-increasing (a positive value) or pollution-decreasing (a negative value) composition effect. Based on an idea that a switch towards energy- and resource-intensive products is driven by consumers (e.g., Brunel 2017; Hart 2018), one can expect (i) that a composition effect is pollution-increasing, (ii) that this effect will typically be underestimated because switches to, e.g., more powerful and heavier cars will not show up in the data, and (iii) that increasing disaggregation may lead towards capturing the "true" value of the technique and composition effects. From Table 5, the composition effect for NO_x emissions, estimated at the two-digit level with the Laspeyres index, is +2.7% (vs. +5.8%) and for VOCs emissions +15.4% (vs. +20.3 %). For PM_{10} emissions, the composition effect is negative, −1.4% (vs. +3.2%), suggesting a shift towards cleaner goods in the mix of industries. Thus, with more aggregated data, the brown shift is smaller in magnitude, and, as in the case with PM_{10} emissions, the results of the decomposition analysis on the role of compositional changes may point to an opposite direction. Thus, the missed effects may either reinforce or counteract the effects found at the aggregate level.

Table 5 Decomposition analysis at the two-digit level, 2007-2017

	Δ Total Pollution	Scale	Laspeyres		Paasche	
			Composition	Technique	Composition	Technique
	(1)	(2)	(3)	(4)	(5)	(6)
NO_x	−0.069	−0.033	0.027	−0.063	0.122	−0.158
PM_{10}	−0.475	−0.033	−0.014	−0.427	0.070	−0.512
SO_2	−0.338	−0.033	0.037	−0.342	0.118	−0.423
VOCs	−0.041	−0.033	0.154	−0.162	0.331	−0.338

Table reports estimates from a decomposition of the change in air pollution intensity of the Swedish manufacturing sector between 2007 and 2017. The industries are defined as two-digit codes under the NACE Rev. 2 classification. Column 1 reports the percentage change in aggregate emissions from the manufacturing sector compared to emissions in the year 2007. The aggregate pollution is decomposed into the scale (column 2), composition and technique effects using the Laspeyres'-type index (columns 3 and 4) and the Paasche's-type index (columns 5 and 6). Each row reports estimates for a different air pollutant

Regarding the composition effect, the brown shift shown in Figure 1 is clearly not driven by one or two specific industries. The pattern reflects a persistent tendency to move towards more polluting manufacturing goods. The brown shift in manufacturing started already in 2001 in the EU and after the financial crisis in China (Brunel 2017; Cole and Zhang 2019). Thus, the increasing specialisation towards "dirty" goods, captured in this paper, is part of a bigger picture—this supply shift away from cleaner industries extends across several states (advanced economies within the EU and China) and a longer period, from 2001 onwards. The brown shift appeared when additional and more stringent environmental policies were implemented in the EU.

Three additional tables show the results with alternative versions of the same dataset (Tables 10 and 11) or alternative data on pollution emissions and methods (Table 6). There is a reasonable concern that the results might be affected by the inclusion of the years around the financial crisis in the analysis. To address the issue, I re-run the decomposition for a shorter period—between 2010 and 2017. From Table 11, the decomposition method appears to be sensitive for the choice of the studied period: as the scale effect is large and positive (+10%), the composition effect for NO_x, PM_{10} and SO_2 estimated using the Laspeyres index changes its sign to the opposite. The alternative results in Table 10 are to check whether the choice of the deflator might have led to an underestimation of the role of the technique effect and a corresponding overestimation of the composition effect, or led to an overestimation of the importance of the computer industry for the overall clean-up in manufacturing (Tables 10, 11).

