Carbon Pricing and Firm-Level CO_2 Abatement: Evidence from a Quarter of a Century-Long Panel

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Abstract

Sweden, as one of the first countries in the world, introduced a carbon tax in 1991. In our study, we assemble a unique and comprehensive dataset tracking all CO_2 emissions from the Swedish manufacturing sector between 1990 and 2015, then estimate the impact of carbon pricing (through taxes and traded emission rights) on firm-level emissions. We first document that the vast majority of manufacturing CO_2 emissions can be attributed to a few sub-sectors, in which, due to the design of the carbon tax, firms were often taxed at low or zero marginal tax rates. In panel regressions, spanning twenty-six years and around 4,000 manufacturing firms, we find a statistically robust and economically meaningful inverse relationship between CO_2 emissions and carbon pricing. We estimate the CO_2 emissions-to-carbon pricing elasticity to be 0.019 for the manufacturing sector. Aggregate manufacturing CO_2 emissions decreased by about 31% between 1990 and 2015, while output decreased by 3% over the same period. We estimate that 13 of the 31 percentage point decrease in aggregate emissions can be attributed to carbon pricing.

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1 Introduction

Anthropogenic climate change is one of the most pressing issues of our time, and represents a massive market failure in need of policy intervention (e.g., Stern (2008)).[1] Carbon taxation is often emphasized as one of the most important policy tools for achieving decarbonization (e.g., Rockström et al. (2017); Sterner et al. (2019)) and create a more sustainable growth path for the economy (e.g., Acemoglu et al. 2012; Acemoglu et al. (2016); Aghion et al. (2016); Golosov et al. (2014); Nordhaus (1993)).[2] Still, there is a paucity of comprehensive empirical evidence on whether, and if so, to what extent, carbon taxation and pricing actually affects carbon dioxide (CO_2) firm-level emissions (Burke et al. (2016)).[3]

In this study, we construct the longest firm-level panel to date on economic activity and CO_2 emissions for Sweden, one of the earliest adopters of a carbon tax.[4] Equipped with this dataset, we explore four aspects of carbon pricing and firm-level CO_2 emissions. First, we document from where in the manufacturing sector the CO_2 emissions emanate (section 3). Second, we describe how these emissions are priced (on average and at the margin) through the different carbon pricing mechanisms (the different regimes of Swedish carbon taxation and the European Union Emissions Trading System (EU ETS)) (section 3). Third, we estimate panel regression models and test the relationship between carbon pricing and firm-level CO_2 emissions (section 4), and, fourth, we quantify the impact of carbon pricing on aggregate manufacturing CO_2 emissions since 1990 (section 5).

Sweden serves as an ideal testing ground for analyzing the incidence and impact of

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[1] There is widespread consensus of anthropogenic climate change (e.g., Hoegh-Guldberg et al. (2018). From page 6 in III (2014): "CO_2 emissions from fossil fuel combustion and industrial processes contributed about 78% of the greenhouse gas [(GHG)] emission increase from 1970 to 2010, with a similar percentage contribution for the period 2000–2010". See e.g., Stott et al. (2004) on the contribution of human activity to the 2003 heat wave in Europe, Nicholls and Cazenave (2010) on climate change and the sea level rise, Knutson et al. (2010) on the increasing frequency of tropical cyclones, Dai (2013) on climate change and drought, and the literature survey of Dell et al. (2014).

[2] Furthermore, there is theoretical evidence that carbon taxation is the most efficient policy tool in the quest to mitigate the increase in global temperature (Jaffe et al. (2002)).

[3] Some previous work suggests that carbon taxation increased patenting of clean innovation. Aghion et al. (2016) document that higher fuel prices (partly a consequence of taxation) increased clean innovation in the auto sector, and evidence in Calel and Dechezlepretre (2016) suggests that plants covered under the European Union Emission Trading System (EU ETS) increased innovation in low-carbon technologies compared to others. A related literature documents empirical evidence of how changes in price and policy induce a shift away from dirty fossil-fuel- based technical change to clean technologies (see e.g., Newell et al. (1999); Popp (2002); Hassler et al. (2012)). The paper closest to ours is Martin et al. (2014a), who analyze the effect of the 2001 UK carbon tax on manufacturing firms over the following three years, and show a significant negative effect on energy intensity and the use of electricity. They analyze smaller tax changes over a much shorter time period compared to us and do not have access to direct CO_2 emissions data.

[4] See Brännlund et al. (2014) and Scharin, H and Wallström, J (2018) for overviews.

carbon pricing. It was one of the first countries to introduce a carbon tax in 1991, levied on the heating emissions from manufacturing firms (see section 2 for details), and the nominal carbon tax rate in Sweden is today the highest in the world (World Bank (2020)).[5] In addition, several subsequent changes in tax rates, exemptions, and the introduction of the EU ETS give substantial variation in effective tax rates in the cross-section and over time, which facilitates econometric identification. Our unique data contains information on both financials and CO_2 emissions for the complete set of manufacturing firms over the period 1990-2015.

We first document that only a small fraction of narrowly defined manufacturing sectors make up the vast majority of aggregate manufacturing CO_2 emissions. The top 10% of sectors in terms of CO_2 emission intensity in 1990, comprising, on average, 15-20% of manufacturing output, represent about three quarters of aggregate manufacturing CO_2 emissions. Soon after the initial introduction of the carbon tax, the Swedish government introduced various exemptions and rate reductions for the highest carbon-emitting firms, motivated by the need of mitigating carbon leakage (i.e. CO_2-emitting plants closing in Sweden and/or moving to other jurisdictions). As a result of these exemptions, the 10% of firms with the highest CO_2 emissions (including most firms in the steel, cement, and oil refinery subsectors) ended up having very small, and sometimes zero, marginal tax rates, despite paying substantial amounts in carbon tax (reducing their pre-tax margins by more than 6 percentage points on average).[6] Consistent with the lower marginal incentives, we find that the carbon intensity (measured as emissions relative to sales) of the high-emitting firms decreased modestly between 1990 and 2015. In contrast, we find that the remaining 90% of firms, who faced high and varying marginal carbon tax rates, experienced significantly higher reductions in their carbon intensity.

Next, we use the variation in tax rates across firms and time to examine the relationship between emission intensity and marginal carbon tax rate. Using data from about 4,000

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[5] Finland and the Netherlands were the first countries that introduced a carbon tax in 1990, followed by Sweden and Norway in 1991 (see Shah and Larsen (1992)).

[6] The feature of capping carbon tax payments changed in 1993 (a substantial lowering of the nominal tax rate and abolition of the exemptions) and again in 1997 as a version of the 1991-1992 exemptions were brought back together with an increase in the nominal rate. The next major change to carbon pricing during our sample period is the introduction of the European Union Emission Trading System (EU ETS). At the end of our sample period, firms covered under the EU ETS comprises over 90% of Swedish manufacturing sector CO_2 emissions.

manufacturing firms, covering 85-90% of Sweden's manufacturing CO_2 emissions over 1990-2015, we document a strong inverse relationship between firm-level CO_2 emission intensity and the marginal cost of carbon emissions. In our main specification, which includes firm and year fixed effects, we document that a one percent increase in the marginal tax rate reduces the carbon emissions per unit of sales by about 3-3.5%.[7] This relationship is stable over the introduction of the EU ETS in 2005 and to the inclusion of different firm-level control variables. The carbon pricing effect is stronger for firms in industries with lower pollution abatement costs and with a lower ability to move operations abroad.

Finally, we link carbon pricing to aggregate CO_2 emissions reduction in the Swedish manufacturing sector. CO_2 emissions from the Swedish manufacturing sector decreased by 31% during 1990-2015. First, standard decomposition techniques from the environmental economics literature (e.g., Grossman and Krueger (1993), Levinson (2009), Shapiro and Walker (2018)) attribute 36% of that decrease to the changing composition of the Swedish manufacturing sector away from CO_2 emitting industries to less emitting ones. By construction in this approach, the remaining 64% (i.e., the residual) would then be due to changes in technology. Second, following Shapiro and Walker (2018), we estimate the CO_2 emissions elasticity with respect to the CO_2 abatement cost share by emissions intensity deciles in order to calculate how much of the aggregate emissions reductions in the Swedish manufacturing sector which was due to carbon pricing. We estimate that carbon pricing account for 13 of the 31 percentage points decrease in aggregate manufacturing CO_2 emissions since 1990.

We explore the external validity of our findings by comparing the structure and distribution of CO_2 emissions and sales in Sweden with a sample of twenty comparable developed countries. We show that CO_2 emissions are highly concentrated to the same handful of sectors in the international sample as in Sweden. Using the international dataset, we create a counterfactual Sweden by creating a synthetic control group (e.g., Andersson (2019)). High-emissions-intensity manufacturing sectors experience a similar evolution in CO_2 emissions over time relative to the synthetic control group, whereas low-emissions-intensity sectors display clearly larger emissions reductions in Sweden compared to the control group (as well as relative to the world average). This finding is consistent with the

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[7] The marginal tax rate is expressed as Swedish Krona (SEK) per kilogram (Kg) of CO_2 emissions.

construction of the Swedish carbon tax providing higher marginal cost to emitting CO_2 for low-emissions-intensity relative to high-intensity firms.

Our study contributes to the existing literature in several ways. First, thanks to a long time series and detailed micro-data on firm emissions and financials, we are able to produce more precise estimates of carbon pricing elasticities compared to earlier literature. As already mentioned, there is a paucity of *ex-post* empirical analyses on the impact of carbon pricing (Burke et al. (2016)).[8] Only a handful of countries have had carbon pricing regulation in place for any longer period of time, and even for fewer of these exist micro-level data necessary to produce precise estimates.[9] We believe our micro-level estimates should be valuable to the fast growing macroeconomic literature on climate change and growth (e.g., Acemoglu et al. (2016); Golosov et al. (2014)).

Our study is also relevant for discussions on how to design optimal carbon taxation (e.g., Nordhaus (1993); Bovenberg and De Mooij (1994); Lans (1996); Pindyck (2013)). While we acknowledge that our estimates ignore many general equilibrium effects, our results show that firms do respond to the marginal cost of emitting CO_2. Therefore, it is likely the most efficient to ensure that all firms always face positive marginal carbon tax rates.

Finally, our findings are relevant for policy makers in the pursuit of combating climate change as well as for research in macroeconomics and climate change mitigation more broadly. The manufacturing sectors (together with construction) account for about one-fifth of global CO_2 emissions from the combustion of fuel (Ritchie and Roser (2017)) and about one hundred corporations account for more than 70% of the cumulative industrial greenhouse gas emissions in the last thirty years (Griffin and Heede (2017)). Our evidence show that manufacturing CO_2 emissions indeed are concentrated to a few sectors and just a few firms within these sectors. This empirical fact carries important implications for how to design policy.

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[8] We note the recent study by Metcalf and Stock (2020) studying aggregate data for thirty-one European countries and Andersson (2019) focusing on mobile, CO_2 emissions from transportation in Sweden.

[9] According to World Bank (2020), there are about sixty carbon pricing regulations in place in 2020 (covering about one-fifth of global CO_2 emissions). Six of these have been in place for longer than twenty years (the Nordic countries (excluding Iceland), Poland and Slovenia) and two-thirds have been introduced after 2010.

2 Institutional setting

2.1 The carbon tax and environmental regulation in Sweden

Energy taxation is a central environmental policy measure and is essentially a surcharge on fossil fuels in different forms, but closely related to their energy content or their CO_2 emissions when burned.[10] Taxes on energy use are quoted as a percentage of the sales price (ad-valorem taxes), and publicly available price information is used to translate ad-valorem rates into per-unit rates.[11]

Energy taxes on fuels and electricity were introduced largely for fiscal reasons. (SEPA and SEA (2007))[12] However, the transformation of energy tax into a carbon tax was motivated by environmental concerns.[13] Carbon taxation comprises together with energy taxation on fuels and on electricity the largest share of total environmental taxation in the overall economy (Figure A.1). From a peak of almost 70% of total environmental taxes in manufacturing, the share of carbon taxation has fallen to about 40% (Figure A.2). The falling share of carbon taxation in total environmental taxes is due to that the vast majority of manufacturing CO_2 is regulated under EU ETS. We describe the design of the carbon tax in more detail next.

2.2 The design of the Swedish carbon tax

The carbon tax is technically an energy tax. It is levied on fossil fuels used in combustion engines (so called mobile sources of emissions) or for heating (so called stationary sources of emissions). The carbon tax on mobile emissions is included in the after-tax fuel price and affects road transportation. Heating fuels are used for fuel combustion in industrial (mostly manufacturing) processes. Furthermore, manufacturing production releases two

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[10] Therefore, both the general excise tax on fuels (and electricity) as well as the carbon tax are classified as energy taxes.

[11] Converting ad-valorem taxes into per-unit taxes enables the calculation of effective tax rates on energy and carbon across different bases, but the calculated unit taxes are contingent upon observed prices (OECD (2019)). We also note that these instruments do not include value added taxes (VAT) or sales taxes. The reason is that VAT and sales taxes generally apply equally to a wide range of goods and do not change relative prices between energy sources or factors of production.

[12] We describe the historical background of the tax as well as political process behind the introduction and changes of the carbon tax in Appendix A.

[13] Both the energy and carbon tax are levied on fossil fuels when used as heating and motor fuels, hence their economic impacts are qualitatively similar. The difference between these instruments stems from the level of the taxes and what is charged upon the combustion of one unit of fossil fuel. While the energy tax is tied to the generated heat, the carbon tax is a function of the emitted carbon dioxide.

types of emissions: heating and process CO_2 emissions. The carbon tax on stationary emissions is levied on emissions from fuel combustion only; CO_2 released during production is exempt from the carbon tax.[14] Therefore, a plant must declare the use of its fossil fuel (e.g., if it is going to be used for production or heating).

The level of carbon tax charged on one unit of fossil fuel is closely related to its fossil carbon content since its consumption results in a net increase of CO_2 emissions in the atmosphere. The tax is levied on fuel inputs and not on the actual emission of CO_2, but the carbon tax rate is uniform across fossil fuels.[15]

We show how a manufacturing plant is taxed in Figure 1. The average manufacturing plant in Sweden uses about one-third of its fossil fuel for production, generating so called process emissions, and the remaining two-thirds for heating. In other words, about two-thirds of the Swedish manufacturing sector's stationary CO_2 emissions are subject to carbon taxation.[16] The tax rates are recorded by standard volume or weight units (such as litres of gasoline or tonnes of coal).

The Swedish carbon tax was introduced in 1991 at a rate of 0.25 Swedish Krona (SEK) per kilogram (kg) of emitted CO_2 (Figure 2) across all sectors in the economy (but with firm-specific exemptions which we describe more in detail below). However, in 1993, a two-tier system was introduced exempting firms in mining and manufacturing sectors (due to carbon leakage concerns) from 75 percent of the carbon tax rate (Government Bill 1989/90:111 (1989), Government Bill 1991/92:150 (1991)). Therefore, only households and non-tradable sectors paid the general rate; manufacturing sectors experienced a nominal carbon tax rate decrease in 1993, which remained at the same level until 1997 (when the exemption decreased from 75% to 50%).

The introduction of EU ETS had major implications for the carbon tax design. In-

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[14] To illustrate what is taxed, take steel production as an example (which is produced through multiple steps). The process starts with heating coking coal to around 1000-1100 °C to manufacture coke. In the next step, coke is burned in a furnace and the formed carbon monoxide reacts with iron ore. This key chemical reaction produces iron and CO_2 emissions. The final stage turns iron with some additions of scrap into steel (World Coal Association (2019)). The described phases make the steel production one of the most carbon intensive industrial processes. In particular, the chemical reaction between the iron ore and the carbon monoxide emits the majority of the CO_2. However, the carbon tax is levied only on the heating of the coal and the coke.

[15] However, gasoline for road transport use is subject to additional taxes. See Andersson (2019) for a case study on the carbon taxation component of the taxation of transportation fuel. Also, biofuels and peat are not taxed in Sweden since they are regarded as non-fossil fuels (Scharin, H and Wallström, J (2018)).

[16] Both process and heating CO_2 are regulated under EU ETS.

stallations under the EU ETS were phased out of the Swedish carbon tax regulation during 2008-2011 (Government Bill 2007/2008:1 (2007)). The exemptions for the EU ETS regulated plants have remained. However, the carbon tax rate for the non-EU ETS industrial plants were gradually increased between 2011 and 2015, and from January 2018, all exemptions were removed, making non-EU ETS plants subject to the economy-wide carbon tax rate (Ministry of Environment and Energy (2018)). Installations outside the EU ETS regulation experienced carbon tax rate increases after 2011, and all exemptions as well as special tax rates were also removed (Hammar and Åkerfeldt (2011)). More about the EU ETS in subsection 2.4.

2.3 Special provisions of the carbon tax

Swedish carbon taxation incorporates multiple provisions and exemptions (summarized in Table 1) primarily based on how much carbon tax a firm had to pay relative to its output. In 1991, the sum of carbon and energy taxes could not exceed 1.7% of a firm's sales, but the threshold was lowered to 1.2% in 1992 (Government Bill 1989/90:111 (1989)). In 1993, these firm-level exemptions were removed for almost all industries and replaced with a two-tier system where mining and manufacturing sectors paid 25% of the general carbon tax rate, or 0.08 (SEK) per kilogram (kg) of emitted CO_2 (Government Bill 1991/92:150 (1991)). The only exceptions were the cement, glass, and lime industries[17], whose carbon tax payments were still capped at 1.2% of their sales (this is called the 1.2% rule).

In 1997, a new and more complex system reintroduced exemptions. A new carbon taxes paid-to-sales break-point of 0.8% was introduced, above which the tax rate was reduced by 75% (this is labeled as the 0.8% rule). In other words, manufacturing firms would pay 0.19 SEK per kg CO_2 until total tax payments reached 0.8% of firm sales, and 0.09 SEK per kg emitted CO_2 above this break-point.[18] The 0.8% rule was in force up to 2010, after which the break-point was first increased to 1.2% in 2011, and then removed completely in 2015, leading to a substantial increase in the manufacturing carbon tax rate.

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[17] Since these industries are very vulnerable to the costs of environmental taxation (Government Bill 1989/90:111 (1989), Government Bill 1991/92:150 (1991))

[18] The cement, glass, and lime sectors could still apply their 1.2% rule if their payments (i.e. carbon tax up to 0.8% sales plus the product of the excess emission and the quartered industrial rate) exceed 1.2% of their sales. The 1.2% rule for the cement, and glass industries was removed in 2007.

2.4 The introduction of the EU ETS

In 2005, the European Union introduced a cap-and-trade scheme for CO_2 emissions, the EU ETS (*European Union Emissions Trading System*). A cap was set on EU aggregate greenhouse gas emissions from EU plants, which in turn determined the number of allowances that would be given to firms.[19] Emission allowances were allocated for free to the participating plants (or "installations") in the pilot phase (i.e., 2005-2007). The majority of emission rights were distributed for free in the second trading phase (i.e., 2008-2012), but a small fraction of allowances exchanged owners by auctions. In the third phase, starting in 2013, the method of auctioning out emission rights became the default tool in allowance allocation.

Participation and monitoring of CO_2 is mandatory for firms in the energy sector and in energy-intensive industries. In some sectors, only plants above a certain size are included in the trading system. Governments can exclude small installations from the system if fiscal or other measures that cut their emissions by an equivalent amount are in place (for further details on the institutional settings, see Sajtos (2020)). About 700 Swedish installations (the majority being manufacturing plants) became regulated under EU ETS in 2005 according to the European Union Transaction Log, the registry database of the EU ETS.

3 Carbon Pricing Across Firms, Sectors, and Over Time

3.1 Data and sample construction

Our sample is constructed by matching plant- and firm-level registry data (including accounting variables, number workers, sector classification, etc.) with CO_2 emissions for the time period 1990-2015. *Swedish Environmental Protection Agency* (SEPA) provided data on CO_2 emissions at plant- and firm-level (including emissions under the EU ETS), and the firm-level registry data is from *Upplysningscentralen* (UC) for the period 1990-1997 and from Bisnode Serrano for 1998-2015.[20]

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[19] One unit of emission right allows a firm to emit greenhouse gases equivalent to one metric tonne of CO_2. The granularity of our data enables us to disentangle the different types of greenhouse gases emitted.

[20] The industrial classification systems (equivalent to NACE codes) were revised three times during our sample period. We harmonize these industry codes using the plant-level data, which includes industry affiliation codes in multiple nomenclatures during some of the transitional years.

The sample criteria is to include firms with observable sales and emissions in order to be able to compute emission intensities. The data collection for CO_2 emissions changes during our sample period (see Table B.1), most notably in 1997-1999 and 2003-2006 when only larger plants are considered. This, however, does not change the fraction of aggregate CO_2 emissions covered over time. Our sample covers on average 85% of aggregate manufacturing CO_2 heating emissions (between 80-95%) (Figure A.3). The coverage during the periods when only larger plants were considered is not systematically different from other years. Finally, our sample covers, on average, 87% of total (process plus heating) CO_2 emissions (Figure A.4).

Our total sample covers around 50,000 firm-year observations in the Swedish manufacturing sector during 1990-2015. In the regression analysis, we require firms to have at least five consecutive observations to be included resulting in a sample size of about 32,000 firm-years. Descriptive statistics for the key variables used in this study across the two samples are displayed in Table 2. Additional detail on the data and sample construction (including how we handle EU ETS as well) can be found in subsection B.1, subsection B.2, and Sajtos (2020).

3.2 Swedish manufacturing CO_2 emissions, 1990-2015

First, we want to document how CO_2 emissions evolve over our sample period across different manufacturing sub-sectors. Since firms enter and exit the sample over time, we divide firms into four-digit industries and track the evolution of industry emissions from 1990 and onward. Specifically, we sum up all (heating) CO_2 emissions as well as PPI-adjusted sales across all firms in each four-digit industry each year. We then rank the industries depending on the ratio between aggregate emissions divided by aggregate sales in 1990 (the year before the introduction of the carbon tax) from highest to lowest and divide them into deciles. This results in ten bins of about twenty industries each. We compile summary statistics over emissions-to-sales, the share of manufacturing fossil CO_2 emissions and share of carbon tax payments by decile in 1990 (panel A), 2007 (panel B), and 2015 (panel C) in Table 3.[21]

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[21] We choose 2007 as a reference year because it is the last year when all Swedish manufacturing plants were subject to the domestic carbon tax. Following the introduction of EU ETS, plants entering the emissions trading system were gradually phased out of the Swedish carbon tax system.

In 1990, the emission intensity of the Swedish manufacturing sector as a whole was 0.0084, i.e. for every SEK of sales (in 2010 prices), 0.0084 kg (or 8.4 grams) of CO_2 was emitted. The heterogeneity across manufacturing firms is substantial, however, with a large concentration of emissions in decile 10, with an emissions intensity of 0.0313 compared to 0.0019 in decile 5. Firms in decile 10 accounted for 72% of aggregate CO_2 emissions in 1990, and decile 9 for another 10%. The remaining eight deciles combined thus comprised less than 20% of aggregate CO_2 emissions in 1990. We also present the share of total carbon tax payments in 1991 in panel A. Since carbon tax payments were capped at 1.7% of sales when the tax was introduced in 1991, a large fraction of the CO_2 emissions for high-emitting firms was effectively exempt from taxes (we discuss this in detail in subsection 3.3). As a consequence, decile 10 firms only made up 54% of the carbon tax payments in 1991 despite emitting 80% of aggregate CO_2. In contrast, the share of tax payments exceeded the share of CO_2 emissions for the other nine deciles.