I also test whether the main results are sensitive to the source of pollution data. As the Swedish PRTR contains self-reported plant-level data from facilities that emit above certain thresholds, it does not include emissions from smaller polluters. To address these concerns, I employ data on manufacturing pollution emissions from the AEA and present the results in Table 6. The data is only available at the two-digit level, and it starts from the year 2008. With a higher level of aggregation, there are fewer zeroes in the sample, and I can use the log-mean Divisia index,

Table 6 Decomposition analysis using alternative methods and data sources, 2008-2017

	Benchmark*		AEA*		AEA, LMDI	
	Composition	Technique	Composition	Technique	Composition	Technique
	(1)	(2)	(3)	(4)	(5)	(6)
SO_2	0.076	−0.350	−0.011	−0.237	0.02	−0.259
NO_x	0.044	−0.059	−0.003	−0.145	0.02	−0.161
PM_{10}	0.024	−0.185	−0.015	−0.366	−0.002	−0.379
VOCs	0.240	−0.210	0.132	−0.38	0.25	−0.398

Notes: Table shows estimates from a decomposition of the change in air pollution intensity for the Swedish manufacturing sector between 2008 and 2017. Columns 1 and 2 present the benchmark results obtained as in Table 3 but for the period 2008–2017 due to data availability. Columns 3–6 show the results for the decomposition analysis using data on pollution emissions at two-digit level from the Air Environmental Accounts from Statistics Sweden. The results marked by * are obtained using the Laspeyres'-type index. The last two columns, 5 and 6, show the estimates from a decomposition using the log-mean Divisia decomposition index which does not leave a residual term as the Laspeyres or Paasche index.[16] As shown in Table 6, the main results—the importance of technique in the overall manufacturing abatement and the brown shift—persist regardless of the decomposition method and data source but the magnitude is different.

6 Conclusions

In this paper, I have shown that decomposition analysis with four-digit data on manufacturing production and actual emissions reveals a substantial shift in the composition of Swedish manufacturing towards pollution-intensive production, despite rapid increases in the pollution-efficiency of technology. Improvements in technology are presumably driven by increasingly stringent environmental regulations, regulations which might be expected to push patterns of production and consumption in the same (environmental-friendly) direction. I find the largest technique effect for PM_{10} and SO_2 emissions—47 and 38% using the Laspeyres index and 51 and 42% using the Paasche index, respectively.

The findings suggest that in the absence of changes in scale and technique, SO_2 emissions would increase by 7% and VOCs emissions would rise by as much as 20% compared to the level of the year 2007. Taking into account that similar patterns were observed in the EU manufacturing sector already at the beginning of the 2000s' (Brunel 2017) and in a more recent period in China (Cole and Zhang 2019), the results in this paper might indicate that the increasing specialisation towards more pollution-intensive production is a part of a larger shift, extending across several states.

The paper sheds light on heterogeneity within the manufacturing sector in Sweden. For the most pollution-intensive industries that account for more than 80% of the gross manufacturing air pollution emissions, the technique and composition effects differ both in magnitude and sign. They also vary across pollutants. For instance, for the paper and pulp industry, the technique effect is almost one-tenth of the value for the whole sector and plays a minor role in the reductions of NO_x emissions. Being aware of heterogeneity within the manufacturing sector is important from a policy perspective but also for future research as it emphasizes the importance of data disaggregation. Employing more detailed data may lead towards capturing the "true" value of the technique and composition effects. I show that with more aggregated data, the brown shift is smaller in magnitude.

This study's major implication is that policy makers should take into account that manufacturing producers may shift to more dirty goods at the same time as reducing the emissions intensity of existing products. For Sweden, as for other countries within the EU, multiple ambitious goals such as improved energy efficiency, increased share of renewables in energy consumption and reduced air emissions in the nearest 10–25 years are on agenda. To achieve the targets, it is important to be aware of the strengths of the composition and technique effects to minimize the risk that an emission-reducing policy might

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[16] For the decomposition of emissions with the LMDI, I use the formula for the index in its multiplicative form, i.e., the change in total emissions between year 0 and year T equals to the product of changes in the scale, composition and technique between years 0 and T. For example, the technique effect is calculated as $\sum_i L(P_i^T, P_i^0) \ln\left(\frac{z_i^T}{z_i^0}\right)$ where $L(a, b) = \frac{(a-b)}{\ln a - \ln b}$.