In panels B and C, we see that aggregate CO_2 emissions-to-sales decreased from 0.0084 to 0.0067 between 1990 and 2007 and has remained at a similar level thereafter.[22] In 2007, changes in the tax system (to which we will return below) made the share of CO_2 emissions and carbon tax payments more similar across groups: decile 10's share of CO_2 emissions is 81% while the share of carbon tax payments is 75%. In 2015, the majority of high-emitting plants had transitioned into the EU ETS, leading to a sharp reduction in decile 10's share of carbon tax payments from 2007 to 2015.

We report additional emission statistics across deciles in Table 4. Panel A reports averages over 1991-1995, to smooth out the volatility in manufacturing sales stemming from the deep recession Sweden experienced in the early 1990s (and the subsequent rebound). The fraction of carbon tax payments-to-sales was 0.0018 for the total manufacturing sector in the early years, ranging from a high of 0.0055 in decile 10 to a low of 0.0002 in decile 1. We also relate carbon tax payments to firm operating profits, measured by Earnings Before Interest and Taxes (EBIT). Tax payments amounted to 3.2% of EBIT for the manufacturing sector as a whole. In decile 10, however, carbon tax payments reduced firms' pre-tax margins by more than 6 percentage points. In comparison, the Swedish corporate

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[22] Since firms enter and exit the sample over time, these changes reflect a combination of technological and compositional changes, which we will later try to decompose. In Figure A.5 and Figure A.6 we show the evolution of emission intensities over time for a balanced sample of manufacturing firms.

tax rate was 30% (1991-93) - 28% (1994-2008) over this period (calculated on earnings *after* interest). Finally, the table shows that 70-75% of all CO_2 emissions from manufacturing originate from decile 10 firms, while only accounting for around 16% of total output.

Figure 3, Figure 4, and Figure 5 display the evolution of CO_2 emissions, output, and carbon tax payments, respectively, across emission deciles over time. In Figure 3, we see that CO_2 emissions in the Swedish manufacturing sector have decreased over the sample period together with a contemporaneous increase in the concentration of emissions to the firms in decile 10. In contrast, Figure 4 shows that the shares of manufacturing output have been quite stable over this period. Finally, Figure 5 shows that decile 10's share of carbon tax payments decreased to below 40% as the heaviest emitters transitioned into the EU ETS.

3.3 Carbon tax regimes

Our identification strategy relies on cross-sectional differences in marginal tax rates across firms, which allows us to control for time and firm fixed effects in order to isolate the effect of carbon pricing on emissions. This identification is made possible due to the various exemptions that high-emitting firms enjoyed at various points in our sample period, illustrated in Figure 6.[23]

When the tax was first introduced in 1991, CO_2 emissions were taxed at 0.25 SEK per kg, but with exemptions for the highest-emitting firms. In 1991, taxes were capped at 1.7% of sales, which was further reduced to 1.2% in 1992, implying that firms above the threshold faced a zero marginal tax rate on emissions. In 1993, the tax rate for manufacturing firms was reduced significantly in combination with the removal of the tax cap, so all firms (except for cement, glass and lime, where exemptions were still in place) were taxed at a constant rate of 0.08 SEK per kilogram. This meant that lower-emitting firms experienced a marginal tax decrease, while high-emitting firms that were previously above the tax cap threshold went from a zero to a positive marginal tax rate.

The carbon tax system was changed again in 1997, when the tax rate for manufacturing

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[23] Calculations here are only for illustrative purposes in order to clarify how the different carbon tax regimes affected a synthetic firm at different levels of carbon tax payments. Here we consider a firm with 50,000 SEK in sales. For 1991 and 1992, we assume that the firm only burns coal in order to avoid having to deal with energy taxation which manufacturing was exempted from in 1993 (see Table 1).

more than doubled to 0.19 SEK per kg of CO_2 emitted.[24] At the same time, a new exemption was introduced for high-emitting firms, where the standard rate of 0.19 was paid until total payments reached 0.8% of sales, after which the marginal tax rate was reduced to 0.046 SEK per kg of CO_2 (or 25% of the standard rate).

The manufacturing carbon tax rate was raised again in 2011 together with an increase in the exemption cutoff from 0.8% to 1.2% of sales. Finally, in 2015 all firm exemptions are removed and the manufacturing carbon tax rate is doubled to 0.63 SEK per kg CO_2 emissions. By this time, however, most high-emitting plants had transitioned into the EU ETS and were no longer subject to the Swedish carbon tax.

3.4 Divergence in average and marginal tax rates

As Figure 6 illustrates, the numerous changes of the carbon tax system results in substantial variation in both average and marginal tax rates in both the time-series and the cross-section, which will be key to our identification of tax elasticities. Figure 7 shows the average, effective tax rate, computed as total carbon taxes paid divided by total CO_2 (heating) emissions (*Average tax*), together with the marginal tax rate for the next emitted unit of CO_2 (*Marginal tax*) for two groups of firms. The first group comprises firms with emissions below the thresholds for tax reductions (i.e., that never receive any exemptions) and also remain outside the EU ETS throughout the whole sample period. For these firms, the average tax rate equals the marginal tax rate across all years. The second group consists of firms whose emissions lie above the carbon tax-to-sales threshold for all years where exemptions are in place and whose plants transition into the EU ETS. Prior to the EU ETS (and with the exception of 1993-1996), the average carbon tax rate exceeded the marginal tax rate for this group of firms. As EU ETS was introduced, their implicit marginal tax rate, as reflected by the price of emission rights, increased considerably (subject to price fluctuations in emission rights), while their average tax rate stayed more or less the same (because most emissions allowances were granted for free, see subsection 2.3).

The significant differences in marginal and average tax rates across groups, seen in

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[24] This marginal tax increase was a result of a reduction in the tax discount for firms in the manufacturing sector. Upon the introduction in 1993, manufacturing firms paid only 25% of the nominal carbon tax rate (i.e., 0.32 x 0.25 = 0.08 SEK/kg in 1993). In 1997, this discount was changed to 50% (i.e., 0.37 x 0.50 = 0.185 SEK/kg).

Figure 7, have important economic implications, as firms' incentives to reduce their CO_2-emissions depend on the former while their tax burden depend on the latter. For the most extreme period in 1991-1992, the highest emitting group paid taxes amounting to 0.3-0.45 SEK per kg of emitted CO_2 on average, but had a tax rate of zero on the next unit of emitted CO_2. During 1997-2008, firms granted exemptions paid an average carbon tax rate of about 0.07-0.1 SEK/kg compared to only a marginal cost of 0.04-0.05. The relevant pricing signal is 0.04-0.05 and not 0.07-0.1 per unit of emitted CO_2.

With the introduction of EU ETS there is a shift for the group of high-emitting firms, as the plants regulated under EU ETS are beginning to be phased out from the carbon tax system. While the average tax rate for the non-EU ETS part of their CO_2 emissions increased, they paid no tax on the part covered by EU ETS as long as their emissions were lower than their free allowance of rights, resulting in no major change in average taxes.

The most important consequence of the EU ETS, however, was that the marginal cost of emitting CO_2 (i.e. the cost of the next unit of emission) now became the market price of one emission permit rather than the statutory carbon tax rate, which in turn depends on the supply and demand in the market for emission permits.

As explained in subsection 2.3, during the transition period between 2008 and 2011, the marginal cost of emissions equalled the sum of emission allowance prices and marginal carbon tax rates for firms under the EU ETS (the latter could be equal to 0 if the combined costs of emissions exceed the designated exemption threshold). From 2011 plants covered by the EU ETS were completely exempt from the carbon tax.

In Figure A.7, we report how much of manufacturing sales, CO_2 emissions and carbon tax payments that can be attributed to firms facing exemptions as well as firms eventually covered under EU ETS regulation over different time periods in our sample. Before EU ETS, the firms with exemptions, who faced a very low marginal tax for most of the period, only accounted for a small fraction of total manufacturing output, but a considerable fraction of total emissions. From 2008 and onward, firms covered by the EU ETS (which include both the firms previously subject to exemptions as well as some firms below the exemption thresholds) account for close to half of total manufacturing output and 80-90% of total emissions.

3.5 Firm-level response to early carbon tax changes

Here, we provide some descriptive difference-in-difference evidence around the early changes in carbon pricing in Sweden. We balance the panel and only consider firms in the sample during the first thirteen years (1990-2002).[25] Table 5 reports changes in the marginal cost of emitting CO_2 (panel A) and in emission intensity (panel B) around the introduction of the carbon tax in 1991 and around the 1993 change (when the high emitters went from having zero to a positive marginal tax rate). We sort firms into those qualifying for exemptions in 1991-1992 and those that did not.

The first column covers the firms with exemptions. These firms did not experience a change in marginal costs following the introduction of the carbon tax in 1991. However, after 1993, they experienced an increase from 0 to 0.086 SEK/kg per unit of emitted CO_2. On the other hand, firms without exemptions went from paying no carbon tax in 1990, to paying 0.227 SEK/kg in 1991-1992, to paying 0.086 in 1993-1996. We report the difference-in-difference in the column farthest to the right in Table 5. Following 1991, the group of firms without exemptions experienced a relative increase in the marginal cost of 0.227 compared to the firms with exemptions. On the flip side, following the 1993 tax change, the firms with exemptions experienced a relative increase in marginal cost of emitting CO_2 equivalent to 0.227 (0.086 minus -0.141).

In panel B, we evaluate how the corresponding CO_2 emissions-to-sales changed around the same events. The average emission intensity of firms with exemptions increases relatively more than for firms with exemptions (a relative change of 0.023), which is consistent with the marginal cost changes reported in panel A. Also, following the 1993 tax change, firms that enjoyed exemptions in the 1991-1992 period display lower emission intensity relative to firms without exemptions (a relative change of -0.059), which again is consistent with the results in panel A. It becomes clear from panel C that very few firms qualified for exemptions (nine out of 234 firms in the balanced sample), but these firms made up a considerable amount of emissions.

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[25] The choice of thirteen years is quite arbitrary. The results in this sub-section are qualitatively similar if we consider slightly shorter or longer time periods.

4 Estimation of Carbon Pricing Elasticities

4.1 Main specification

We now turn to estimating the longer-term impact of carbon pricing on firm-level CO_2 emissions. As it is the *marginal* (rather than the *average*) cost that should affect firm incentives (e.g., Fazzari et al. (1988)), we model firm CO_2 emission intensity as a function of the marginal carbon tax rate. We have to tackle a few specification issues. First, it is not theoretically clear at what time lag carbon pricing affects firms' CO_2 emissions.[26] Second, while we do have plenty of time series and cross-sectional variation in the marginal carbon tax rate, we do not have any periods of one group being affected by a change and another unaffected. This means that we do not have a proper control group to derive counterfactual CO_2 emissions in the absence of a tax. With these caveats in mind, we proceed with our baseline specification of the relationship between CO_2 emissions per unit of output and the carbon tax rate.

$$ln\left(\frac{E_{\mathrm{i,t}}}{Y_{\mathrm{i,t}}}\right) = \omega + \sum_{s=0}^{q} \sigma_{\mathrm{s}} \cdot ln(\tau_{\mathrm{i,t\text{-}s}}) + \delta_{\mathrm{i}} + \delta_{\mathrm{t}} + \epsilon_{\mathrm{i,t}}, \qquad (1)$$

where E is kilograms (kg) of CO_2 heating emissions divided by purchasing-power adjusted sales (in 2010 Swedish Krona (SEK)) of firm i in year t. τ captures the marginal carbon tax rate for firm i in year t. For firms with plants covered under EU ETS we compute the marginal tax rate as the emission-weighted average of the marginal tax rate under the Swedish carbon tax system (for the installations not under EU ETS) and the market price of the emission trading permits (for the installations covered by EU ETS). δ_i accounts for any firm specific, time invariant factor that impacts the relation between CO_2 emissions and sales. δ_t captures specific changes in CO_2 emissions common to all manufacturing firms in Sweden in a given year. The lagged terms of τ capture that changes in firm-level CO_2 emissions respond with some delay. We show results with up to three yearly lags of carbon taxation (which is also our preferred specification).

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[26] Similarly, deciding the lag length is also challenging when it comes to the empirical modeling of how the capital-output ratio responds to changes in marginal taxation (Bond and Xing (2015)).

4.2 Baseline results

We report baseline results from estimating Equation 1 with q=0 up to q=3 in columns 1-4 in Table 6. In column 1, we report evidence without including any lags of τ.[27] The level of the marginal tax rate is strongly inversely related to firm-level carbon emissions intensity. The result implies that one percent increase in the marginal carbon tax rate is associated with a 2.8% decrease in the CO_2 emissions-to-sales ratio. In the next three columns, we add lags to the specification and also present the sum of the σ's and the joint significance. Adding one lag, as we do in column 2, leads to a larger joint estimate. The contemporaneous marginal tax rate coefficient drops slightly to -2.244 and the σ for q=1 is highly significant and is estimated at -1.091. The sum of the two coefficients is 20% higher than the estimated effect in column 1. We add additional lags in columns 3 and 4 and only observe marginal increases in the sum of the σ's. We do note that the σ estimated at q=3 is statistically significant, and we therefore use the lag structure in column 4 as our baseline specification.[28] Accounting for time delay in the response to carbon pricing, our baseline estimate suggests that one percent increase in the marginal carbon tax rate is associated with a 3.4% decrease in the CO_2 emissions-to-sales ratio.

Finally, in column (5) of Table 6, we only include firms from the industries in decile 10, which accounts for 70-80% of manufacturing CO_2 emissions and includes many firms with tax exemptions. Estimating Equation 1 using firms only from decile 10 yield results with statistical significance at all lags and a sum of σ's larger than for the full sample in column 4. A one percent increase in marginal carbon taxation for decile 10 firms is associated with a 4.6% decrease in firm-level carbon intensity.

4.3 Robustness

Next, in Table 7, we consider the robustness of the findings in Table 6 in two dimensions. First, since the introduction of the EU ETS represents a significant policy change to how CO_2 emissions are regulated, we augment Equation 1 with a full set of interaction terms between the marginal tax rate and an indicator variable taking on the value one if the firm

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[27] We take one plus the marginal carbon tax rate to also include the firm-years with a zero tax rate. We also take one plus CO_2 emissions-to-sales. Our results are robust to not adding by one.

[28] The results in the remainder of section 4 are robust to considering shorter and longer lag lengths.

is regulated under EU ETS ($ETS_{\text{i,t}}$).

$$ln\left(\frac{E_{\text{i,t}}}{Y_{\text{i,t}}}\right) = \omega + \sum_{s=0}^{q} \sigma_{\text{s}} \cdot ln(\tau_{\text{i,t-s}}) + \sum_{s=0}^{q} \gamma_{\text{s}} \cdot ln(\tau_{\text{i,t-s}}) \cdot ETS_{\text{i,t}} + ETS_{\text{i,t}} + \delta_{\text{i}} + \delta_{\text{t}} + \epsilon_{\text{i,t}} \quad (2)$$

In column 1 in Table 7, we allow *EU/ETS* to vary by firm-year (implying that *EU/ETS* is zero for all firms prior to 2005 and turns one for the firms that have at least one plant regulated under EU ETS in 2005). The contemporaneous interaction between the level of marginal carbon pricing and the EU ETS indicator variable is positive and significant implying that the immediate carbon pricing effect for EU ETS firms is significantly lower than for non-EU ETS regulated firms (-3.816 + 3.192 = -0.624). However, given that we are agnostic regarding the timing of the carbon pricing effect we focus on the joint sum of σ's and γ's. The sum of coefficients for all firm-years outside EU ETS is considerably larger than the baseline result in reported in Table 6, -5.142. The sum of coefficients for EU ETS firm-years is -3.403 and highly significant.

In column 2, we code the EU ETS indicator variable to one for all firm-years if a firm eventually becomes regulated under EU ETS in 2005. This way, we test whether the difference between non-EU ETS and EU ETS firm-years is driven by the introduction of EU ETS or that the firms regulated under EU ETS are different.[29] The uninteracted *EU-ETS* variable drops out due to the firm fixed effect in column 2. It turns out that the result in column 2 is very similar to the result presented in column 1 suggesting it is not necessarily the introduction of the EU ETS that lowers the carbon pricing effect. Overall, we conclude that our estimation results reported in Table 6 are stable over the entire time period including the introduction of the EU ETS.

Second, we add additional firm-level control variables to Equation 1. We include (natural logarithms of) the number of workers (to control for firm size) and capital stock per worker (to control for capital intensity).[30] We report estimation results using Equation 1 controlling for employment in column 4, capital intensity in column 5 and both in column 6. Number of workers are inversely related to CO_2 emissions-to-sales and capital intensity is (statistically) unrelated based on the evidence in Table 7. More importantly, the carbon

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[29] The firms who have plants regulated under EU ETS are certainly different.

[30] The choice of control variables is inspired by Brännlund et al. (2014).

pricing effect is basically unchanged when we include these additional controls.

4.4 Abatement costs and mobility

We now consider two additional factors that have been shown to impact plant- and firm-level emissions and activity: the impact of pollution abatement costs expenditures (PACE) (e.g., Greenstone, 2002) and the geographic mobility of assets (e.g., Ederington et al., 2005). We use US industry-level data to measure PACE, essentially assuming that abatement costs (which should be a function of production technologies) do not differ significantly across countries for a given industry. Specifically, we first calculate the ratio of the sum of PACE and aggregated industry sales for each four-digit US industry in 1990.[31] We split the sample into low (below median-industry PACE) and high (above median-industry PACE) abatement expenditures in columns 1 and 2 of Table 8. The statistical power is reduced due to the smaller sample sizes, but we find a larger effect among low-PACE sector firms compared to in high PACE. This is to a large extent driven by a larger contemporaneous effect for low-PACE firms, which makes intuitive sense. The sum of σ's (in column 1) is twice the size as the baseline result in Table 6. The sum of σ's for high-PACE firms is slightly smaller than the baseline estimate. This result suggests that firms with lower PACE can respond more quickly, and at a lower cost, to a change in carbon pricing.

We also consider how the geographic mobility of assets impacts firms operating in low- and high-PACE sectors. We follow Ederington et al. (2005) and measure the mobility of assets by plant fixed costs, again, using data for US four-digit industries in 1990 (from the NBER-CES Manufacturing Industry Database, (Becker et al., 2013)).[32] Firms above (below) the median in plant fixed costs are referred to as low (high) mobility. We present results for low- (high-) PACE industries divided up to low and high mobility in columns 3

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[31] The data is from U.S. Bureau of the Census (1990), and we use the four-digit SIC 1987 values of the sum of the PACE for capital expenditures and operating costs. We normalize this sum by the corresponding value of shipments for each four-digit sector in 1990 using data from Becker et al. (2013). We then match this number to the corresponding four-digit sector using the Swedish SNI codes for 2007. This process leads to a significant loss in observations as we can only match about half of all firm-years. For the baseline specification in column 4 in T7, we have a total of 20,296 observations. If we re-estimate that specification using only firm-years matched with PACE data, we have 9,530 observations. The baseline result in this smaller sample is slightly smaller in economic magnitude (-2.648 compared to -3.403), but it is still statistically significant at below one percent.

[32] Specifically, plant fixed costs is measured as the ratio between the real structures capital stock and the value of shipments. Also, similarly as with the PACE data, we lose quite a lot of observations in the process of converting 1987 SIC codes to 2007 SNI codes.

(5) and 4 (6) (in Table 8). There are two takeaways from the estimation results in columns 3 to 6. First, carbon pricing has a drastically larger effect on emissions for firms in low-PACE and low-mobility industries. This is expected as firms operating in low abatement-cost industries and with immobile assets can more easily and cheaper respond to carbon pricing and do not have the option to evade the tax by moving production facilities abroad. Second, although we suffer from lower power due to a smaller sample size, the estimated response to carbon pricing for firms in high-mobility sectors is similar to our baseline estimates in Table 6.

5 Aggregate Effects: Understanding the Pricing Effect

5.1 Decomposing Sweden's manufacturing CO_2 emissions

We now decompose the change in aggregate development of CO_2 emissions in the manufacturing sector since 1990 using the framework developed in Grossman and Krueger (1991) and Grossman and Krueger (1993).[33] The decomposition separates the change in emissions into three parts. The first part is a "scale" effect, which captures how CO_2 emissions would have developed if the composition of the manufacturing sector and production technologies had remained at their 1990 level. The second part is a "composition" effect, which captures to what extent the mix of sub-sectors making up the manufacturing sector changes over time and how that affects aggregate CO_2 emissions. The third part is a "technique" effect and captures the effect of changing production technologies on CO_2 emissions per unit of output produced.

In order to measure the contribution of each of the three mechanisms we follow the approach in Levinson (2009). The results are presented in Figure 8.[34] We compute the "scale" effect by plotting PPI-adjusted, total sales for Swedish manufacturing with 1990 as base year (Line (1) in Figure 8). If the composition and production technologies had remained constant since 1990, CO_2 emissions from Swedish manufacturing would have decreased by 3% in 2015 relative to 1990 levels. Line (2) in Figure 8 plots the aggregate

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[33] This approach is formalized in Copeland and Taylor (1994) and discussed in light of the broader trade and environment literature in Copeland and Taylor (2004).

[34] Levinson (2009) applies this decomposition to understand the evolution of sulphur dioxide emissions from the U.S. manufacturing sector 1987-2001. See section I of their article for a more detailed description of this approach.

CO_2 emissions for Swedish manufacturing with 1990 as base year. This represents the combined scale, composition and technique effect. The level of overall CO_2 emissions in 2015 represents a decrease by 31% relative to in 1990. Finally, line (3) captures the scale and composition effects, holding technology constant, measured as the carbon intensity (aggregate CO_2 emissions divided by aggregate PPI-adjusted sales) in each four digit industry in 1990 multiplied by its annual PPI-adjusted sales. In other words, line (3) represents what total CO_2 emissions would have been each year if each manufacturing sub-sector had kept its output share and produced emissions at the rate of the 1990 production technology. Swedish manufacturing CO_2 emissions would have been 13% lower given the changes in scale and composition but holding production technology constant.

Given the time series development of lines (1)-(3) in Figure 8 (presented in the first three columns in Table 10) we can back out the composition and technique effects. The composition effect is obtained by the difference between line (1) and line (3) in Figure 8. Since the scale effect can account for a 3% reduction and the scale and composition effects combined for a 13% (line (3)) reduction, the composition effect alone accounts for a 10% drop in CO_2 emissions relative to 1990 levels (column (4) in Table 10 (Panel A)). In other words, changes in the composition of the Swedish manufacturing industry towards less carbon-intensive sub-sectors explains slightly more than a third of the 28 percentage point gap between total manufacturing sales and total CO_2 emissions (column (1) in Table 10 (Panel B)).[35]

Finally, the technology effect is the difference between lines (2) and (3) in Figure 8. Scale, composition and technique (line (2)) together lowered CO_2 emissions by 31%. Holding technology constant, scale and composition (line (3)) decreased emissions by 13%. Accordingly, the technique effect amounts to an 18% drop in emissions (column (5) in Table 10 (Panel A)). The technology effect explains almost two thirds of the total difference in sales and CO_2 emissions (column (2) in Table 10 (Panel B)).[36]

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[35] This is consistent with the findings in Jiborn et al. (2018) that finds that Sweden have changed the composition of both imports and exports toward more (less) carbon intensive imports (exports).