lead to countervailing changes in the mix of industries and goods. Thus, either the technique effect has to be even stronger, or compositional changes towards dirty goods should be prevented. For this, more research is needed to identify the sources of both brown shift and pollution-decreasing technique effect. If the latter is primarily due to, for instance, firms switching to another type of fuel, it might have a limited effect on the future cleanup as firms do not adopt new technologies. For the pollution-increasing composition effect, it is important to identify whether it is driven by the demand or supply side. If it occurs on the producers' side there is a need for even more stringent regulations on firms and their emissions.

Appendix

Data: additional details

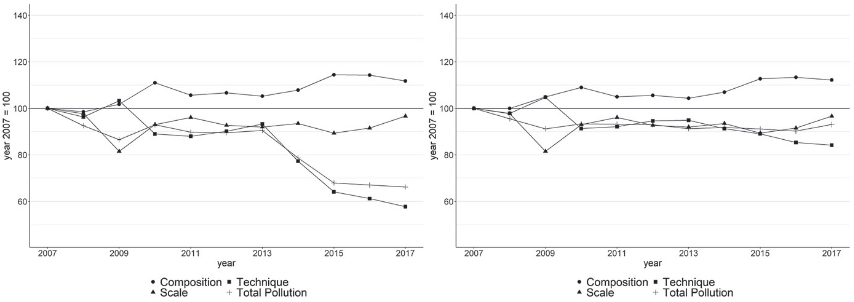
For every pollutant, the Swedish Pollutant Release and Transfer Register (PRTR) contains data on its plant-level annual emissions. Data on pollution emissions from 431 manufacturing plants (191 manufacturing firms) is included in the analysis. For every facility, there is a name of the facility together with the firm's name and its Swedish id-number but it does not contain industry codes under the NACE Rev. 2 classification. I use the id-numbers to extract four-digit industry codes from the database Retriever that contains data on the majority of Swedish firms for the period 2010–2019. Using the four-digit codes, I keep only manufacturing facilities, i.e., facilities with four-digit codes within the range 10.11–33.20 under the NACE Rev. 2 classification. To merge the data on pollution emissions with output data from Statistics Sweden, I aggregate plant-level emissions to a four-digit level. The output data from Statistics Sweden does not always contain data for each four-digit sector separately. For some sectors, it reports data for a group of sectors for one or several years. To deal with it, I combine output for those affected sectors into larger groups (e.g., all sectors between 19.10 and 20.17 are combined into one group, 19.10–20.17). The data on pollution emissions is aggregated in the same way.

Table 7 Descriptive statistics

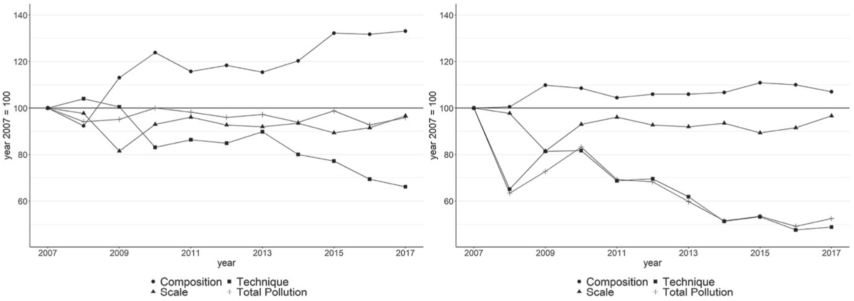
Variables	*N*	Mean	SD	Min	Max
Value of output per 4-digit industry, bln SEK	1738	10.14	25.80	0.0164	273.8
Total value of output, bln SEK	11	1603	80.86	1403	1 721
Industry's share in total output	1738	0.00633	0.0161	0.0000105	0.170
Emissions of SO_2, tons	1738	51.56	312.8	0	3 826
Emissions of NO_x, tons	1738	132.5	877.6	0	11 003
Emissions of VOCs, tons	1738	166.1	1213	0	11 681
Emissions of PM_{10}, tons	1738	23.05	194.1	0	3 585
Emissions intensity, SO_2, tons/bln SEK	1738	1.885	10.91	0	132.4
Emissions intensity, NO_x, tons/bln SEK	1738	7.699	54.97	0	816.1
Emissions intensity, VOCs, tons/bln SEK	1738	4.128	21.78	0	235.1
Emissions intensity, PM_{10}, tons/bln SEK	1738	0.734	5.675	0	80.32