[36] We note however, that this decomposition framework has shortcomings. For instance, if firms can move establishments abroad without any effect on domestic sales, this might be interpreted as "technique" rather than carbon leakage.

5.2 How much of the CO_2 emissions reduction is due to carbon pricing?

5.2.1 CO_2 emissions elasticity

In order to estimate the effect of carbon pricing on aggregate CO_2 emissions, we need to apply proper estimates of carbon pricing elasticities for different firms and apply them to the decomposition analysis in subsection 5.1. We have so far documented a robust inverse relationship between the level of the marginal carbon tax rate and carbon emissions intensity over time for the average firm. To be able to account for heterogeneity in carbon pricing elasticities across firms, we build on the approach in Shapiro and Walker (2018), who estimate emission intensities as a function of the pollution abatement cost share (defined as pollution abatement costs relative to factor costs). However, we do not have access to data on actual abatement costs by firm or sector. We therefore assume that the costs a firm faces for CO_2 emissions abatement are related to the cost of its carbon emissions (under the Swedish carbon tax and, later, for some, the EU ETS) relative to its total costs (measured as cost of goods sold). In other words, we assume that a firm's response to carbon pricing is driven by the firm's marginal price on emitting carbon multiplied by its CO_2 emissions relative to its total factor costs. Our approximation of the firm-level CO_2 emission abatement cost share effectively means that we assume that in sectors where emission costs account for a high fraction of their total costs have higher abatement costs.

We validate this assumption using data for US manufacturing from the Pollution Abatement Costs and Expenditures (PACE) survey for 1990 (U.S. Bureau of the Census (1990)).[37] We report aggregate CO_2 emissions scaled by sales and costs, and PACE expenditures scaled by sales and total costs by emission-intensity decile in Table B.2. Comparing the emissions-to-sales (column 1) and emissions-to-cost (column 2) ratios shows that they are very similar, with a correlation coefficient of 0.998.

In columns 3 and 4, we show that decile 10 also has disproportionately higher PACE relative to both sales and costs. The CO_2 emissions-to-sales ratio in decile 10 is around three times higher than the average manufacturing ratio (0.0313 relative to 0.0084). This stark difference is also present in the PACE numbers, where the PACE-to-sales ratio

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[37] We merge the PACE survey information with data on sales and total costs from the NBER-CES Manufacturing Industry Database (Becker et al. (2013)). The PACE survey and NBER-CES Manufacturing Industry Database contains data at the 1987 four-digit SIC industry level. We create a correspondence key between SIC 1987 to SNI/NACE 2007.

is more than three times higher (0.0088 vs. 0.0021) and PACE-to-cost is more than twice as high for decile 10 relative to the manufacturing sector as a whole (0.0109 vs. 0.0032). All four variables in Table B.2 are highly correlated, with CO_2 emissions-to-sales having a correlation coefficient of 0.98 and 0.96 with to PACE-to-sales and PACE-to-cost, respectively.[38]

Following Shapiro and Walker (2018) we estimate the regression

$$\Delta ln\left(\frac{E_{\mathrm{i,t}}}{Y_{i,t}}\right) = \omega + \frac{1-\alpha}{\alpha}\Delta ln(1-a_{\mathrm{i,t\text{-}1}}) + \delta_{\mathrm{i}} + \delta_{\mathrm{t}} + \epsilon_{\mathrm{i,t}}, \tag{3}$$

where $a_{i,t\text{-}1}$ is the beginning of the year CO_2 emission abatement cost share, estimated using the approach just described. The coefficient α is elasticity of the CO_2 emission intensity to the relative abatement cost.

We report results from estimating Equation 3 for the manufacturing sector as a whole as well as individual deciles in Table 9. The elasticity for aggregate manufacturing is 0.019, implying that a one percentage point increase in the CO_2 emissions abatement cost share is associated with a 1.9% decrease in the CO_2 emissions-to-sales ratio. Or, put differently, the response of a typical manufacturing firm to carbon pricing is consistent with an abatement cost equal to 1.9% of total production costs.

When we consider subgroups of firms according to their emissions intensity, Equation 3 shows that elasticity is considerably higher in decile 10 than for the manufacturing sector as a whole. In fact, there is a fairly close relationship between the emissions-intensity decile and the magnitude of the elasticity.[39] Equipped with estimates of CO_2 emissions-to-abatement cost shares by decile, we can now proceed to approximate the aggregate impact of carbon pricing.

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[38] These results are not surprising. CO_2 emissions and air pollution tend to originate from similar production processes. The highest CO_2 emitting sectors are cement production, oil refineries and steel manufacturing. These sectors are also the highest in terms of air pollution and subsequently pollution abatement cost expenditures.

[39] This result is similar in magnitude to the evidence in Shapiro and Walker (2018) (their table 2). Their aggregate manufacturing pollution elasticity is 0.011. They also estimate separate elasticities by two-digit manufacturing sector and find that four sectors have a higher pollution elasticity than the manufacturing average: Paper and publishing; Coke, refined petroleum, fuels; Chemicals; Other non-metallic minerals; Basic metals. We note that most of the decile 10 (four-digit) sectors in our study are from these five industries. In fact, when we re-estimate Equation 3 by two-digit manufacturing sectors we obtain very similar results (see Table B.3). The same five two-digit manufacturing industries also display a higher elasticity than the aggregate manufacturing elasticity in our sample. The 'Food, beverage, and tobacco products' sector is also higher than the aggregate manufacturing elasticity in our setting. We do note, however, that this elasticity is imprecisely estimated and not significant at conventional levels.

5.2.2 Impact of carbon pricing

Our goal is to estimate how much of the 31% CO_2 emissions decrease in Swedish manufacturing that can be attributed to carbon pricing. In order to do this, we aggregate the emissions abatement cost share (a) by decile and year, multiply it with its corresponding elasticity from Table 9, and aggregate across all deciles for each year. Finally, we convert this value to an index with *1990=100* and plot the corresponding index (dotted markers) in Figure 9 alongside the scale, composition and technique effect from Table 8. The carbon pricing effects index display its largest effects on CO_2 emissions in 1991 (year of the introduction of the Swedish carbon tax), 1997 (the year of the doubling of the manufacturing carbon tax rate) and 2015 (when there was a large increase in carbon tax rates and firm exemptions were abolished). We estimate that 13 percentage points of the 31 percentage point decrease in manufacturing CO_2 emissions (i.e. roughly 40% of the total) can be attributed to carbon pricing. We summarize the results from Figure 8 and Figure 9 in Table 10. This approach does not enable us to decompose the carbon pricing effect into composition versus technique effects, however.

5.3 Manufacturing CO_2 emissions in similar countries without carbon taxation

Another way to assess the impact of the Swedish carbon pricing policy is to compare the CO_2 emissions in the Swedish manufacturing sector with other developed countries who did not introduce such policies. We start by showing how manufacturing emissions and sales are distributed across industries over time in other developed countries. We then estimate how manufacturing CO_2 emissions-to-sales in Sweden *could* would have evolved in the absence of a carbon tax.

5.3.1 The distribution of combustion CO_2 emissions and output in other developed countries

To compare manufacturing manufacturing CO_2 emissions across countries we rely on data from the International Energy Agency (IEA). We complement this data with value-added and producer-price deflators obtained from the OECD and the UN. Our comparison sample consists of countries that did not have a carbon tax and for which data on CO_2 emissions, value added and price deflators are available from 1989 to 2015. Using this criterion, the comparison sample consists of the following fourteen OECD countries: Australia,[40] Austria, Belgium, Canada, France, Germany, Iceland, Ireland, Italy, Japan, New Zealand, Portugal, Spain, and the United Kingdom. We divide the manufacturing sector of each country into a high and low carbon intensive segment. The high carbon intensive segment includes all sub-sectors classified as being in the top 10 decile in our previous analysis. See subsection C.1 for additional details on this sample.

In Figure 10 we plot the aggregate CO_2 emissions in both high (dotted area) and low (solid fill) carbon intensity sectors across all eleven comparison countries. Consistent with our previous results, the high-emitting sectors in the international sample account for on average roughly 85% of all combustion CO_2 emissions in manufacturing. In other words, the observed concentration of CO_2 emissions to sectors such as Basic metals, Oil refineries, Cement production and Paper manufacturing is not a particular feature of the Swedish manufacturing sector. We also plot sales across high and low carbon intensity manufacturing sectors (Figure 11). The high carbon-intensity sub-sectors comprise about 40% of output (compared to around 20% in decile 10 for Sweden). This discrepancy stems from the higher level of aggregation in the international sample.

5.3.2 Sweden and synthetic Sweden

We now use our international sample to construct a counterfactual of how Swedish emissions would have evolved in the absence of carbon pricing using a synthetic control algorithm.[41] This methodology[42] addresses counterfactual questions involving a singular treated unit relative to control units. Intuitively, the synthetic control method constructs a weighted average of control units that is as similar as possible to the treated unit regarding the pre-treatment outcome variable and covariates (Firpo and Possebom (2016)). For this reason, this weighted average of control units is known as the synthetic control. We compile information on the details of how we constructed the synthetic control group in

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[40] Australia did introduce a carbon pricing mechanism in 2011. But this was later repealed in 2014.

[41] Synthetic control method has emerged as a standard approach to conduct comparative studies (including e.g. natural resources and disasters (Barone and Mocetti (2014), economic and trade liberalization (Billmeier and Nannicini (2013)), education and research policy (Belot and Vandenberghe (2014)).

[42] It was originally proposed by Abadie and Gardeazabal (2003).

subsection C.2.[43]

Figure 12, 13, and 14 report emission intensity series for the overall manufacturing sector, and the high and low carbon-intensity sub-sectors, respectively. They show that emission intensities in Sweden and in its synthetic counterpart track each other closely, verifying that our synthetic control captures the trend prior to treatment. Furthermore, Table B.4 compares the values of the key predictor variables used to construct the synthetic control. While not completely identical, we believe there is a reasonable fit between Sweden and the synthetic control prior to the 1991 treatment year.[44]

Turing to the post-treatment patterns, Figure 12 and Figure 13 show that Swedish emission intensities evolve quite similarly to the synthetic counterpart (and both closely follow the evolution of the world average). For the low emission-intensity sectors (Figure 14), however, Swedish emissions are significantly lower, both relative to the synthetic control group as well as the world average. For this group, both the world average and the synthetic control decrease emissions by about 30% 1990 and 2007, compared to a decrease of about 60% for Sweden. These results are consistent with our findings on the Swedish carbon tax. Firms with positive marginal tax rates, i.e. low emission-intensity firms without exemptions, experience larger emissions reductions.[45]

6 Conclusions and Implications

As one of the first countries in the world, Sweden introduced a carbon tax in 1991, which still remains the world's highest. We assemble a comprehensive dataset and track firm-level CO_2 emissions during 1990-2015. Our panel includes more than 4,000 manufacturing firms covering almost all CO_2 emissions in the Swedish manufacturing sector. We document a statistically robust and economically meaningful inverse relationship between CO_2 emissions and the marginal carbon cost of emitting CO_2. Using our preferred method, we estimate the CO_2 emissions-to-carbon pricing elasticity to be 0.019 for the manufacturing sector.

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[43] We stop the analysis in 2007 because the introduction of EU ETS would drastically lower the number of countries we could use in the synthetic control group and also due to data quality issues for some countries post 2007.

[44] Since we construct counterfactual emission intensities based on OECD's sectoral-level data, which is more aggregate than our data, the differences in granularity should rationalize the observed discrepancies.

[45] However, the statistical inference procedures offered by e.g. Abadie et al. (2010), and Abadie et al. (2015) do not yield statistically significant differences for the lower-emitting sectors, which may stem from the granularity of the data described above. See subsection C.3 for robustness results and placebo tests.

Aggregate Swedish manufacturing CO_2 emissions decreased by about 31% between 1990 and 2015, while total output of the Swedish manufacturing sector decreased by 3% over the same period. Finally, we estimate that 13 of the 31 percentage point decrease in aggregate manufacturing CO_2 emissions can be attributed to carbon pricing.

6.1 Policy to combat climate change

The manufacturing sector (together with construction) accounts for about one-fifth of global CO_2 combustion emissions (Ritchie and Roser (2017)). Including both direct (scope 1) and indirect (scope 3) greenhouse gas emissions, 100 large corporations account for more than 70% of the cumulative industrial greenhouse gas emissions in the world since 1988 (Griffin and Heede (2017)). Our evidence confirm that manufacturing CO_2 emissions are concentrated to a few sectors, and a handful of firms within these sectors. These results can help inform the fast-growing macroeconomic literature on climate change and growth (e.g., Acemoglu et al. (2016); Golosov et al. (2014)) that need to factor in how CO_2 emissions are distributed in the economy in order to model the impact of carbon pricing on emissions reductions and long-run economic growth.

6.2 How to a structure a carbon pricing mechanism

Our study is also relevant for discussions on how to design optimal carbon pricing mechanisms (e.g., Nordhaus (1993); Bovenberg and De Mooij (1994); Lans (1996); Pindyck (2013)). While our study is not able to account for general equilibrium effects, we believe our results on the impact of statutory versus marginal tax rates carry important implications. Sweden initially opted for a carbon tax with a relatively high nominal tax rate coupled with firm-specific exemptions to "protect" certain sectors whose competitiveness would suffer from paying very high carbon taxes relative to output. As a result, however, vast quantities of CO_2 emissions where effectively exempt from taxation and the low marginal incentives drastically reduced the incentive effect from the carbon tax on firm behavior. Our analysis confirms that firms respond to the marginal carbon tax rate rather than the amount of taxes paid. Exemption policies for high emitters are particularly problematic since one of the most important roles of a carbon tax is to re-direct technical change away from fossil based toward low or no CO_2 emitting technologies (e.g., Jaffe et al. (2002)).

While the highest-emitting firms in Sweden paid low or zero taxes for a large fraction of their CO_2 emissions, their carbon tax payments were still substantial, amounting to as much as 15% of operating profits.

6.3 Technology adoption and development

Our evidence on the sector-concentration of CO_2 emissions carry important implications for the dynamic technology response to carbon pricing. When designing a carbon pricing mechanism, or a climate change mitigation policy in general, it is of first order importance to factor in how increasing costs can impact technology adoption and development in these high-emitting sectors. For instance, the extreme heat required to produce steel makes it challenging to substitute away from coal with existing technology. In Sweden a consortium of large firms together with the government have recently joined forces in developing hydrogen steel making (Åhmana et al. (2018)), which we believe is a good example of a sector-specific policy solution with the potential to significantly lower manufacturing greenhouse gas emissions. While it is hard to prove the extent to which this initiative would not have taken place without carbon pricing, it still suggests the importance of providing marginal incentives for high-emitting sectors to invest in carbon-abatement technologies.

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Figure 1: Carbon and energy taxation of an industrial plant

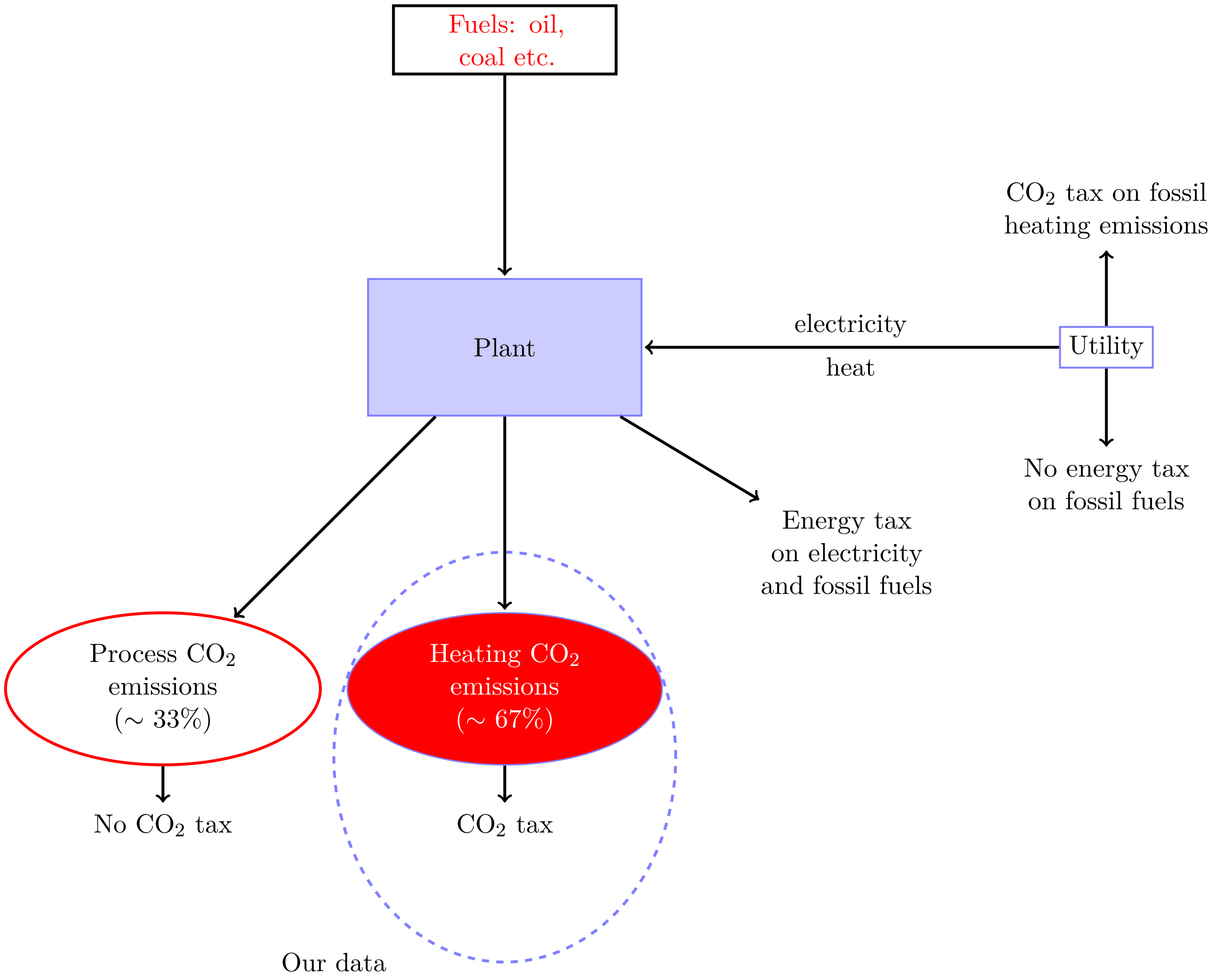

Figure 1 illustrates the carbon and energy taxation for a manufacturing plant in Sweden in 2019. *Heating* CO_2 *emissions* refers to the emissions released from the combustion of fossil fuels. *Process* CO_2 *emissions* refers to the carbon dioxide emissions released in the actual manufacturing process (i.e. not combustion of fossil fuels). *Utility* is the power plant that produces heat and/or electricity, *Plant* is the industrial manufacturing plant.

Figure 2: Carbon tax rate, in nominal values

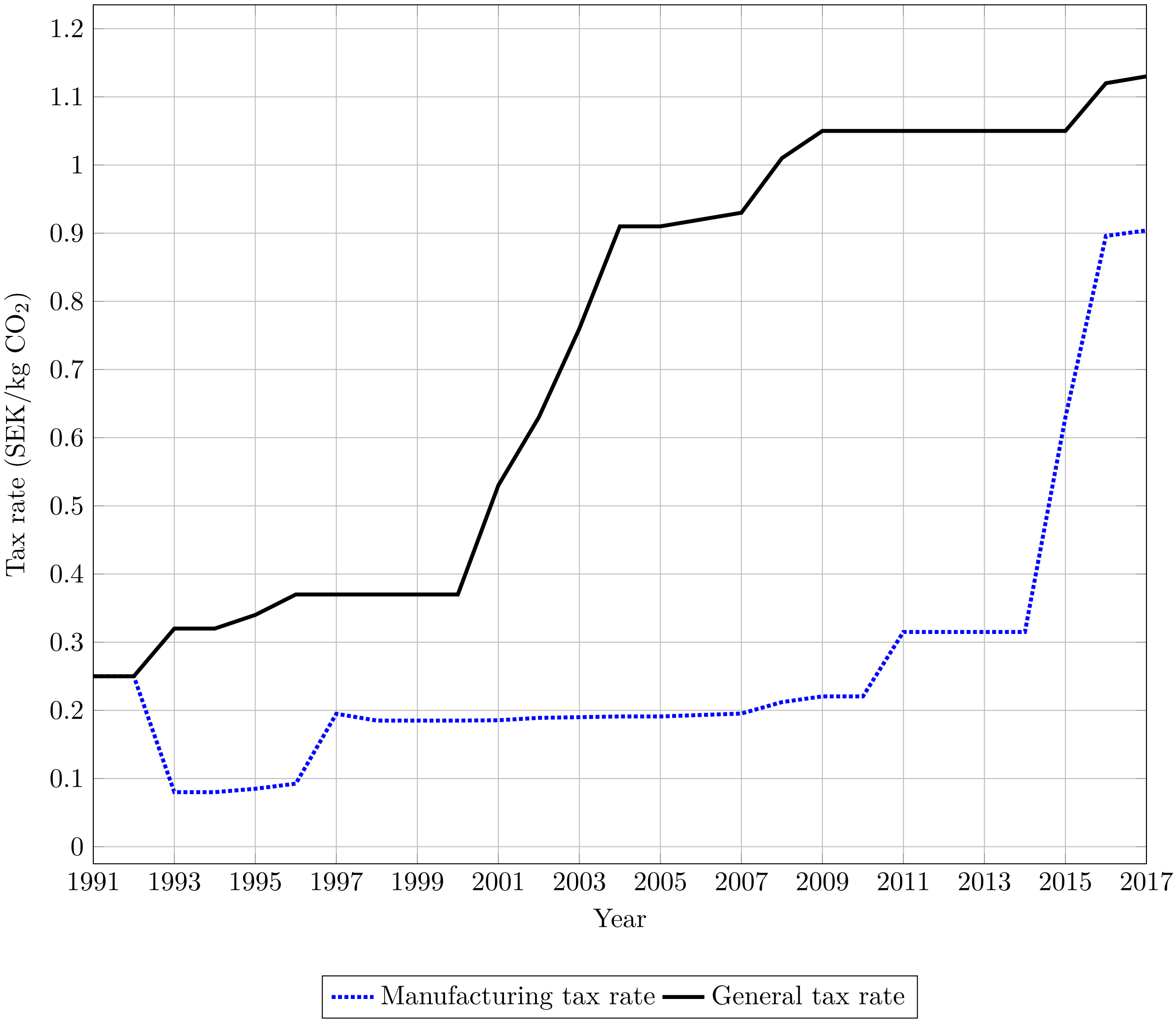

Figure 2 displays the nominal carbon tax rates (Swedish krona per kilogram of emitted carbon dioxide) for Sweden from 1991 to 2017. *Manufacturing tax rate* refers to the tax rate for the manufacturing sector (SNI 10-33 in the SNI2007 nomenclature), while *General tax rate* refers to the tax rate for non-industrial firms and households.

Figure 3: Distribution of CO_2 emissions from Swedish manufacturing (1990-2015)

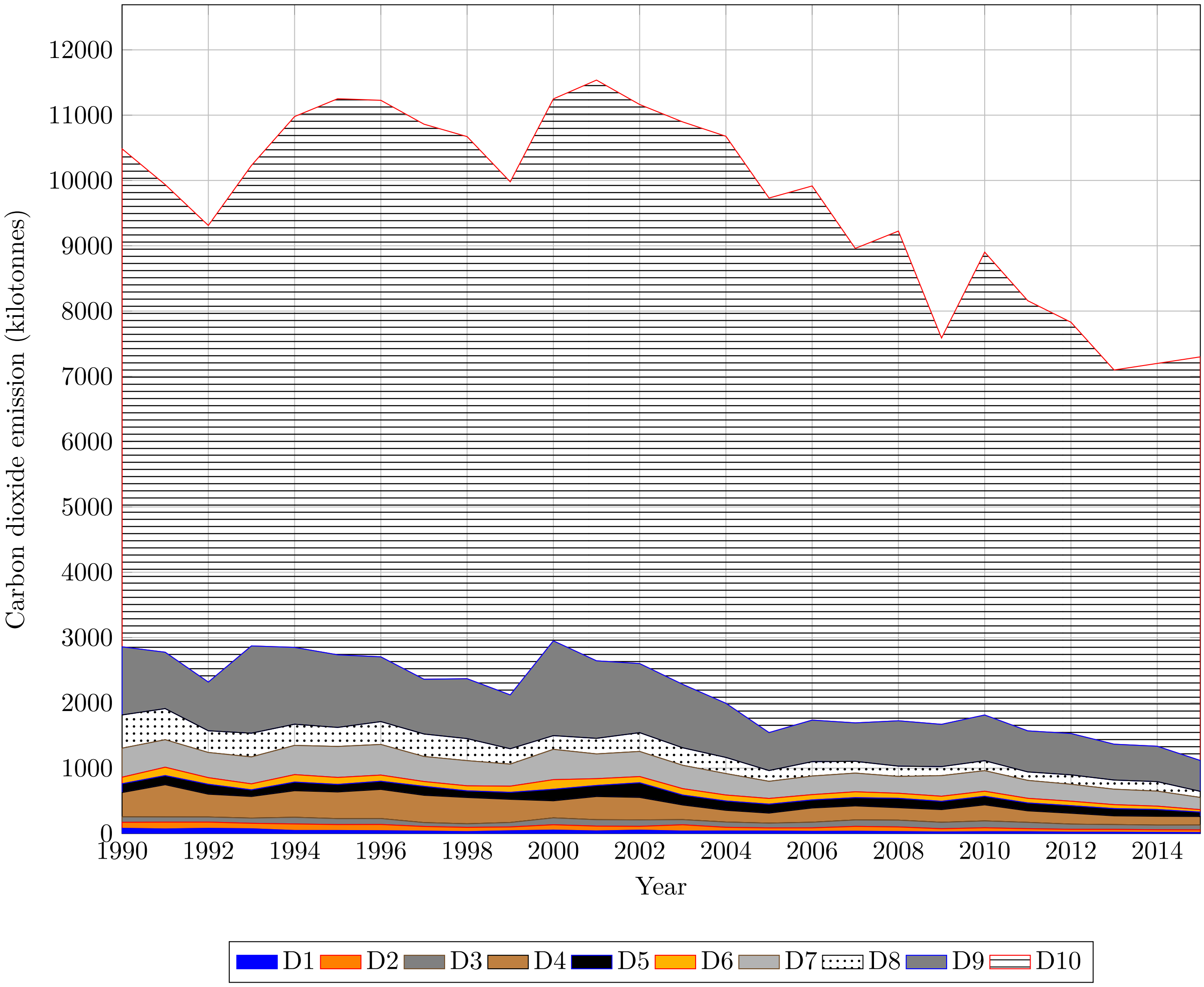

Figure 3 reports the distribution of CO_2 emissions in the Swedish manufacturing sector. The sample is divided into ten deciles based on the firms' carbon intensity (i.e. CO_2 emissions over sales) in 1990.

Figure 4: Distribution of sales in the Swedish manufacturing sector (1990-2015)

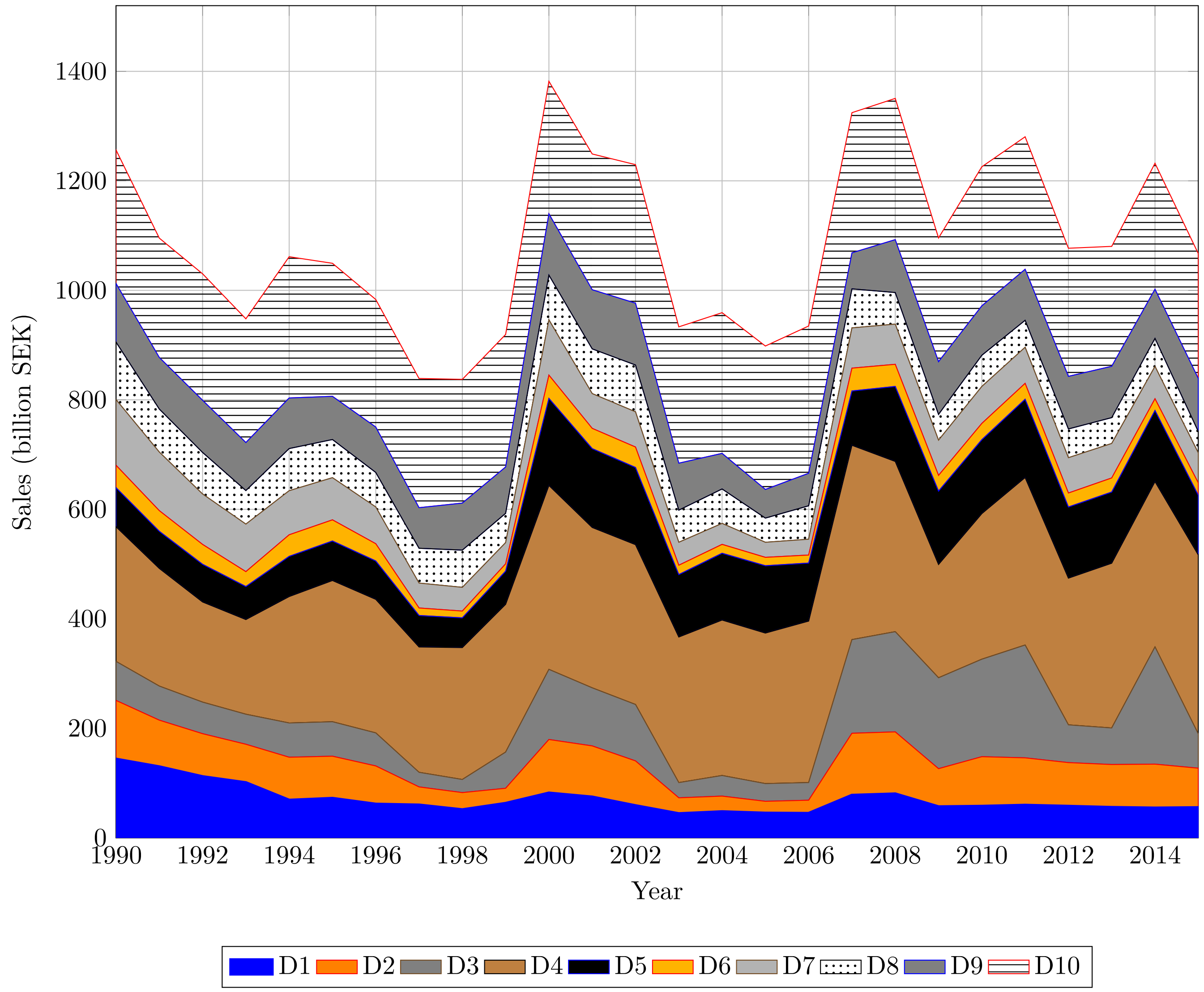

Figure 4 reports the distribution of PPI-adjusted sales in the Swedish manufacturing sector. The sample is divided into ten deciles based on the firms' carbon intensity (i.e. CO_2 emissions over sales) in 1990.

Figure 5: Carbon tax payments from Swedish manufacturing (1990-2015)

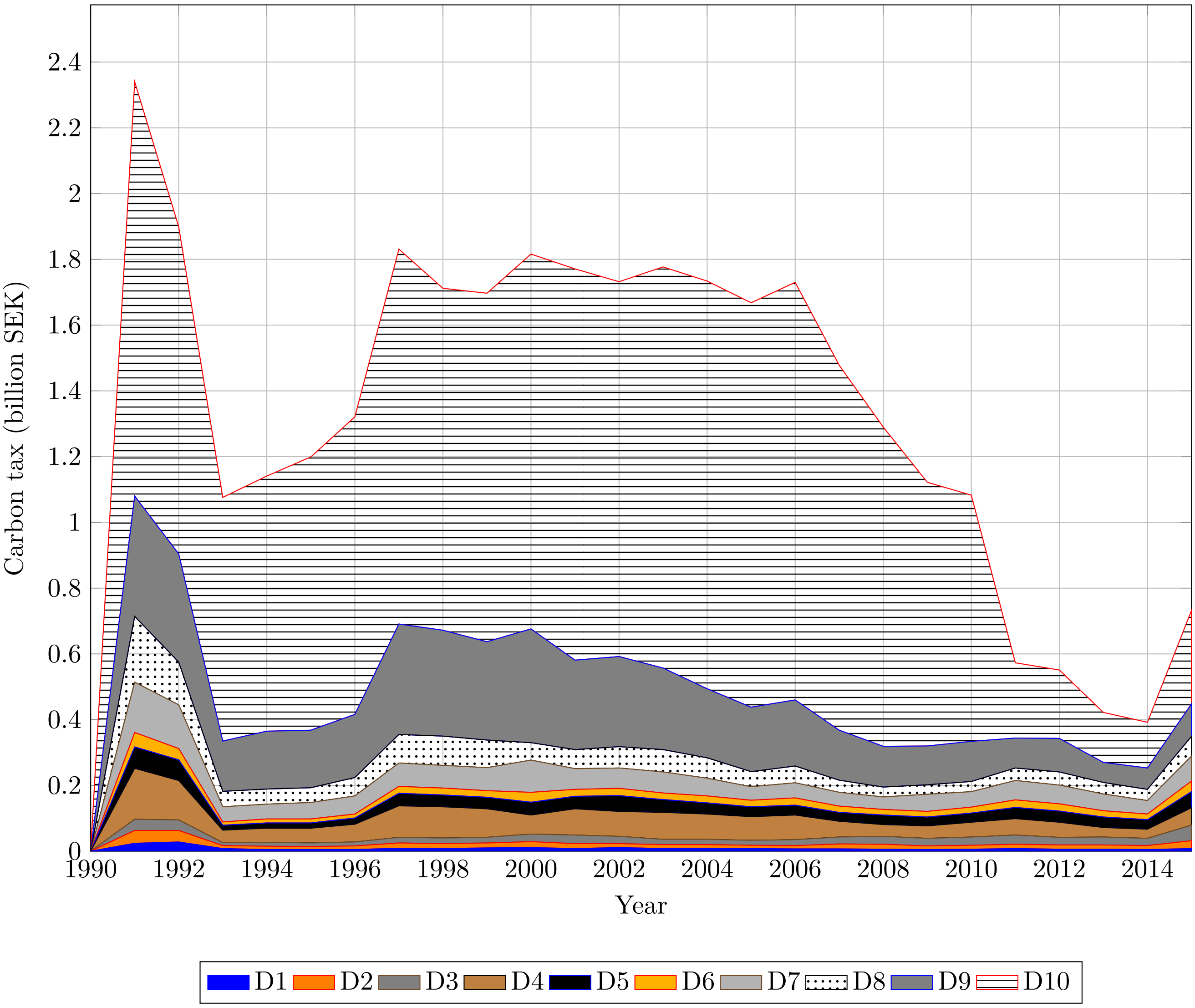

Figure 5 reports the distribution of carbon tax payments in the Swedish manufacturing sector. The sample is divided into deciles based on the firms' carbon intensity (i.e. CO_2 emissions over sales) in 1990.

Figure 6: Changes to the carbon tax: emissions and carbon tax payments by regime

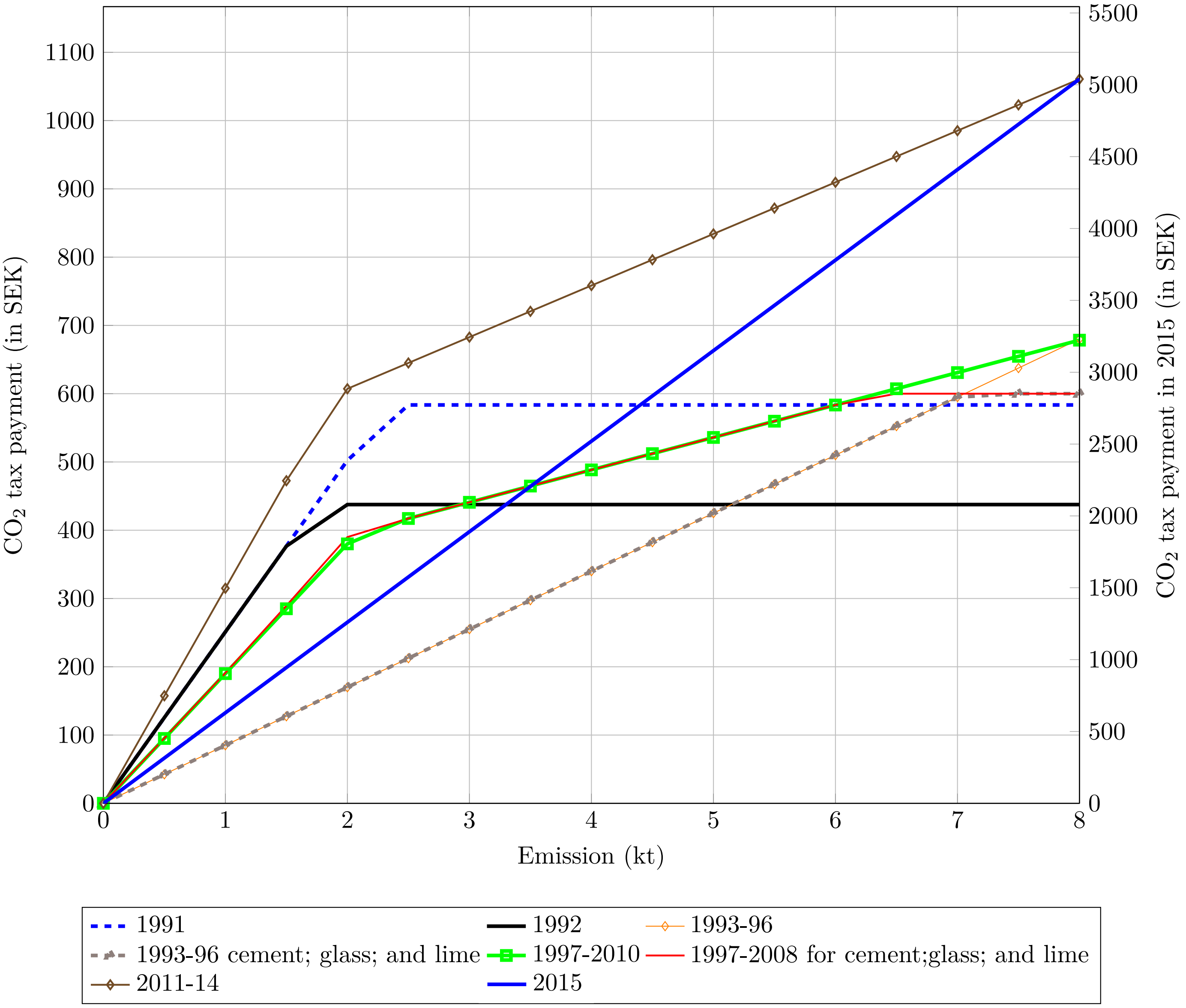

Figure 6 compares the carbon tax payments under the different regimes through a representative manufacturing firm. The hypothetical firm earns 50,000 SEK each year, and assumed to burn only coal in 1991 and 1992. All carbon tax payments with the exception of 2015 are shown on the vertical axis on the left side. Carbon tax payments in 2015 are shown on the vertical axis on the right side.

Figure 7: Average and marginal tax rates (1990-2015)

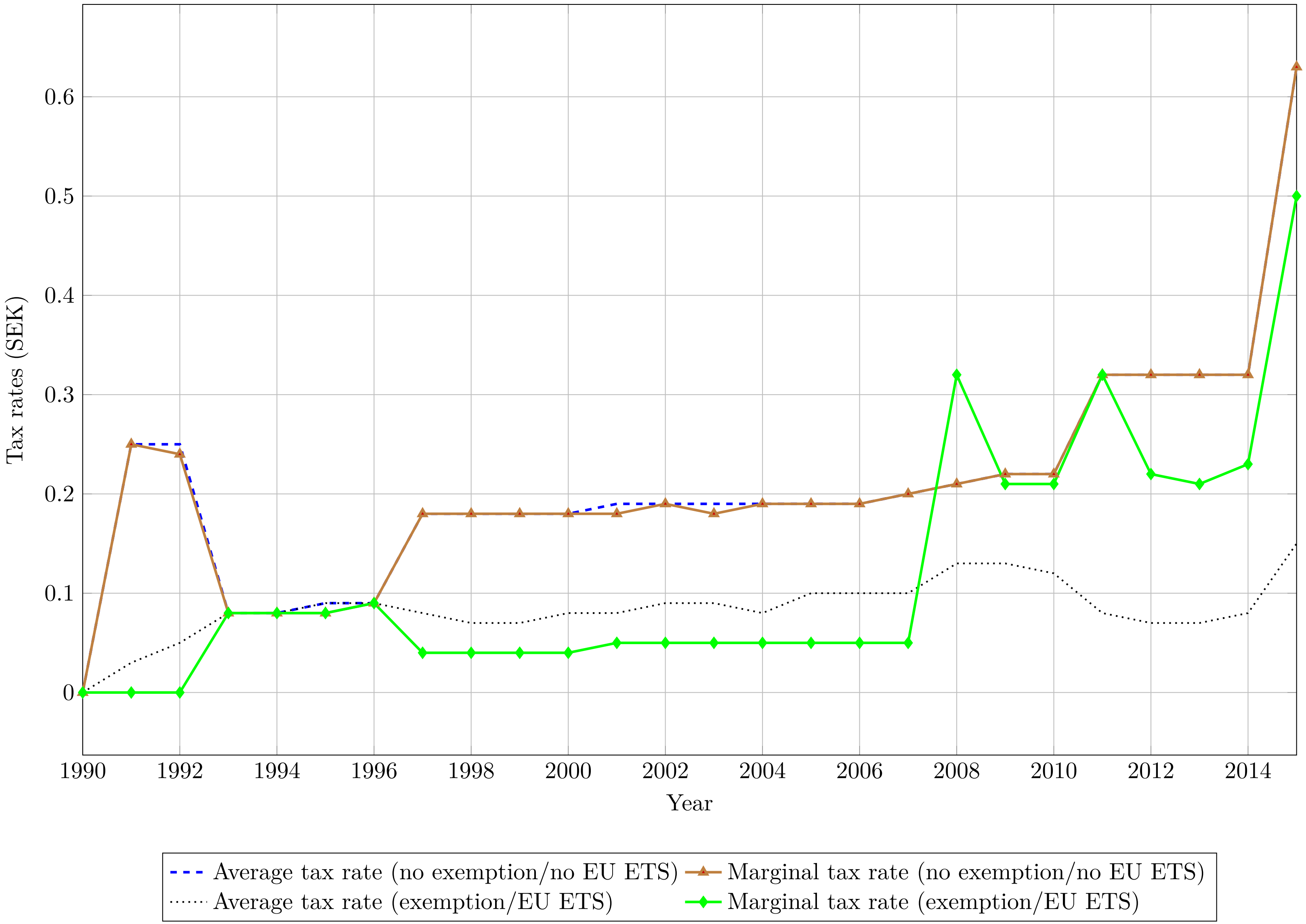

Figure 7 displays the average and marginal tax rates depending on whether the firm is eligible for carbon tax exemptions and covered by the EU ETS. *no exemption/no EU ETS* denotes firms that are not regulated by the EU ETS and are not entitled to carbon tax cut, *exemption/EU ETS* refers to the firms with available exemptions until they enter the emission trading scheme. Average tax rates are backward-looking effective tax rates. Marginal tax rates are obtained as forward-looking effective tax rates. Marginal tax rates for EU ETS are the price for emission rights. Average tax rates for EU ETS are backward-looking, consider historical prices and free distribution of emission rights.

Figure 8: Carbon dioxide emissions from Swedish manufacturing (1990-2015)

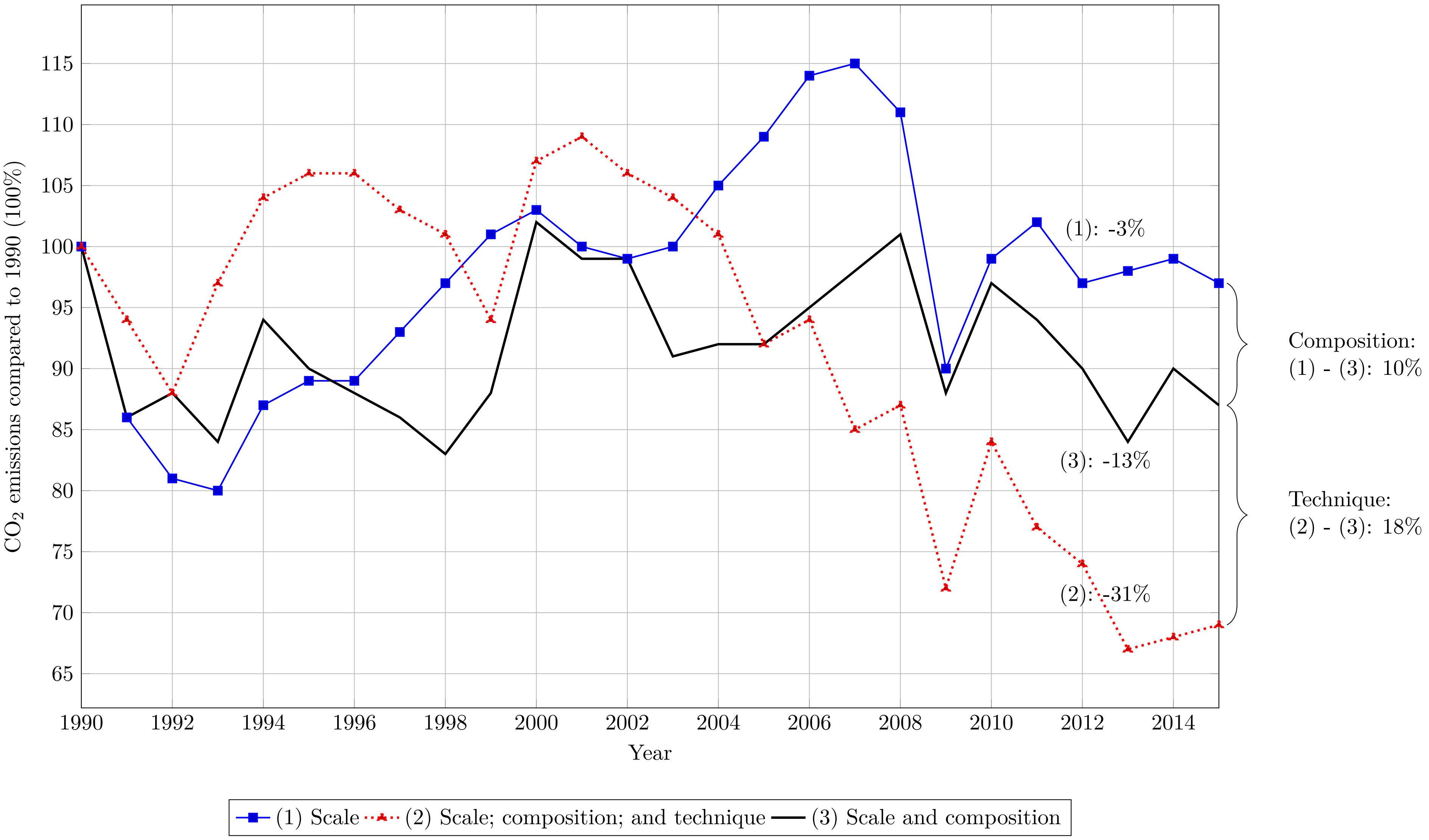

Figure 8 displays the decomposition of the Swedish carbon dioxide emission reduction. *Scale* captures how emissions would have evolved without tangible technological progress and structural changes in the manufacturing sector. *Composition* refers to the change in industry composition (e.g. booming IT sector), *Technique* captures the technological progress in the industrial sector.