Additional results

See Fig. 3 and Table 8.



(a) SO_2 (b) NO_x



(c) VOCs (d) PM_{10}

Fig. 3 Decomposition of air pollution emissions from Swedish manufacturing, 2007-2017. *Notes* The technique effect is calculated by taking the percentage change in a Paasche's-type index as in Eq. (5). The composition effect is calculated as the difference between the change in the aggregate pollution, the scale effect and the technique effect. Values are normalized to 100 in 2007

Table 8 Decomposition of Swedish Manufacturing CO_2 Emissions, 2007–2017

	Δ Total pollution	Scale	Laspeyres		Paasche	
			Composition	Technique	Composition	Technique
	(1)	(2)	(3)	(4)	(5)	(6)
CO_2	0.041	−0.033	0.070	0.005	0.147	−0.073

Table reports estimates from a decomposition of the change in CO_2 emissions intensity of the Swedish manufacturing sector between 2007 and 2017. Data on CO_2 emissions are obtained from the Swedish PRTR. The industries are defined as four-digit codes under the NACE Rev. 2 classification. Column 1 reports the percentage change in aggregate emissions from the manufacturing sector compared to the year 2007. The aggregate pollution is decomposed into the scale (column 2), composition and technique effects using the Laspeyres'-type index (columns 3 and 4) and the Paasche's-type index (columns 5 and 6). Each row reports estimates for a different air pollutant

Robustness checks

See Tables 9, 10, 11.

Table 9 Decomposition analysis without pollution-intensive industries, 2007-2017

	Δ Total Pollution	Scale	Laspeyres		Paasche	
			Composition	Technique	Composition	Technique
	(1)	(2)	(3)	(4)	(5)	(6)
NO_x	−0.214	−0.036	0.167	−0.345	0.255	−0.433
PM_{10}	−0.600	−0.096	−0.124	−0.380	0.025	−0.528
SO_2	−0.146	−0.029	0.351	−0.468	0.395	−0.512
VOCs	−0.241	−0.097	0.049	−0.193	0.075	−0.219

Table reports estimates from a decomposition of the change in air pollution intensity of the Swedish manufacturing sector between 2007 and 2017. The industries are defined as four-digit codes under the NACE Rev. 2 classification. The table reports the result of the decomposition analysis without five most pollution-intensive industries. The industries are excluded based on an average emission intensity for each pollutant. Column 1 reports the percentage change in aggregate emissions from the manufacturing sector compared to emissions in the year 2007. The aggregate pollution is decomposed into the scale (column 2), composition and technique effects using the Laspeyres'-type index (columns 3 and 4) and the Paasche's-type index (columns 5 and 6). Each row reports estimates for a different air pollutant. The removed four-digit industries are different for different pollutants

Table 10 Decomposition analysis using alternative samples, 2007–2017

	Without Computers		Overall PPI	
	Composition	Technique	Composition	Technique
	(1)	(2)	(3)	(4)
NO_x	0.026	−0.094	0.016	−0.223
PM_{10}	0.000	−0.473	−0.064	−0.548
SO_2	0.039	−0.375	−0.028	−0.448
VOCs	0.172	−0.211	0.121	−0.299