Figure 9: Carbon dioxide emissions from Swedish manufacturing (1990-2015)

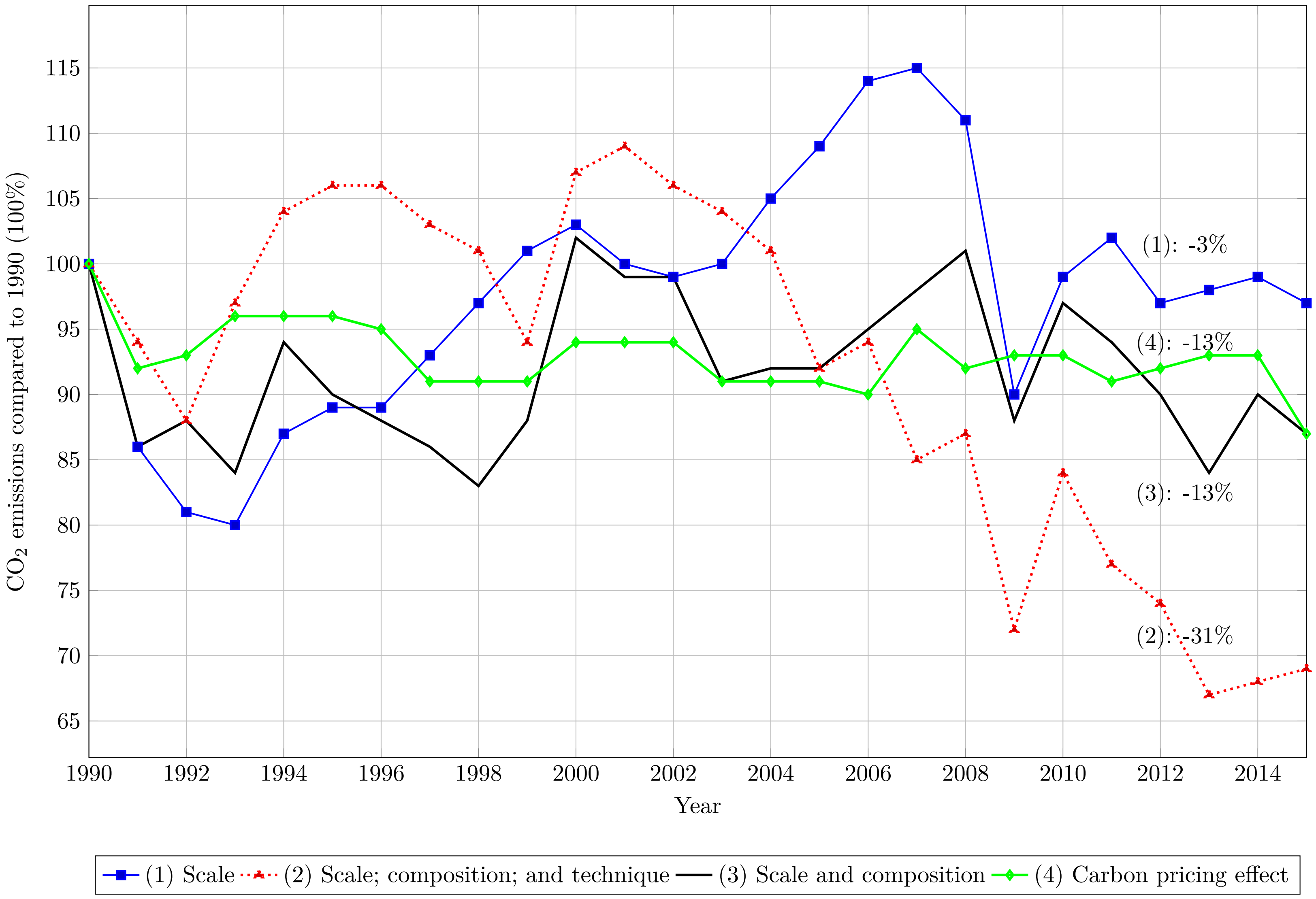

Figure 9 displays the decomposition of the Swedish carbon dioxide emission reduction. *Scale* captures how the emission would have evolved without tangible technological progress and structural changes in the manufacturing sector. *Composition* refers to the change in industry composition (e.g. booming IT sector), *Technique* captures the technological progress in the industrial sector. *Carbon pricing effect* captures the effect of carbon pricing (i.e. carbon tax and EU ETS)

Figure 10: Distribution of carbon dioxide emissions in the international sample (1990-2015)

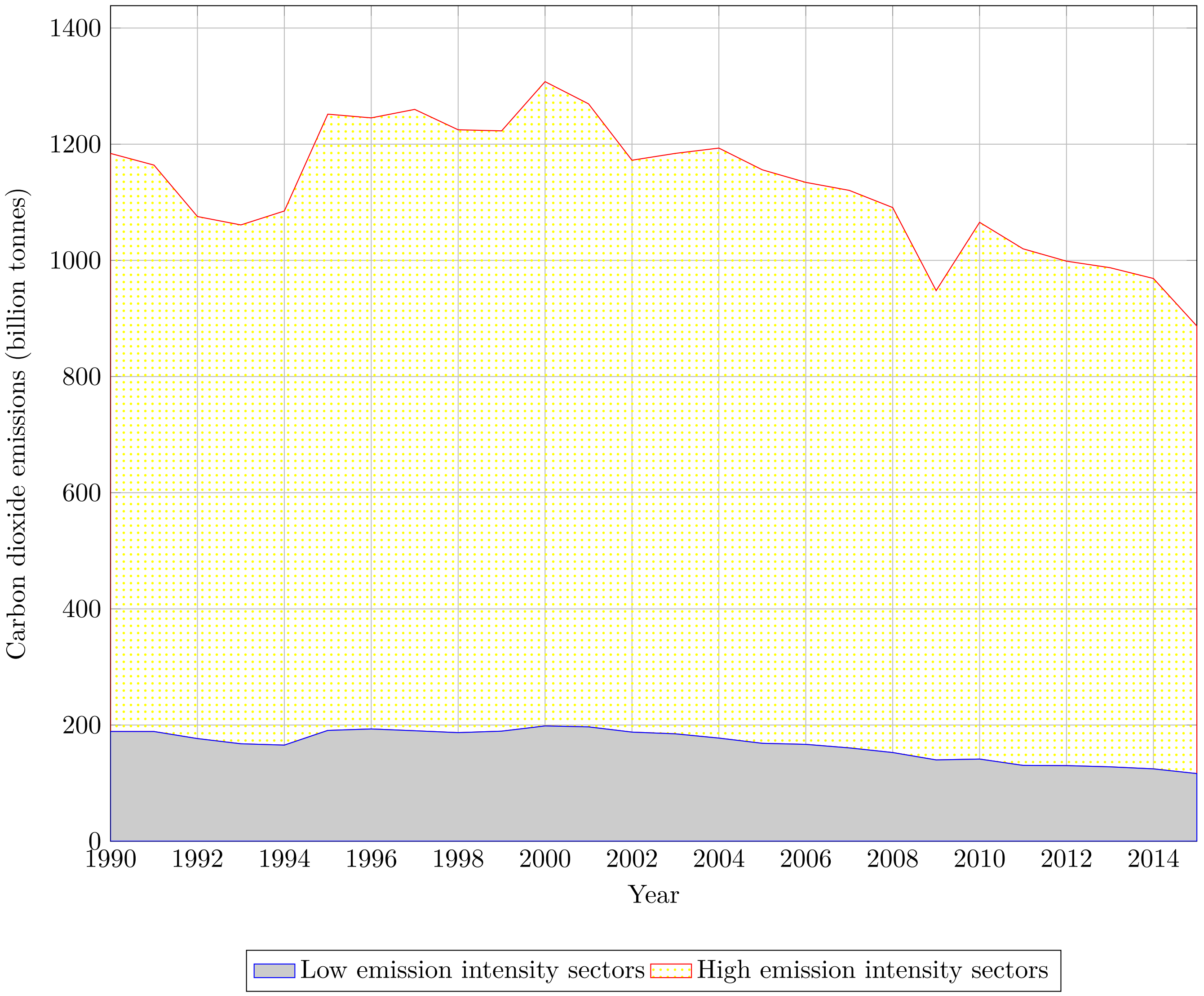

Figure 10 reports the carbon dioxide emissions in our international sample (OECD without Sweden) for lower- and higher-emitting sectors.

Figure 11: Distribution of sales in the international sample (1990-2015)

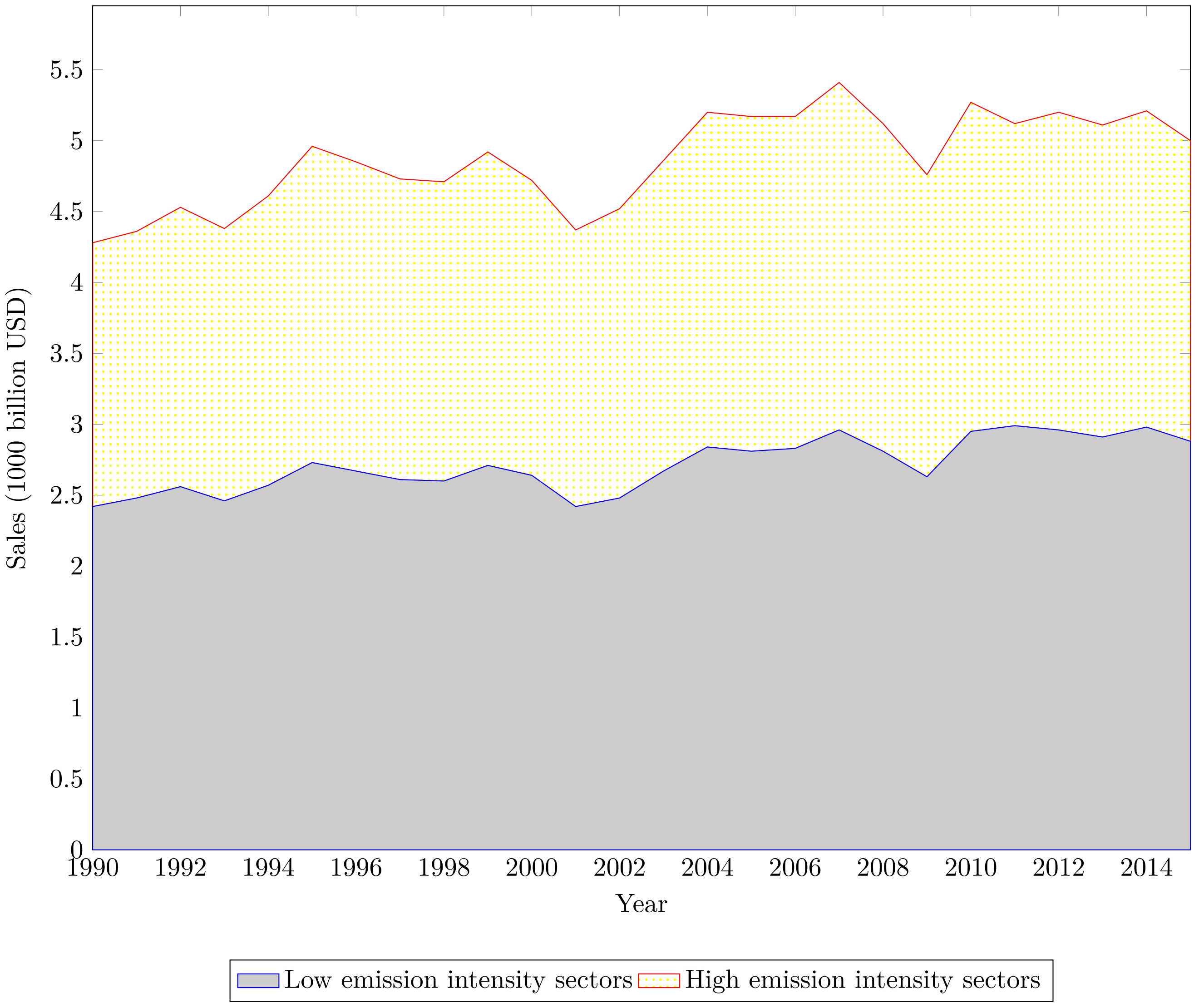

Figure 11 reports the distribution of sales (PPI-adjusted, in 2010 values) in our international sample (OECD without Sweden) for lower- and higher-emitting sectors.

Figure 12: Sweden and synthetic Sweden

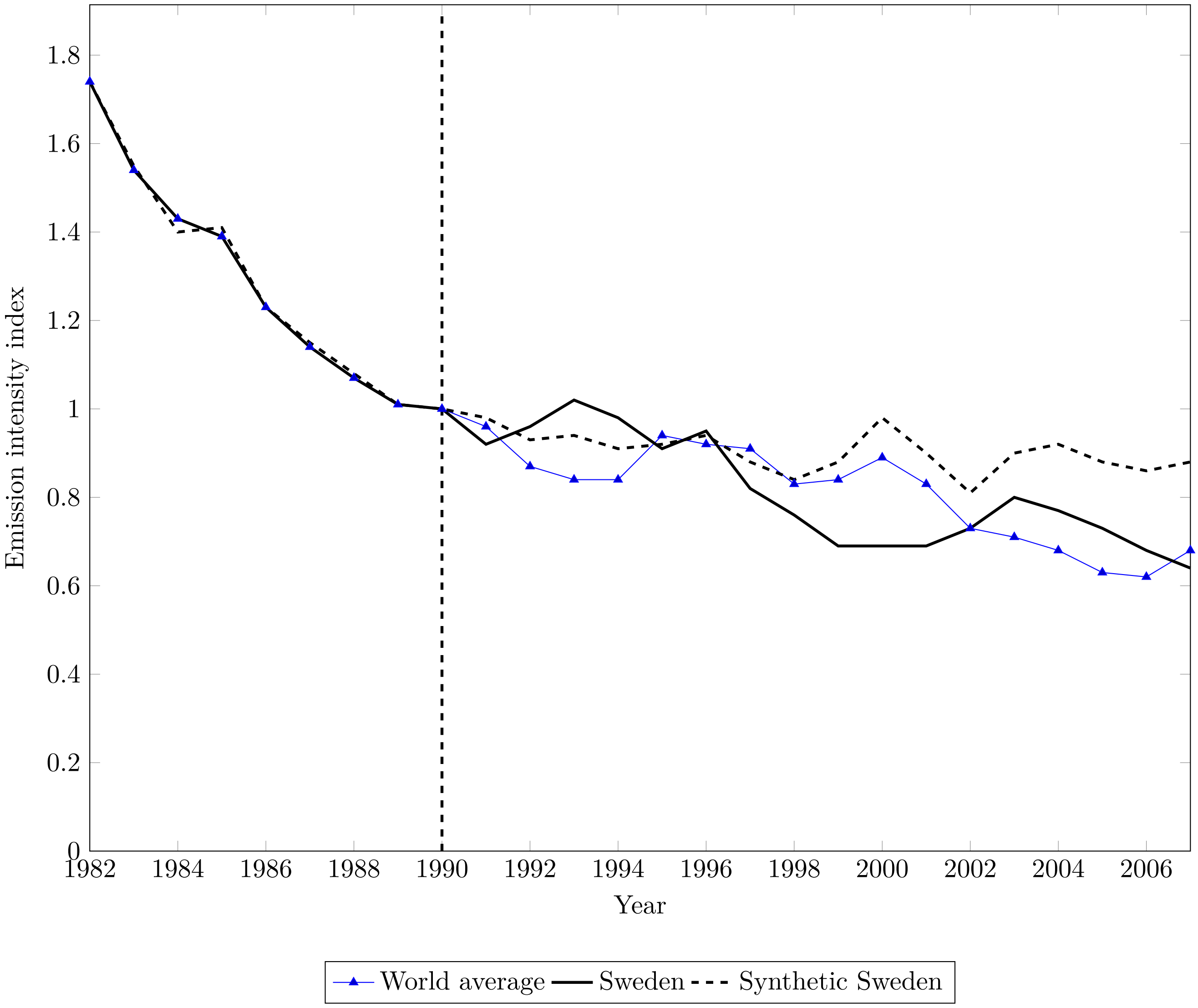

Figure 12 reports the overall economy's emission intensities relative to 1990 for Sweden and synthetic Sweden. *World average* refers to the world-level manufacturing value added (in constant 2010 dollars, reported by World Bank) normalized by the aggregate carbon dioxide emissions from IEA.

Figure 13: Sweden and synthetic Sweden

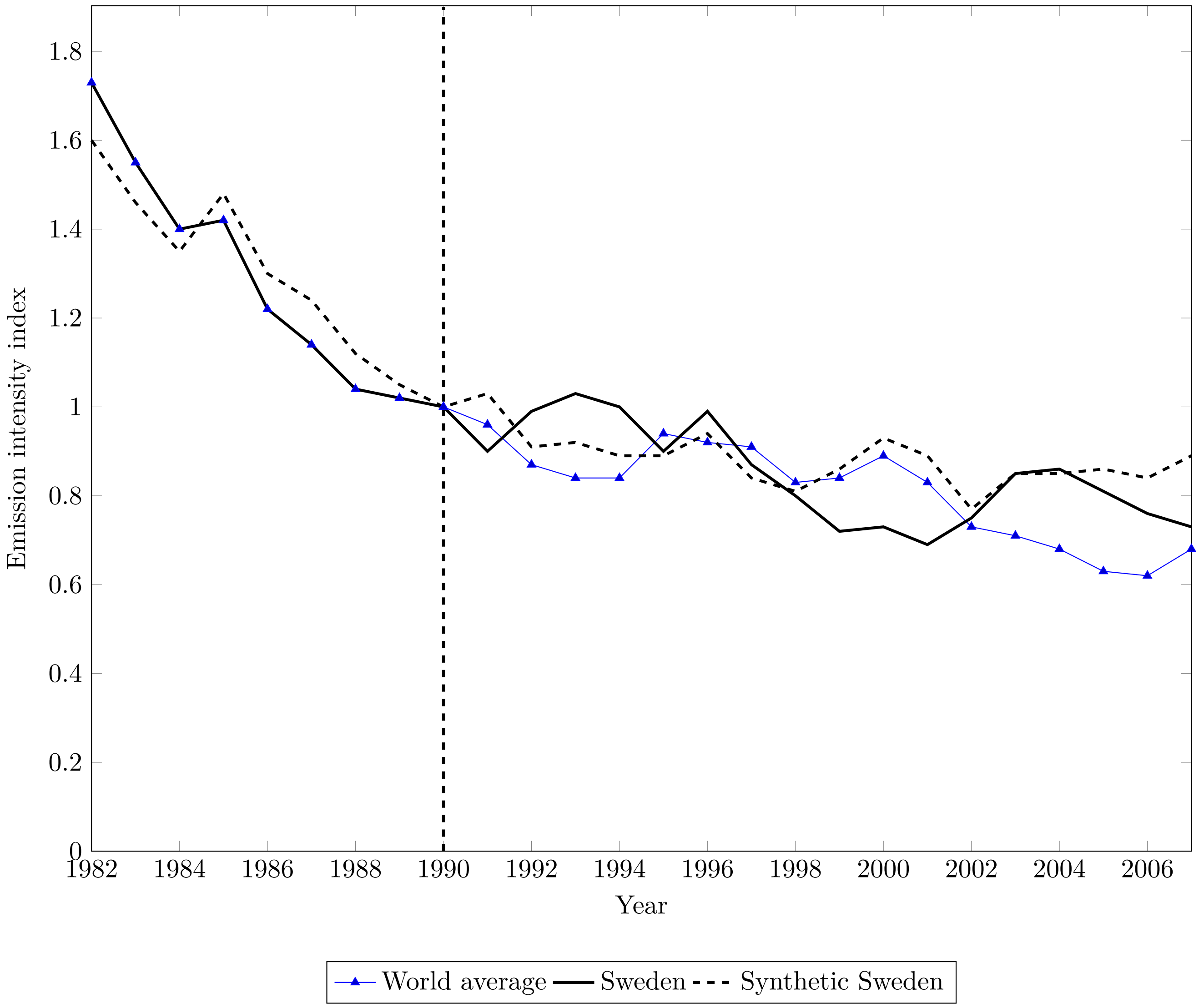

Figure 13 reports the most-emitting sectors' emission intensities relative to 1990 for Sweden and synthetic Sweden. *World average* refers to the world-level manufacturing value added (in constant 2010 dollars, reported by World Bank) normalized by the aggregate carbon dioxide emissions from IEA.