Table shows estimates from a decomposition of the change in air pollution intensity for the Swedish manufacturing sector between 2007 and 2017. The industries are defined as four-digit codes under the NACE Rev. 2 classification. Columns 1 and 2 report the results for the sample without industry "Manufacture of computer, electronic and optical products" (26). In columns 3 and 4, the sample is similar to the benchmark but the output values are deflated using the overall PPI. Each row reports estimates for a different air pollutant. In all cases, the Laspeyres'-type index is used

Table 11 Decomposition analysis with shorter sample, 2010-2017

	Δ Total pollution	Scale	Laspeyres		Paasche	
			Composition	Technique	Composition	Technique
	(1)	(2)	(3)	(4)	(5)	(6)
NO_x	−0.003	0.103	−0.022	−0.084	0.105	−0.211
PM_{10}	−0.369	0.103	−0.084	−0.388	−0.014	−0.458
SO_2	−0.288	0.103	−0.015	−0.377	0.063	−0.455
VOCs	−0.041	0.103	0.130	−0.274	0.341	−0.485

Table reports estimates from a decomposition of the change in air pollution intensity of the Swedish manufacturing sector between 2010 and 2017. The industries are defined as four-digit codes under the NACE Rev. 2 classification. Column 1 reports the percentage change in aggregate emissions from the manufacturing sector compared to the year 2007. The aggregate pollution is decomposed into the scale (column 2), composition and technique effects using the Laspeyres'-type index (columns 3 and 4) and the Paasche's-type index (columns 5 and 6). Each row reports estimates for a different air pollutant

EU legislation implemented in Sweden

- Directive 80/779/EEC on air quality limit values and guide values for sulphur dioxide and suspended particulates. Repealed by Council Directive 1999/30/EC.
- Directive 85/203/EEC on air quality standards for nitrogen dioxide. Repealed by Council Directive 1999/30/EC.
- In 1996, Integrated Pollution Prevention and Control (IPPC) Directive (96/61/EC) set out the main principles for the permitting and control of installations based on an integrated approach and the application of so-called *best available techniques* (BAT), i.e., the most effective techniques taking into account environmental protection, costs and benefits. According to the IPPC directive, producers in pollution-intensive industries were obliged to apply for permission. The IPPC directive was transposed into the Swedish national law through the Swedish Environmental Code (Miljöbalken). Repealed by Directive (2010/75/EU) on industrial emissions. Following the Environmental Code, facilities with great environmental impact must have a license to operate but this requirement applies to a larger number of activities than were covered initially by the IPPC Directive. In particular, the permit requirement is applied to hazardous activities labelled as class A (e.g., large scale production of wood pulp or large scale production of pharmaceuticals, including intermediates) or B (e.g., facilities that produce glass, including fiberglass, with a melting rate of more than 20 tonnes per day or more than 5000 tonnes per calendar year). The activities of class C (e.g., industrial manufacture of briquettes of coal) require only a notification to the Environment Committee of the municipality before starting up.[17]
- The Air Quality Framework Directive (96/62/EC) set out the principles of ambient air quality monitoring, assessment and management. The directive was fol-

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[17] The classification of activities is regulated by the Environmentally Hazardous Activities and Health Protection Ordinance (1998:899) and its successor, the ordinance (2013:251), https://www.riksdagen.se/sv/dokument-lagar/dokument/svensk-forfattningssamling/_sfs-2013-251/, viewed 07 April 2020.

lowed by four daughter directives which detailed the limit values for specific pollutants. The directive was repealed by Directive 2008/50/EC.

  - First Daughter Directive: Directive (1999/30/EC) limited values for sulphur dioxide, nitrogen dioxide and oxides of nitrogen, particulate matter and lead in ambient air. Repealed by Directive 2008/50/EC.
  - Second Daughter Directive: Directive 2000/69/EC limited values for benzene and carbon monoxide in ambient air. Repealed by Directive 2008/50/EC.
  - Third Daughter Directive: Directive 2002/3/EC related to ozone in ambient air. Repealed by Directive 2008/50/EC.
  - Fourth Daughter Directive: Directive 2004/107/EC sets out limits of arsenic, cadmium, mercury, nickel and polycyclic aromatic hydrocarbons in ambient air.

- Directive (2001/81/EC) on national emissions ceilings (NEC). It set binding emission ceilings that each member state should achieve by 2010. The directive covers four air pollutants: sulphur dioxide, nitrogen oxides, non-methane volatile organic compounds, and ammonia. The directive was revised and replaced by the new NEC directive in 2016 (2016/2284/EU).
- The large combustion plants (LCP) Directive (2001/80/EC) covered plants with a rated thermal capacity of at least 50 megawatts (MW) and set emission standards for both new and existing plants. The directive contained emission limit values for sulphur dioxide, nitrogen oxides and dust, varying according to the age and capacity of the plants, as well as the type of fuel burned. Repealed by Directive (2010/75/EU) on industrial emissions.
- Regulation 166/2006 on the European Pollutant Release and Transfer Register (E-PRTR) regulates creating a register that gives the public access to detailed information on the emissions and the off-site transfers of pollutants and waste from industrial facilities in all Member States and Iceland, Liechtenstein and Norway. The register contains data reported annually by some 30 000 industrial facilities covering 65 economic activities across Europe.
- Directive (2008/50/EC) on ambient air quality and cleaner air for Europe. The Directive merges the existing air quality legislation into a single directive, except for the Fourth Daughter Directive, with no change of air quality objectives. The Directive introduces air quality objectives for $PM_{2.5}$ (fine particles), including the limit value and exposure-related objectives that entered into force 2015. The permissible levels stipulated in the directive are the minimum values that EU states must strive to achieve, i.e., each country may introduce more demanding standards. The directive does not say anything about how the limit values should be achieved. But it does require that each member country takes proper actions when the requirements are not met.
- Directive (2010/75/EU) on industrial emissions (IED) establishes the main principles for permitting and control of large industrial installations based on an integrated approach and the application of BAT. All facilities undertaking the industrial activities listed in Annex I of the IED are required to operate

in accordance with a permit. The permit is issued by the authorities in the Member States. This permit should contain conditions set following the principles and provisions of the IED. One significant change, compared with the former IPPC directive, is that emission limit values that can be achieved using the BATs become binding values. These values are introduced into the Swedish Industrial Emissions Ordinance (Industriutsläppsförordning (2013:250)). The IED replaced several previously existing directives (including, in particular, the IPPC Directive). It entered into force in January 2011 and had to be transposed by the Member States by January 2013. For what types of industrial activities there is a requirement to obtain a permit is transposed into the Swedish legislation through Miljöprövningsförordning (2013:251).

- Directive (2015/2193/EU) on medium combustion plants (MCPD) regulates emissions of sulphur dioxide, nitrogen oxides and dust from the combustion of fuels in plants with a rated thermal input between 1 and 50 MW thermal.
- A new National Emissions Ceilings (NEC) Directive (2016/2284/EU) entered into force on 31 December 2016. It replaced Directive (2001/81/EC) and sets 2020 and 2030 emission reduction commitments for five main air pollutants: NO_x, VOCs, SO_2, NH_3 and $PM_{2.5}$. It also ensures that the emission ceilings for 2010 set in the earlier directive remain applicable for Member States until the end of 2019.