Figure 14: Sweden and synthetic Sweden

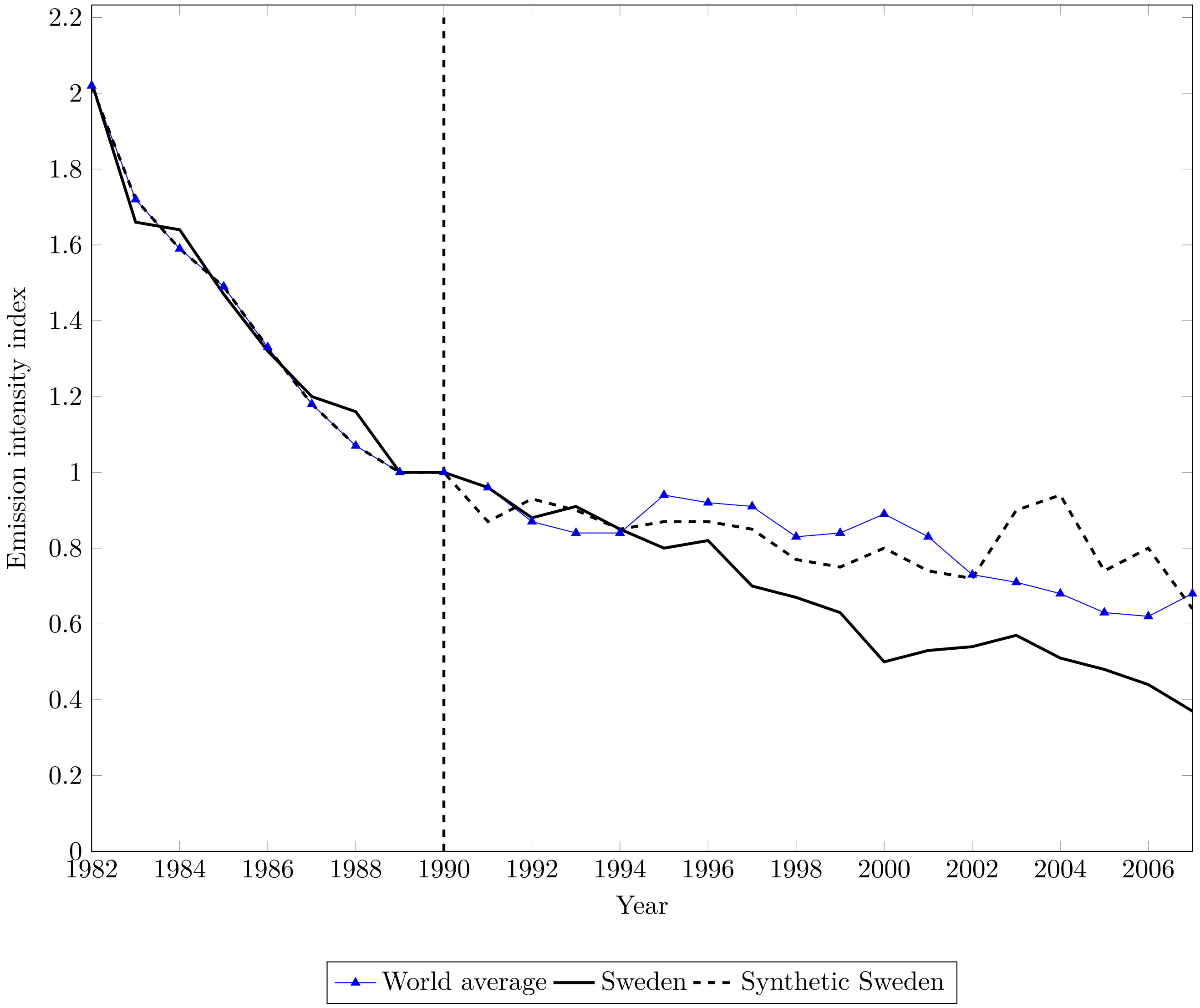

Figure 14 reports the low-emitting sectors' emission intensities relative to 1990 for Sweden and synthetic Sweden. *World average* refers to the world-level manufacturing value added (in constant 2010 dollars, reported by World Bank) normalized by the aggregate carbon dioxide emissions from IEA.

Table 1: Summary of the rates in the Swedish carbon tax system.

			Carbon tax rates (SEK/kg)		
Year	Standard rate	Manufacturing rate	General exemptions	Cement, glass lime	Firms in EU ETS
1990	No tax	No tax	No tax	No tax	Before EU ETS
1991	0.25	0.25	Manufacturing rates if CO_2 + Energy tax<= 1.7% of sale, untaxed further emissions	Manufacturing rates if CO_2 + Energy tax<= 1.7% of sale, untaxed further emissions	
1992	0.25	0.25	Manufacturing rates if CO_2 + Energy tax<= 1.2% of sale, untaxed further emissions	Manufacturing rates if CO_2 + Energy tax<= 1.2% of sale, untaxed further emissions	
1993	0.32	0.08	Manufacturing rate	Industry rate up to 1.2 % of sales, untaxed further emissions ("1.2% rule")	
1994	0.32	0.08			
1995	0.34	0.09			
1996	0.37	0.09			
1997	0.37	0.19	Manufacturing tax rate up to 0.8% of sales, exceeding emissions: 25 % of general manufacturing CO_2 tax rate ("0.8 % rule")	0.8% rule is applied first, emissions exceeding 1.2 % of sales are untaxed	
1998	0.37	0.19			
1999	0.37	0.19			
2000	0.37	0.19			
2001	0.53	0.19			
2002	0.63	0.19			
2003	0.76	0.19			
2004	0.91	0.19			
2005	0.91	0.19			Manufacturing rate + exemptions where applicable
2006	0.92	0.19			

Carbon tax rates (SEK/kg)

Year	Standard rate	Manufacturing rate	General exemptions	Cement, glass lime	Firms in EU ETS
2007	0.93	0.20		Special exemption removed	
2008	1.01	0.21			EU ETS+15% of standard rate for plants under EU ETS
2009	1.05	0.22			
2010	1.05	0.22			
2011	1.05	0.315	Manufacturing rate up to 1.2%: Exceeding: 24% of manufacturing rate		No CO_2 tax for installations covered by EU ETS
2012	1.05	0.32			
2013	1.05	0.32			
2014	1.05	0.32			
2015	1.05	0.63	Special exemption removed		
2016	1.12	0.90			
2017	1.13	0.90			

Table 1 summarizes the special provisions that enacted tax reliefs for certain industrial enterprises. *Standard rate* applies for households and non-industrial firms, *Manufacturing rate* is the applicable rate for manufacturing enterprises (SNI10-33 under SNI2007 nomenclature), the exemptions in *Manufacturing rate + exemptions where applicable* are the 0.8% and the 1.2% rules.

Table 2: Summary statistics

	All firm-years						Regression sample					
	OBS	Mean	Median	St.dev	Min	Max	OBS	Mean	Median	St.dev	Min	Max
CO_2 emissions (kt)	50,501	5	0.093	53	0	N/A	32,345	8	0.14	66	0	N/A
Sales (PPI, 2010, MSEK)	50,501	563	60	3,610	0	151,000	32,345	784	85	4,360	0	128,000
CO_2 emissions-to-sales	50,501	0.006	0.002	0.015	0	0.122	32,345	0.007	0.002	0.018	0	0.141
Carbon taxes paid (2010, MSEK)	50,501	0.589	0.016	7	0	394	32,345	0.886	0.025	8	0	394
EBIT (2010, MSEK)	50,501	32	2	543	-25,500	65,800	32,345	44	3	522	-6 880	29,800
Carbon taxes paid-to-EBIT	50,434	0.012	0.003	0.093	-0.439	0.561	32,301	0.015	0.003	0.107	-0.475	0.676
Marginal tax rate	50,501	0.192	0.191	0.122	0	0.702	32,345	0.2	0.212	0.128	0	0.702
Average tax rate	50,501	0.190	0.191	0.119	0	1	32,345	0.196	0.195	0.124	0	1
Nr of workers	50,080	168	33	732	0	22,460	32,209	221	43	868	0	21,305
PPE (2010, MSEK)-to-workers	49,741	0.504	0.277	0.758	0	5	31,976	0.519	0.316	0.87	0.003	6

Table 2 tabulates summary statistics over key variables in the overall and the regression sample. The regression sample consists of firms with at least five consecutive firm-year observations. Both *Marginal tax rate* and Average tax rate are expressed in SEK/kg emitted CO_2. *PPE* stands for Property, Plant, and Equipment.

Table 3: Emission intensities, CO_2 emissions, and carbon tax payments

	All	D10	D9	D8	D7	D6	D5	D4	D3	D2	D1
	Panel A: 1990										
Emissions-to-sales	0.0084	0.0313	0.0097	0.0048	0.0037	0.0024	0.0019	0.0015	0.0012	0.0008	0.0006
Share of fossil CO_2 emissions	1.0000	0.7216	0.0987	0.0481	0.0421	0.0094	0.0128	0.0353	0.0079	0.0086	0.0075
Share of CO_2 tax payments (1991)	1.0000	0.5385	0.1564	0.0855	0.0654	0.0188	0.0279	0.0662	0.0145	0.0165	0.0104
	Panel B: 2007										
Emissions-to-sales	0.0067	0.0284	0.0089	0.0025	0.0039	0.0021	0.0013	0.0006	0.0006	0.0007	0.0004
Share of fossil CO_2 emissions	1.0000	0.8094	0.0656	0.0201	0.0319	0.0100	0.0141	0.0240	0.0110	0.0083	0.0038
Share of CO_2 tax payments	1.0000	0.7500	0.1027	0.0248	0.0283	0.0129	0.0182	0.0325	0.0141	0.0101	0.0049
	Panel C: 2015										
Emissions-to-sales	0.0068	0.0271	0.0049	0.0024	0.0034	0.0016	0.0006	0.0004	0.0012	0.0006	0.0002
Share of fossil CO_2 emissions	1.0000	0.8457	0.0647	0.0127	0.0256	0.0050	0.0093	0.0179	0.0101	0.0057	0.0018
Share of CO_2 tax payments	1.0000	0.3869	0.1349	0.0813	0.1035	0.0433	0.0670	0.0715	0.0644	0.0332	0.0112

Table 3 tabulates emission intensities as well as the distribution of carbon dioxide emissions and carbon tax payments in 1990, 2007, and 2015. The sample is divided into ten deciles, based on the sampled firms' carbon intensities in 1990. *Share of fossil CO_2 emissions* and *Share of CO_2 tax payments* report the average contribution of each decile to the overall fossil carbon dioxide emissions and carbon tax payments of the manufacturing sector, respectively. Average contribution is defined as total tax payments (emissions) in a decile relative to the number of firms.

Table 4: Emission intensities and taxes paid averages

	All	D10	D9	D8	D7	D6	D5	D4	D3	D2	D1
	Panel A: Average 1991-1995										
Emissions-to-sales	0.0100	0.0324	0.0117	0.0063	0.0048	0.0030	0.0019	0.0019	0.0014	0.0012	0.0006
CO_2 tax payments-to-sales	0.0018	0.0055	0.0035	0.0017	0.0011	0.0007	0.0006	0.0004	0.0003	0.0004	0.0002
CO_2 tax payments-to-EBIT	0.0324	0.0647	0.0404	0.0261	0.0200	0.0113	0.0083	0.0294	0.0081	0.0055	0.0033
Share of manufacturing sales	1.0000	0.1611	0.0866	0.0700	0.0856	0.0346	0.0661	0.2047	0.0579	0.0759	0.0926
	Panel B: 2007										
Emissions-to-sales	0.0067	0.0284	0.0089	0.0025	0.0039	0.0021	0.0013	0.0006	0.0006	0.0007	0.0004
CO_2 tax payments-to-sales	0.0011	0.0042	0.0025	0.0005	0.0006	0.0005	0.0003	0.0001	0.0001	0.0001	0.0001
CO_2 tax payments-to-EBIT	0.0161	0.0455	0.0539	0.0088	0.0116	0.0112	0.0027	0.0035	0.0013	0.0016	0.0014
Share of manufacturing sales	1.0000	0.1925	0.0495	0.0536	0.0553	0.0314	0.0746	0.2669	0.1286	0.0857	0.0579
	Panel C: 2011-2015										
Emissions-to-sales	0.0065	0.0266	0.0060	0.0027	0.0039	0.0023	0.0008	0.0005	0.0006	0.0005	0.0003
CO_2 tax payments-to-sales	0.0005	0.0009	0.0009	0.0009	0.0009	0.0009	0.0003	0.0001	0.0003	0.0002	0.0001
CO_2 tax payments-to-EBIT	0.0072	0.0338	0.0041	0.0199	0.0194	0.0176	0.0014	0.0119	0.0068	0.0028	0.0017
Share of manufacturing sales	1.0000	0.1998	0.0814	0.0814	0.0532	0.0215	0.1113	0.2607	0.1071	0.0694	0.0483

Table 4 tabulates average emission intensities as well as the distribution of carbon dioxide emissions and carbon tax payments over 1991-1995, in 2007, and over 2011-2015. The sample is divided into ten deciles, based on the sampled firms' carbon intensities in 1990. *Share of manufacturing sales* reports the contribution of each decile to the overall sales of the manufacturing sector, defined as the average of average sales per decile over 1991-1995 in Panel A, and over 2011-2015 in Panel C. *CO_2 tax payments-to-sales* and *CO_2 tax payments-to-EBIT* report the average carbon tax over sales (EBIT) per decile (defined as total carbon tax over total sales or EBIT).

Table 5: Difference-in-difference analysis around tax changes

	Firm exemptions (91-92)	**No firm exemptions**	**Relative change**
	Panel A: Marginal cost of emitting CO_2		
1990	0.000	0.000	
1991-1992	0.000	0.227	
1994-1996	0.086	0.086	
Change 90 to 91/92	0.000	0.227	-0.227
Change 91/92 to 94/96	0.086	-0.141	0.227
	Panel B: CO_2 emissions-to-sales		
1990	0.107	0.008	
1991-1992	0.113	0.009	
1994-1996	0.120	0.010	
Change 90 to 91/92	0.058	0.035	0.023
Change 91/92 to 94/96	0.060	0.120	-0.059
	Panel C: Summary statistics		
Nr of firms	9	225	
Total CO_2 (kt) 1990	2,244	4,323	
Total sales (1990, billion SEK)	21.2	538	
CO_2-to-sales	0.106	0.008	

Table 5 reports the change in marginal cost and emission intensity for firms with and without exemptions around the 1991 introduction of the carbon tax and the change in 1993. The sample is limited to a balanced sample of firms between 1990 and 2002. *Panel A* tabulates the marginal taxes for the manufacturing firms, *Panel B* reports the emission intensities, and *Panel C* provides a summary statistics about the sampled firms.

Table 6: Baseline regression results

	(1)	**(2)**	**(3)**	**(4)**	**(5)**
	Dependent variable: log (CO_2/Y)(i,t)				
	All				D10
log (1 + marginal tax rate) (i,t)	-2.758 (0.365)***	-2.244 (0.320)***	-1.967 (0.320)***	-1.859 (0.359)***	-1.962 (0.468)***
log (1 + marginal tax rate) (i,t-1)		-1.091 (0.275)***	-0.848 (0.236)***	-0.693 (0.251)***	-1.146 (0.364)***
log (1 + marginal tax rate) (i,t-2)			-0.595 (0.264)**	-0.366 (0.236)	-0.714 (0.331)**
log (1 + marginal tax rate) (i,t-3)				-0.485 (0.294)*	-0.800 (0.407)*
Sum σ	-2.758	-3.335	-3.410	-3.403	-4.622
F-test	(0.000)***	(0.000)***	(0.000)***	(0.000)***	(0.000)***
Firm fixed effects	Y	Y	Y	Y	Y
Year fixed effects	Y	Y	Y	Y	Y
OBS	32,345	28,387	24,355	20,296	2,026
Adjusted R^2	0.800	0.807	0.816	0.822	0.770

Table 6 tabulates our baseline regression results, i.e. the relationship between lagged marginal tax rates and emission intensities (CO_2/Y).

Table 7: The role of EU ETS and some robustness

	(1)	(2)	(3)	(4)	(5)
	Dependent variable: log (CO_2/Y)(i,t)				
	All				
log (1 + marginal tax rate) (i,t)	-3.816	-3.080	-1.201	-1.330	-1.202
	(0.528)***	(0.517)***	(0,313)***	(0,322)***	(0,313)***
log (1 + marginal tax rate) (i,t-1)	-0.769	-0.655	-0.650	-0.677	-0.651
	(0.319)**	(0.364)*	(0,251)***	(0,252)***	(0,251)***
log (1 + marginal tax rate) (i,t-2)	-0.292	-0.303	-0.541	-0.473	-0.542
	(0.299)	(0.333)	(0,232)**	(0,233)**	(0,232)**
log (1 + marginal tax rate) (i,t-3)	-0.265	-0.768	-0.616	-0.538	-0.617
	(0.325)	(0.365)**	(0,297)**	(0,298)*	(0,297)**
EU ETS	-0.366				
	(0.168)**				
log (1 + marginal tax rate) (i,t) × EU ETS	3.192	2.042			
	(0.492)***	(0.455)***			
log (1 + marginal tax rate) (i,t-1) × EU ETS	0.023	-0.233			
	(0.339)	(0.423)			
log (1 + marginal tax rate) (i,t-2) × EU ETS	-0.135	-0.090			
	(0.304)	(0.384)			
log (1 + marginal tax rate) (i,t-3) × EU ETS	-1.340	-0.165			
	(0.297)***	(0.387)			
log(employee) (i,t)			-0.271		-0.273
			(0,051)***		(0,051)***
Capital/emp (i,t)				0.009	-0.006
				(0,019)	(0,019)
F-test	-5.142	-4.806	-3.007	-3.018	-3.012
	(0.000)***	(0.038)**	(0,000)***	(0,000)***	(0,000)***
Sum β + Sum γ	-3.403	-3.251			
F-test	(0.000)***	(0.000)***			
Firm fixed effects	Y	Y	Y	Y	Y
Year fixed effects	Y	Y	Y	Y	Y
OBS	20,296	20,296	20,074	20,074	20,074
Adjusted R^2	0.824	0.823	0.830	0.828	0.830

Table 7 tabulates our baseline regression results, i.e. i.e. the relationship between lagged marginal tax rates and emission intensities (CO_2/Y), augmented by the effects of the EU ETS.

Table 8: PACE and mobility

	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
	PACE		**Low PACE**		**High PACE**	
	Low	High	Low mobility	High mobility	Low mobility	High mobility
log (1 + marginal tax rate) (i,t)	-3.858 (1.816)**	-1.686 (0.663)***	-21.425 (3.919)***	0.326 (1.491)	-2.812 (1.258)**	-1.367 (1.077)
log (1 + marginal tax rate) (i,t-1)	-1.385 (1.042)	-0.453 (0.366)	-5.802 (2.308)**	-1.766 (1.294)	-0.556 (0.618)	-0.846 (0.645)
log (1 + marginal tax rate) (i,t-2)	-0.596 (0.914)	0.055 (0.361)	-2.797 (1.942)	-1.206 (2.091)	-0.102 (0.691)	0.424 (0.602)
log (1 + marginal tax rate) (i,t-3)	-1.485 (1.217)	0.051 (0.403)	-4.853 (1.343)***	-4.909 (1.766)***	0.021 (0.718)	-0.241 (0.563)
Sum σ	-7.324	-2.032	-34.877	-7.554	-3.448	-2.030
F-test	(0.034)**	(0.075)*	(0.000)***	(0.129)	(0.059)*	(0.335)
Firm fixed effects	Y	Y	Y	Y	Y	Y
Year fixed effects	Y	Y	Y	Y	Y	Y
OBS	4,162	5,188	682	1,120	1,346	1,783
Adjusted R^2	0.801	0.834	0.829	0.791	0.820	0.838

Table 8 tabulates the effect of pollution abatement cost expenditures and geographic mobility of assets.

Table 9: CO_2 emissions elasticity

	$\frac{CO_2 \text{emissions (kg)}}{\text{cost (SEK)}}$	CO_2 emissions elasticity	Coefficient	St. error	T-stat	OBS
Manufacturing	0.0133	0.0190	52.60	7.26	7.24	23,593
D10	0.0486	0.0426	23.45	7.78	3.02	2,168
D9	0.0133	0.0332	30.11	21.94	1.37	1,785
D8	0.0053	0.0164	61.14	14.07	4.35	1,758
D7	0.0042	0.0081	123.00	30.34	4.05	1,988
D6	0.0040	0.0159	62.91	22.37	2.81	3,227
D5	0.0029	0.0106	94.72	29.56	3.20	2,928
D4	0.0016	0.0057	175.08	61.63	2.84	2,871
D3	0.0022	0.0083	120.66	45.92	2.63	4,222
D2	0.0010	0.0177	56.55	37.51	1.51	1,438
D1	0.0010	0.0026	380.38	30.49	12.48	1,094

Table 9 tabulates CO_2 emissions elasticities in different economic sectors. The sample is divided into ten deciles, based on the sampled firms' carbon intensities in 1990. *Manufacturing* refers to the overall manufacturing sector.

Table 10: Carbon dioxide emissions from Swedish manufacturing (decomposed), 1990-2015

Panel A

	Scale effect (1)	Scale, composition and technique (2)	Scale and composition (3)	Composition effect (1) - (3)	Technique effect (2) - (3)
1990-2015	-3%	-31%	-13%	10%	18%
1990-2008	11%	-13%	1%	10%	14%

Panel B

	Fraction of CO_2 emissions reduction due to		
	Composition $\frac{(1)-(3)}{(1)-(2)}$	Technique $\frac{(3)-(2)}{(1)-(2)}$	Carbon pricing (4)
1990-2015	36%	64%	-13%
1990-2008	42%	58%	-8%

Table 10 displays the contribution of several factors to the change in emissions: (1) Scale effect: Total deflated manufacturing output (Index=100 in 1990), (2) Scale, composition, and technique: Total CO_2 emissions for manufacturing sector (Index=100 in 1990), (3) Scale and composition: 1990 Emission intensity · sum of decile output every year, (4) Carbon pricing effect

Appendices

A The Political Process Behind the Carbon Tax

Sweden has taxed the use of fossil fuels for a long time, primarily motivated by the desirability of fuel as a tax base. The government started collecting an excise tax (the energy tax) on gasoline in 1924, originally intended to finance road construction and the electrification of rural areas (Swedish Tax Authority (2012)), but extended the scope of the taxation to other fuels in the following decades. During the oil crisis in the 1970's the energy tax was also seen as an instrument to reduce oil dependence (Scharin, H and Wallström, J (2018)).

In 1988, the *Environmental Charges Commission* was formed (comprising representatives of different stakeholders, including political parties, economists, and industry representatives) to explore the possibilities of using economic instruments in environmental policy. A first report on fees and taxes on sulphur and chlorine was published in July 1989. In the same year, the Swedish Parliament decided to request a program to reduce CO_2 emissions (Scharin, H and Wallström, J (2018)). The Commission's final report proposed the introduction of a carbon tax on fossil fuels, and a 50% reduction in the general energy tax (Environmental Charges Commission (1989)).

The proposed taxonomy was enacted in 1991, followed by subsequent reforms. The implementation and reforms of taxes are tied to a parliamentary legislation process, which can take at least half a year. Stakeholders, therefore, are aware of the upcoming changes in taxation in advance. Can firms take counterbalancing measures prior to the implementation to offset the tax (e.g. relocating production)? In order to assess this possibility, we retrieved not only official reports of government agencies but also newspaper articles that reflected societal sentiment between 1988 and 2010. Our goal was to study stakeholders' sentiment, the political environment, and to measure the length of time between the dissemination and implementation of the new tax rates. We could also use this exercise to assess whether stakeholders could anticipate an increasing tax burden in the long run as well as the likelihood and magnitude of any defensive or precautionary measures to offset increasing financial burden.

The evidence suggests that the governments disclosed the new tax rates during the budget process up to 1993 and after 2000. Hence, the firms had only a few months to prepare for the anticipated new rates in this period. However, a longer uncertain period took place in the middle of the 90's, when the industry faced a doubled tax rate. The road to enforcing the higher tax, however, was not smooth. The incumbent government had to reach an agreement not only with the other parties in the Parliament and the industry union, but also with the European Union. Sweden joined the block in 1995, which made the Union a new stakeholder. The news between 1994 and 1995 indicate a multitude of opinions, but also highlighted the way to arrive at higher tax rates. The first attempt, proposed by the Minister of Environment, met opposition (even within the government), which may be explained by the upcoming parliamentary elections in 1994.