Other taxes and charges aiming for clean production and installation of pollution prevention technologies[18]

- In 1991, a carbon tax was introduced. It mainly affects transport. Industry and agriculture receive a lower CO_2 tax rate.
- In 1991, a sulphur tax for electricity and heat production was introduced. The tax is based on the sulphur content of fuels during combustion and is paid depending on the actual emission of SO_2.
- Starting from the year 1992, there is a Swedish charge on NO_x. The purpose is to reduce emissions NO_x from combustion plants that produce energy. The threshold for the charge had been gradually lowered. It started from 50 GWh per year from a combustion plant in the year 1992 to less than 10 GWh per year after 1997.
- In 2011, an energy tax on fossil heating fuels was introduced. The amount to pay depends on the energy content.

Major air pollutants

See Table 12.

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[18] UN Environment Program, *Sweden—Air Quality Policies*, https://www.unenvironment.org/resources/policy-and-strategy/air-quality-policies-sweden, viewed 10 January 2020.

Table 12 Major air pollutants

Pollutant	Sources of emissions	Thresholds E-PRTR	Air quality
$PM_{2.5}$ & PM_{10}	Combustion engines (both diesel and petrol), solid-fuel (coal, lignite, heavy oil and biomass) combustion for energy production in households and industry, as well as other industrial activities.	50 000 kg/year	$40\ \mu g/m^3$ ($PM_{2.5}$)* $25\ \mu g/m^3$ (PM_{10})*
NO_2 & NO_x	The largest emission of NO_2 occurs during combustion. Car traffic is the largest source of NO_x in urban areas, but energy production and industrial processes also make significant contributions. NO_x is an important constituent of particulate matter and ground-level ozone.	50 000 kg/year (NO_2) 100 000 kg/year (NO_x)	$40\ \mu g/m^3$ (NO_2)*
SO_2 & SO_x	SO_2 is primarily produced from the burning of fossil fuels (coal and oil) and the smelting of mineral ores that contain sulphur.	150 000 kg/year	$100\ \mu g/m^3$ (SO_2)**
VOCs	Emissions from motor vehicle exhaust, industrial facilities, and chemical solvents. VOCs are a precursor of O_3.	100 000 kg/year	–

*—annual mean. **–daily mean. *** – 8-h mean.

Sources: Description of emission sources in the second column is obtained from WHO and EEA. Thresholds in the third column are the thresholds to report emissions to the E-PRTR under the EC Regulation 166/2006. The air quality limit values are given by the EC Directive 2008/50 on ambient air quality and the Swedish Regulation 2010:477 on air quality.

WHO (2019), *Ambient (outdoor) air pollution*, https://www.who.int/en/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health, viewed 9 March 2020. EEA (2019), *Emissions of the main air pollutants in Europe*. https://www.eea.europa.eu/data-and-maps/indicators/main-anthropogenic-air-pollutant-emissions/assessment-6, viewed 9 March 2020. The thresholds are available in the annexes of the EC regulation: https://eur-lex.europa.eu/legal-content/HR/TXT/?uri=CELEX:32006R0166, viewed 9 March 2020. The limit values are available in the annexes of the EC directive (https://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX%3A32008L0050, viewed 31 March 2020) and in the Swedish regulation (https://www.riksdagen.se/sv/dokument-lagar/dokument/svensk-forfattningssamling/luftkvalitetsforordning-2010477_sfs-2010-477, viewed 31 March 2020). For an overview, see also SEPA, *Sammanställning av miljökvalitetsnormer*, viewed 9 March 2020, https://www.naturvardsverket.se/upload/stod-i-miljoarbetet/vagledning/miljokvalitetsnormer/mkn-luft/sammanst-miljokvalitetsnormer.pdf

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ACTA UNIVERSITATIS AGRICULTURAE SUECIAE

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This thesis examines the challenges firms face when deciding whether to pursue environmental innovation and the role of adopting less emission-intensive technologies in reducing emissions. Paper I investigates the driving forces behind the decline of air pollution emissions from the Swedish manufacturing sector. Paper II studies factors that underlie a firm's decision to invest in clean tech innovation. Paper III analyses the impact of competition with imports from China of equipment for renewable energy on innovation in the European Union.

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