However, Social Democrats (the winner party in the elections) and the Swedish Left Party reached an agreement already at the end of November on doubling the tax rates for the entire industry. The government proposed new tax rates in the Spring Budget Bill in 1995, but also in a longer-term economic development plan (entitled "Tillväxtproposition"). The government explained this shift with more ambitious environmental policy both in Sweden and in the European Union. However, this increase did not apply for the most energy-intensive industrial sector (i.e. the exemptions would still be available for them). The newspaper articles from this time also demonstrate the policy uncertainty as the political will to implement the higher rates were doubted even a few days before the proposal. Despite the planned implementation in 1996, the proposed tax schedule could not enter into force until July 1997 as the EU did not endorse the special tax reliefs for the energy-intensive firms. In other words, all industrial firms should pay the same tax rates. After several rounds of negotiations, Sweden could adopt the new taxation in 1997.

The commencement of the emission trading system in 2005 became the next cornerstone in the Swedish environmental policy. The legislation of the trading scheme represented the culmination of the preceding work aimed to comply with the Kyoto Protocol (European Commission (2004)). Some Swedish news between 2000 and 2004 report the opposition of some stakeholders, especially the steel industry. They also argue that the new system in the proposed way would not curb emissions in the steel industry, but would endanger the operators, and may force companies to relocate their production.

The final episode occurred when the government proposed and the parliament endorsed a reform package in 2009 to further encourage the use of renewable energy resources and increase energy efficiency. An acknowledged goal of the package was to levy a more uniform national price on carbon dioxide emissions by reducing existing deviations from the general tax level (Hammar and Åkerfeldt (2011)). To the best of our knowledge, this reform is the first public signal of a planned tax rate convergence. However, many firms had already been operating under the EU ETS by this time.

Formally testing any anticipation effect would be out of the scope for this paper. However, we believe that it is not a key challenge in our setting for multiple reasons. Firstly, the tax rate changes generally took place in a few months after the announcement. Furthermore, the major emitters were usually eligible for generous tax reliefs. The first phase of the EU ETS also granted almost all emission rights free for businesses (European Commission (nd)). This gives significant reduction in the environmental costs of the impacted firms. The announced ambition to close the gap between manufacturing and general tax rate in 2009 is not relevant for the current setting as our sample spans 1990-2008. However, the major emitting industrial plants operate under the EU ETS (and got full exemption from the tax in 2011), which get exemptions to reduce carbon leakage (Martin et al. (2014b)). Hence, we do not expect our results to be affected on a longer horizon either.

B Data and Sample Construction

B.1 Road map

We construct our sample in several steps. First, we begin with the harmonization of the industry classification codes and use micro-level workplace data to obtain a coherent classification using the most recent classification across time.[46] Second, we aggregate our workplace-level data to the level of the firm (since the emissions data is administered at firm-level). For firms with only one workplace or whose workplaces all are classified the same, we simply take the industry classification of the workplace. But, if several installations (with different industry codes) belong to the same firm, we determine the primary one based on the number of employees that belong to the installations under the different codes.[47] We keep all firms which we can assign to a coherent industry classification over the full time period 1990-2015.

Third, we merge CO_2 emissions data to firms with consistent industry classification as reported above. We report the firm count after this step by year in the *"All surveyed firms in manufacturing"* column.

Fourth, we only include firms with available sales data as we scale CO_2 emissions with sales in many of the tests. We display the annual firm count after this step in the *"Matched to firm-level identifier with sales"* in Table B.1. We also deflate sales to 2010 prices using producer price indices at the four-digit industry level. As seen from Figure A.3, we are able to match the vast majority of firms from step 3 with sales data. The top line in Figure A.3 represents the total CO_2 heating emissions for Swedish manufacturing. The middle line represents the total CO_2 heating emissions from the original data supplied by SEPA, and the bottom line (dashed line) represents the aggregate annual CO_2 heating emissions for the firms in our sample. Our sample firms cover, on average during 1990-2015, around 85% of the total, manufacturing CO_2 heating emissions. We also note that there is no systematic difference between the top and bottom lines. In Figure A.4 we also consider process emissions (which were not covered by the tax) and again we can see that our

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[46] As we work with anonymized data, it is unfeasible to unveil the reason for any change in the industry affiliation; therefore, we limit our sample to firms with consistent industry codes. This cut, however, has only a small effect on our final sample.

[47] The amount of information available at the workplace level is somewhat limited in Swedish data. For instance, sales are not reported at the workplace level.

sample covers the vast majority of all manufacturing CO_2 emissions in Sweden over our sample period.

Fifth, and finally, since official firm-level tax records of actual carbon taxes paid are not available, we infer the tax payments from the CO_2 heating emissions using the carbon tax schedule (including exemptions) in place for each year of our sample (we infer the official tax rates and exemptions from government bills, and laws). Between 2008 and 2010, when firms are covered also by the EU ETS, we work with the exemptions and carbon tax rates in force as all emissions are also taxed. From 2011, emissions under the trading systems are not taxed. We approximate carbon tax payments from the comparison of reported EU ETS emissions and total emissions in several steps. As our emissions data report carbon dioxide and other greenhouse gas emissions separately, we can easily isolate emissions from the other sources. Although, we can also observe process and heating emissions under EU ETS separately for each firm, it is not reported in any official sources what fraction of these heating emissions are taxed in Sweden.[48] Therefore, we assume that all heating emissions above the reported EU ETS heating emissions are subject to the Swedish carbon tax.

B.2 Handling the different industrial classification systems

A major challenge in the analysis is handling the revisions of the industrial classification systems in force, which occurred three times in our sample period. NACE[49] is the statistical classification of economic activities in the European Community (Eurostat (2016)), hence implemented in the entire European Union. As Sweden joined the block in 1995, the country had to harmonize its applicable system (SNI69[50]) to NACE Rev.1 (SNI92 in Sweden). The new nomenclature entered into effect in 1993 in Sweden. A minor update in the standard became effective in 2003 (Statistics Sweden (2003)), called NACE Rev 1.1 (SNI2002 in Sweden). A major revision of the international integrated system of economic classifications resulted in the presently used NACE Rev. 2 (Eurostat (2008)). The work took place between 2000 and 2007, which enabled to reflect on the structural changes of the economy since the last update of the system. The new classification came into effect in 2008.

The most recent nomenclature comprises of more subgroups than the previous standards. For example, SNI2002 used 776 groups while SNI2007 classifies industrial enterprises into 821 different categories. The refinement of the classification imposes a significant challenge on longitudinal studies since there is no unique key that maps all firms' classifications. For example, the 01111 (which is cereal cultivation in SNI2002) is separated into seven further

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[48] The European Union Transaction Log, the official registry of the EU ETS, reports only that fraction of the total EU ETS emissions that are covered by purchased emission rights.

[49] NACE is the acronym for "Nomenclature statistique des activités économiques dans la Communauté Européenne"

[50] SNI is the acronym for "Standard för svensk näringsgrensindelning"

categories in SNI2007 (01110, 01120, 01160, 01199, 01302, 01640, 02200). However, correct industrial classification is necessary to draw inferences on the environmental regulation's effects. Our goal was identifying the five-digit identification number that represents the firm's activity between entering to the sample until its exit. We benefited from the following steps to address the multiple classifications:

1. We embarked on the harmonization based on our workplace-level data, due to several reasons. First, the database spans the entire sample horizon, and it is our most complete dataset for the unification purpose. We can trace most of the plant's classification numbers in the entire horizon of the operation. The key feature of this database is that industry affiliation codes are available in multiple nomenclatures in some transitional years. For example, the implementation of SNI2002 formally started in 2003 but the system was applied to data reported between 2000 and 2008 (Swedish National Audit Office (2013)). This generated four overlapping years with the SNI92 classification (i.e. 2000-2003), and one with the SNI2007 (in 2008).

   Hence, we first harmonize the classification on the plant-level. The codes are located in three different columns (one for SNI92, one for SNI2002, and SNI2007), depending on the incumbent nomenclature in a given year. If a plant operates under several standards, the codes are available in both systems in the overlapping years.

   a, The first step was to harmonize the classification in the SNI92 and the SNI2002 systems that we carried out in two steps. We started our inspection with the plants that operate both in the SNI92 and in the SNI2002 standards as their operations are classified in both nomenclatures. We used the corresponding SNI2002 codes for all observed earlier years. For example, if the associated SNI2002 code is 15120 in year t for a given plant, we apply this number for the same plant for all the years when the plant is in the sample.

   b, If a firm's operation is tracked only in one industry standard, we rely on the official keys published by Statistics Sweden (Statistics Sweden). As the first revision of the NACE Rev.1 system was minor, the key between SNI92 and SNI2002 provides an almost unique matching between the two standards. When an identifier in SNI92 corresponds to several different SNI2002 codes, we kept the first one. Since the codes are relatively close to each other, we believe this simple selection does not bring much uncertainty into our analyses.

   c, The next step reconciles the observed SNI2002 and SNI2007 industry codes. As in point a, we started our work with the firms that have overlapping classification numbers. Since our primary objective is to obtain the structuring in the most recent nomenclature, we replaced all SNI2002 codes with the corresponding

SNI2007 identification numbers. This step provides the internal consistency of the categorization in time.

d, We also need to link the SNI2002 and the SNI2007 codes for those enterprises that are categorized only in one system. We address this challenge by keeping the most frequent SNI2007 subgroup that belongs to the same SNI2002 identification number. Similarly to the previous point, we finish this step with copying the obtained SNI2007 codes throughout the sample.

C Appendix Material for "Counterfactual: manufacturing CO_2 emissions in similar countries"

C.1 International sample: additional information

The full database of the Agency contains annual CO_2 emissions from fuel combustion and related indicators for over 185 countries and regional aggregates going back to 1960. The emissions data closely follows the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC (2006)), which is more aggregated than the industry nomenclature for the Swedish data (Nomenclature of Economic Activities (NACE)). The correspondence between these broader categories and the NACE code is described in Table B.6.

We have access only to gross output and value added to normalize emissions. The OECD STAN database points out that production includes intermediate inputs (such as energy, materials and services required to produce final output). Any output of intermediate goods consumed within the same sector is also recorded as output - the impact of such intra-sector flows depending on the coverage of the sector. For this reason, value added is often considered a better measure of output.

In order to classify the IEA industries accordingly, we first compute the carbon intensity for each industry in 1990 similarly to the Swedish analysis. For each industry, we define carbon intensity as the sum of CO_2 emissions across all countries in 1990 divided by the sum of PPI-adjusted dollar equivalent sales across all countries in that industry. Six industries are considerably more carbon-intensive: Non-metallic minerals, Iron and Steel, Non-specified industry, Chemical and petrochemical, Paper, pulp and printing and Non ferrous metals. The other five sectors that display considerably lower carbon intensity are Food and tobacco, Textile and leather, Wood and wood products, Machinery, and Transport equipment. The carbon intensity of the six high-emitting industries is ten times higher than for the bottom five industries. Similarly to the Swedish sample, the six high-emitting industries in the IEA data include all the four biggest emitters (Refineries (Chemical and petrochemical), Basic metals (Iron and steel and Non ferrous metals), Cement production (Non-metallic minerals) and Paper manufacturing (Paper, pulp and printing)).

C.2 Synthetic control method

In this section, we review the mathematical background of the synthetic control method and the main variables we applied in constructing the counterfactual.

Let $J+1$ be the number of countries in the sample, indexed by j , and let $j=1$ denote Sweden, the "treated unit". The units in the sample are observed for time periods $t=1,2,\cdots,T$. In order to construct synthetic Sweden and evaluate the effect of the treatment, it is important to have available data on a sufficient amount of time periods prior to treatment $1,2,\cdots,T_0$ as well as post-treatment $T_0+1,T_0+2,\cdots,T$. Synthetic Sweden is constructed as a weighted average of the control countries $j=2,\cdot,J+1$ and represented by a vector of weights $W=(w_2,\cdots,w_{J+1})'$ with $0\leq w_j\leq 1$ and $w_2+\cdots+w_{J+1}=1$. Each choice of W gives a certain set of weights and hence characterizes a possible synthetic control. We choose W so that the difference between Sweden and the control units on a number of key predictors of the outcome variable and the outcome variable itself is minimized in the pre-treatment period, subject to the above (convexity) constraints[51].

Our dependent variable is the emission intensities relative to their 1990 levels, which is meant to eliminate the effect of exchange rates on outputs[52]. As key predictors, we use GDP per capita (expressed in 2015 dollar values), manufacturing value added per capita (in 2015 dollars), and total factor productivity. When we analyze D10 and D1-D9 industries separately, we add the composition of the sectors (i.e. fraction of total value added originating from the sector) to the set of predictors. The level of GDP per capita is shown in the literature to be closely linked to emissions of greenhouse gases (Andersson (2019)). Manufacturing value added controls for the size effect, i.e. higher output level mechanically implies higher carbon dioxide emissions (similar to "scales" effect discussed in subsection 5.1). Total factor productivity is a measure for production efficiency and hence a proxy for technological development ("technique" effect). We take the mean of the three key predictors over the 1982–1989 period[53]. Finally, we add two lagged years (1982 and 1989) of CO_2 emission intensities. As a majority of manufacturing emissions are covered by EU ETS since 2008, we run the algorithm for only the 1982-2007 time period.

The synthetic control method has some advantages over the differences-in-differences (DiD) estimator, which is frequently used in comparative case studies (Andersson (2019)). Besides simulations, the use of the DiD estimator is the most common research design in evaluations of the effects of carbon taxes (see, e.g., Elgie and McClay (2013), Lin and Li (2011), Andersson (2019)). The synthetic control method relaxes the parallel trends assumption that underlies the DiD estimator by allowing the effects of unobserved

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[51] For a more detailed description of the methodology, see e.g. Abadie et al. (2010), Abadie et al. (2015), Andersson (2019), Firpo and Possebom (2016)

[52] The effect is pivotal in the early 90s when Sweden underwent a deep recession that weakened Swedish krona against USD.

[53] Not all sectors and countries have observable value added data between 1980 and 1982.

confounders on emissions to vary over time (Abadie et al. (2010)). Furthermore, one can weigh the units in the control group and include predictors of manufacturing emission intensities to create a comparison unit that most resembles Sweden.

C.3 Statistical inference and placebo tests

Statistical inference in comparative case studies is challenging because of the small-sample nature of the data, the absence of randomization, and the fact that probabilistic sampling is not employed to select sample units (Abadie et al. (2015)). As there is no standard parametric procedure to determine p-values and confidence intervals, multiple approaches have been suggested in the literature to address these issues. A widespread approach is systematizing the process of estimating the counterfactual of interest. This means that the treatment is iteratively reassigned to every country in the donor pool, again using the synthetic control method to construct synthetic counterparts (Andersson (2019)). This form of permutation test allows for inference and the calculation of p-values: measuring the fraction of countries with results larger than or as large as the one obtained for the treated unit. The test statistic is the ratio of post-treatment mean squared prediction error (MSPE) and the pre-treatment MSPE:

$$RMSPE_j := \frac{\sum_{t=T_0+1}^{T}(Y_{j,t}^{tr} - \hat{Y}_{j,t}^{sy})^2/(T-T_0)}{\sum_{t=1}^{T_0}(Y_{j,t} - \hat{Y}_{j,t}^{sy})^2/(T_0)}$$

where $\hat{Y}_{j,t}^{sy}$ stands for the potential outcome that would be observed for region j in period t if there were no intervention and $Y_{j,t}^{tr}$ in case of intervention. The method gives an insight into whether the result obtained for Sweden is unusually large, by comparing the fraction of MSPEs for Sweden with the placebo countries in the donor pool. The p-value is defined as

$$p := \frac{\sum_{j=1}^{J+1} \mathbb{I}(RMSPE_j \geq RMSPE_1)}{J+1}$$

Due to the lack of a standard parametric inference procedure, we examine statistical inference based on this method as well as Firpo and Possebom (2016) who propose a generalized inference method and confidence bounds based on the above test statistic.

Figure A.8 and Figure A.9 report the difference between the emission intensities of each treated country and its synthetic counterpart. The figures show that Swedish emission intensities do not diverge from the donor pool in either sample, albeit the difference is among the biggest ones for Sweden[54]. Furthermore, the placebo post-treatment differences

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[54] The algorithm could not reach good fit in the pre-treatment period for a few countries. The most noticeable case is Iceland, which is not surprising given that the country has the lowest carbon emissions in the sample. Therefore, we left out Belgium, Iceland, and Ireland when we constructed the figure for the lower-emitting sectors. We did not drop Belgium for the most emitting sectors as the pre-treatment fit is better for that country

are positive and high for several countries (e.g. France and Italy). This translates to higher RMSPE values for these countries than for Sweden (Table B.5) and hence a p-value of 3/15=0.2. The obtained p-value suggests an insignificant difference between the treated and the synthetic counterpart. The confidence interval emerged from the procedure by Firpo and Possebom (2016) suggests statistically significant differences (on 13.3% level) for the last few years for the lower-emitting sectors (Figure A.13) and no significance for the highest-emitting sectors (Figure A.12).

As a further robustness exercise, we iteratively eliminate one of those control countries that got a positive weight to check if the results are driven by one or a few influential controls (leave-one-out test, proposed by Abadie et al. (2015)). Figure A.10 and Figure A.11 report the results of this test. Consistent with earlier findings, there is no systematic divergence for the highly carbon intensive sub-sectors while Sweden deviates from the synthetic counterpart regardless of which country is eliminated from the donor pool.

Figure A.1: Distribution of total environmental taxes in the overall economy

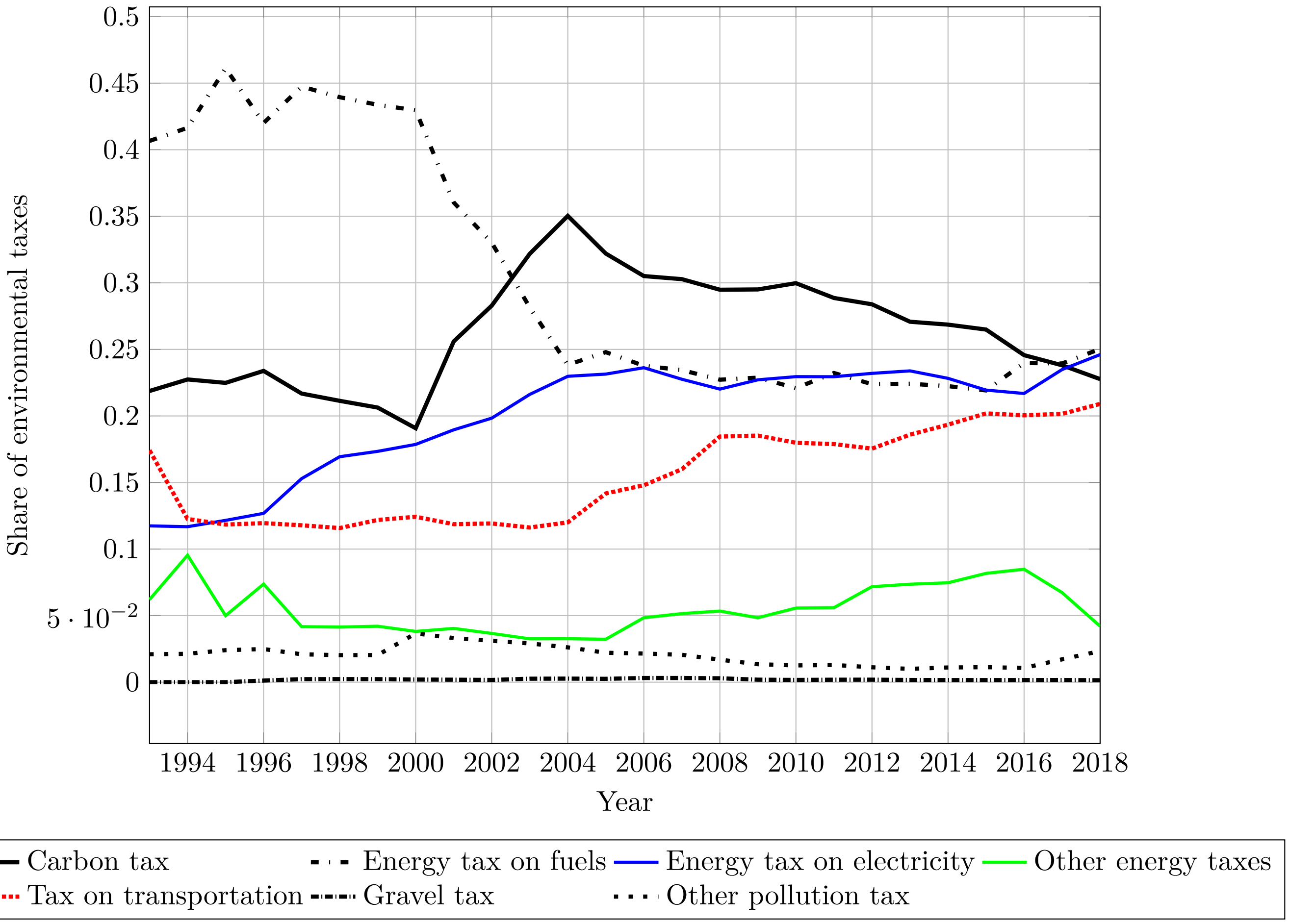

Figure A.1 displays distribution of the Swedish environmental tax payments in the overall economy (including households) from 1993 to 2018.

Figure A.2: Distribution of environmental taxes in the manufacturing sector

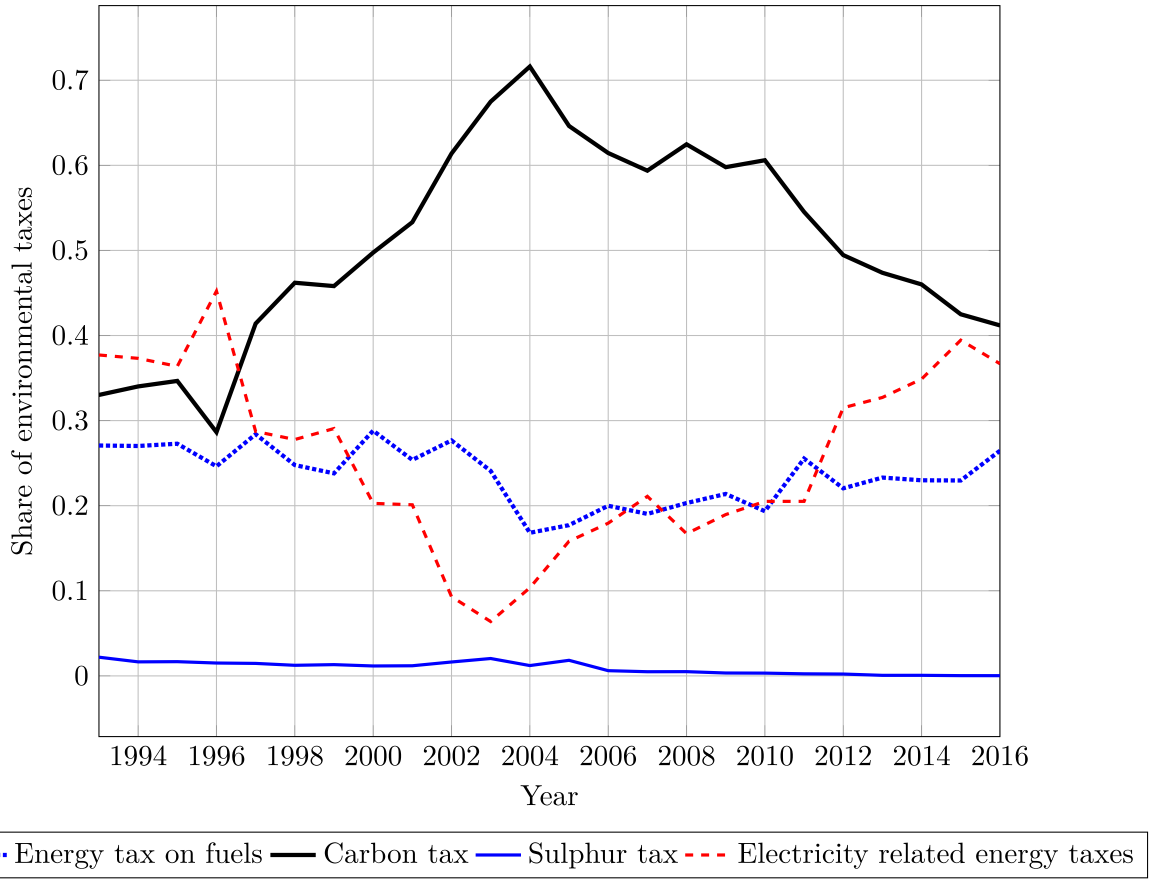

Figure A.2 displays the distribution of the Swedish environmental tax payments in the manufacturing sector (i.e. SNI 10-33 in the SNI2007 nomenclature) from 1993 to 2016.

Figure A.3: Coverage of heating emissions data in our sample

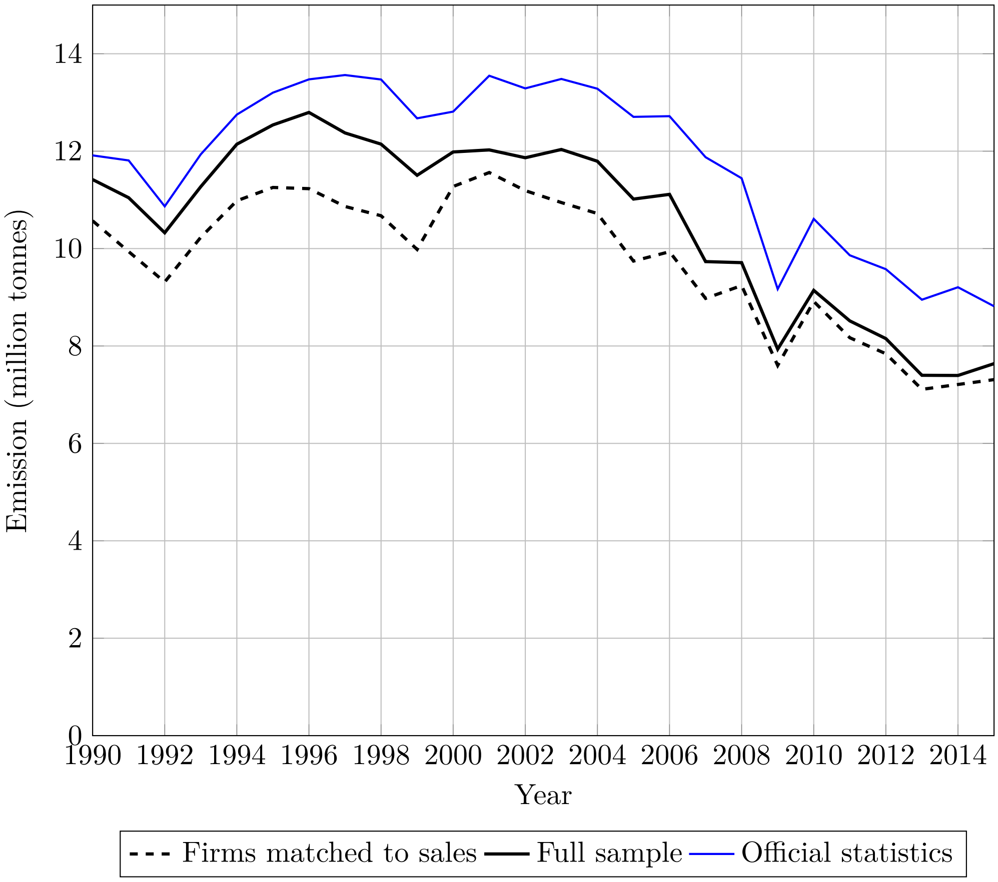

Figure A.3 compares heating emissions calculated from our full sample (*Full sample*) with the official tax payments registered by the responsible authorities and government agencies (*Official statistics*) and with that subsample that has observable sales (*Firms matched to sales*).

Figure A.4: Coverage of total emissions (heating plus process) data in our sample

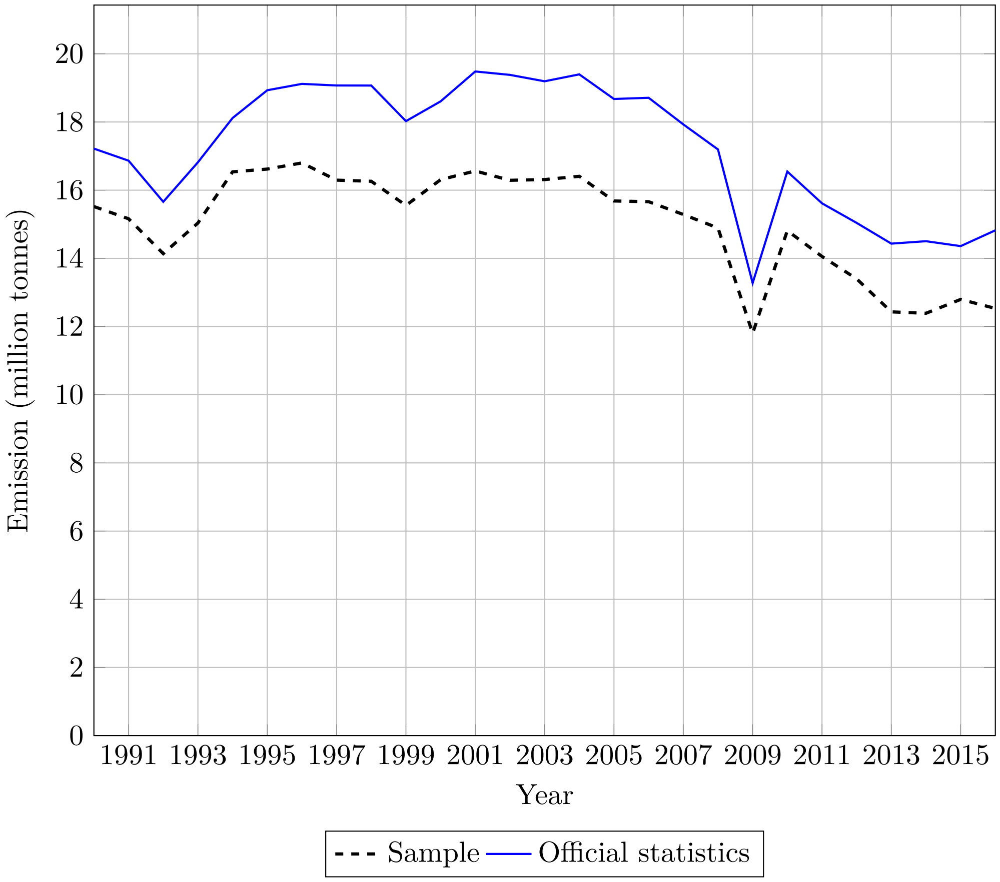

Figure A.4 compares the total emissions (i.e. heating plus process) calculated from our sample (*Sample*) with the official tax payments registered by the responsible authorities and government agencies (*Official statistics*).

Figure A.5: Emission intensities for the balanced sample

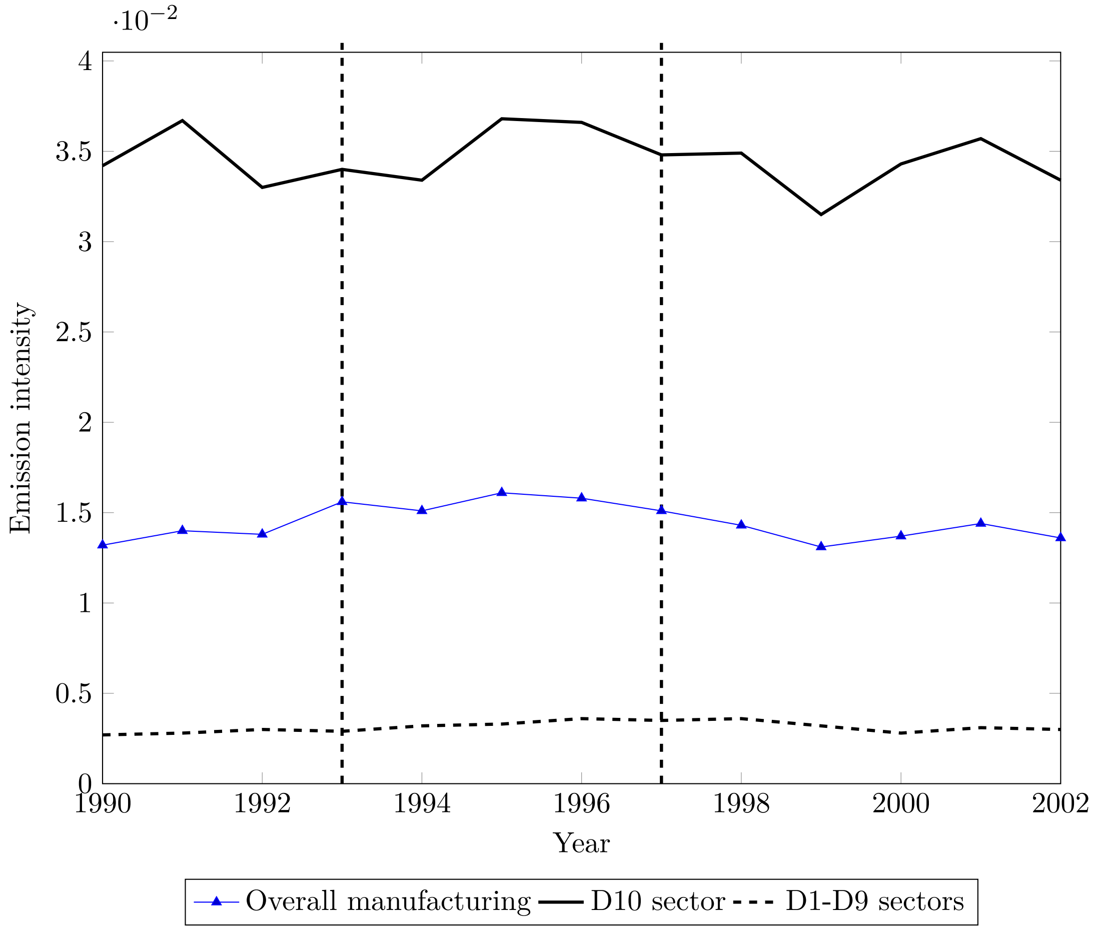

Figure A.5 reports the time series of emission intensities in the overall manufacturing sector, the most polluting (*D10*), and the rest of the manufacturing sector (*D1-D9*)

Figure A.6: Emission intensities for the balanced sample

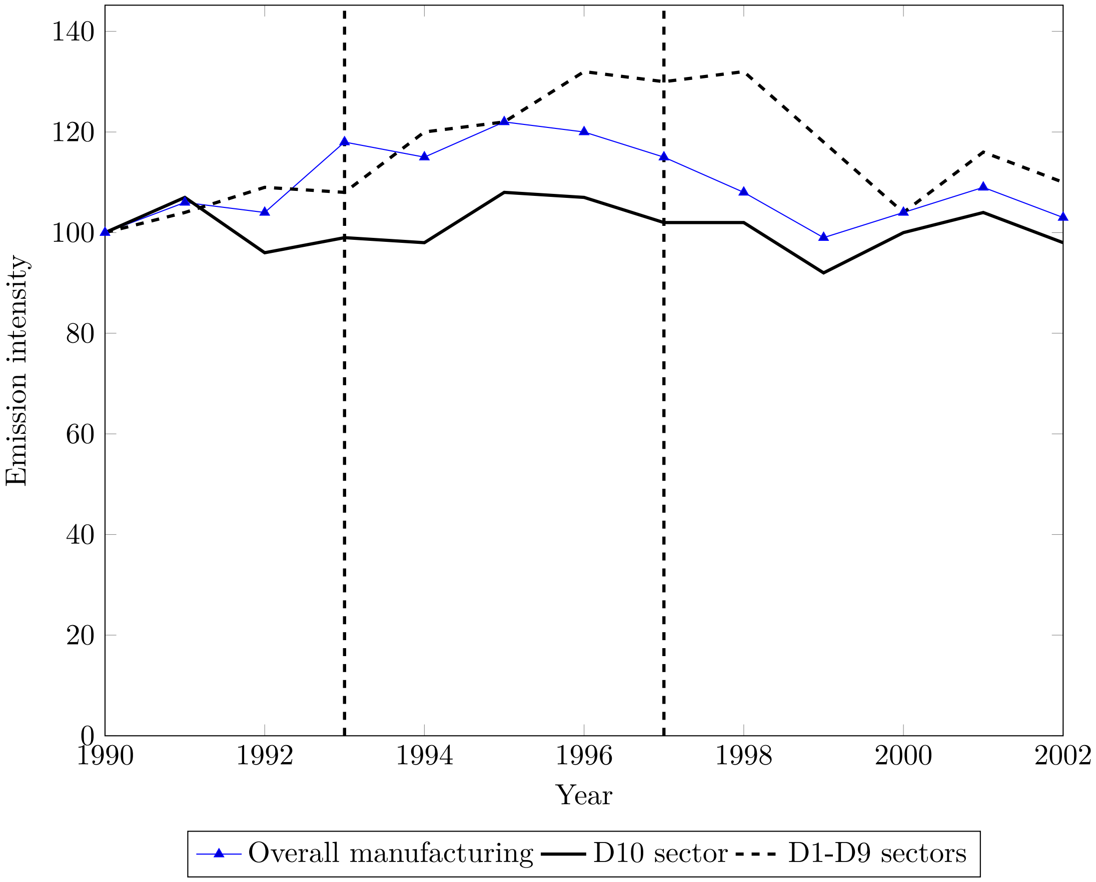

Figure A.6 reports the time series of emission intensities relative to the 1990 level (=100) in the overall manufacturing sector, the most polluting (*D10*), and the rest of the manufacturing sector (*D1-D9*).

Figure A.7: Distribution of sales, carbon dioxide emissions, and carbon tax payments

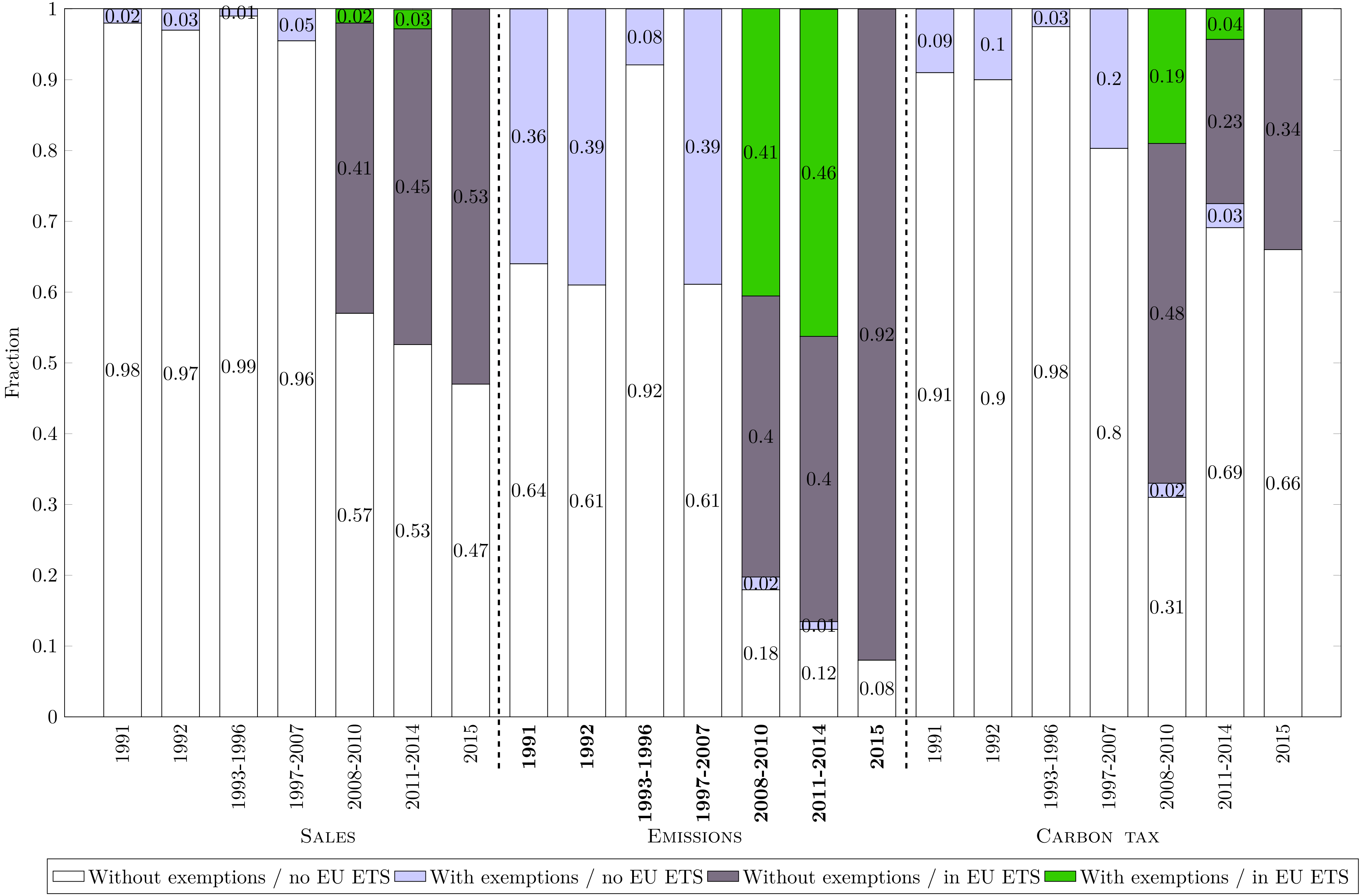

Figure A.7 displays the distribution of sales, carbon dioxide emissions, and carbon taxes paid under different tax regimes. For a description of *Without (with) exemptions/no (in) EU ETS*, see Figure 7.

Table B.1: Sample size by year

Year	All surveyed firms in manufacturing	Matched to firm-level identifier with sales	Year	All surveyed firms in manufacturing	Matched to firm-level identifier with sales
1990	4,239	3,702	2003	583	498
1991	4,475	3,554	2004	564	477
1992	4,255	3,407	2005	485	401
1993	3,551	2,819	2006	511	426
1994	3,794	3,457	2007	2,799	2,651
1995	3,419	3,066	2008	2,794	2,633
1996	3,170	2,776	2009	2,622	2,502
1997	545	465	2010	2,452	2,335
1998	506	421	2011	2,385	2,260
1999	575	462	2012	2,351	2,210
2000	4,004	3,773	2013	2,232	2,128
2001	1,856	1,738	2014	2,130	2,043
2002	1,687	1,575	2015	1,995	1,718

Table B.1 tabulates the size of the Swedish manufacturing emission data. *All surveyed firms in manufacturing* is the number of firms with observable emissions in the data. *Matched to firm-level identifier with sales* is our working sample; i.e. the number of firms with observable emissions and sales.

Figure A.8: Permutation test: higher-emitting sectors

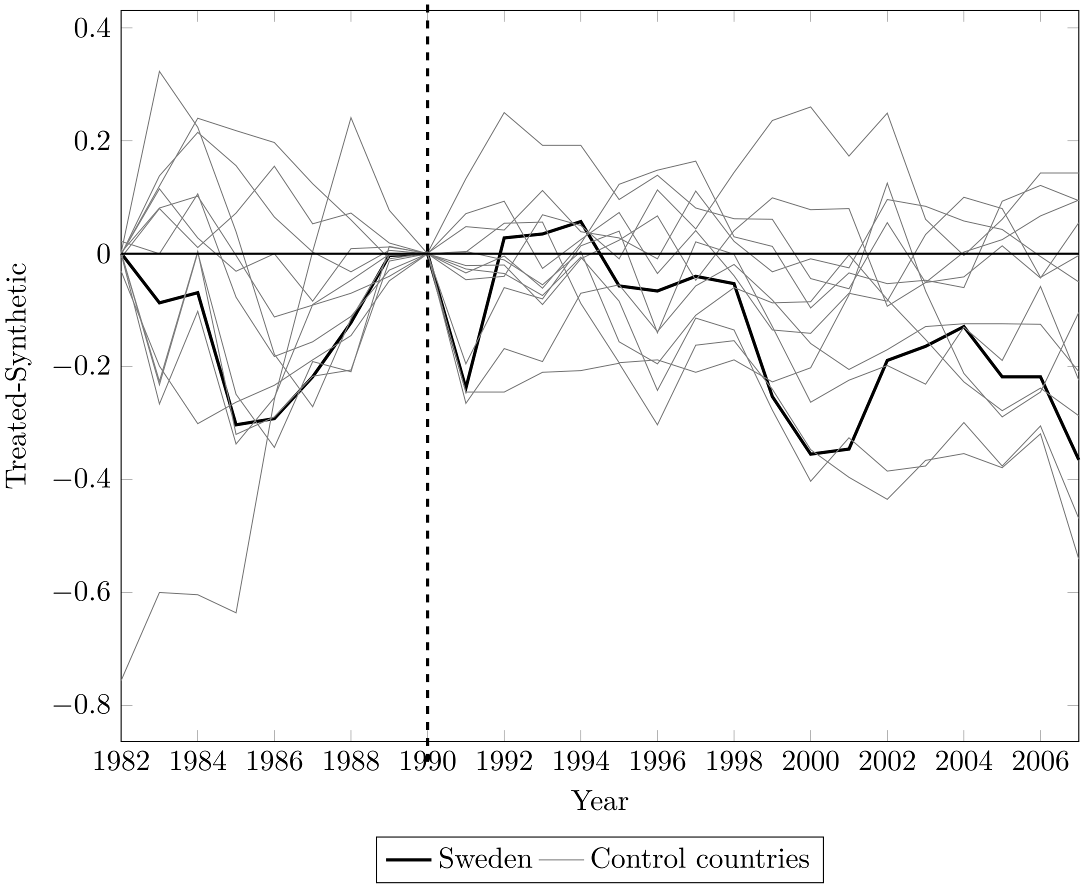

Figure A.8 reports the emission intensity gap for the higher-emitting sectors when the treatment is iteratively reassigned to every country in the donor pool, again using the synthetic control method to construct synthetic counterparts.

Figure A.9: Permutation test: lower-emitting sectors

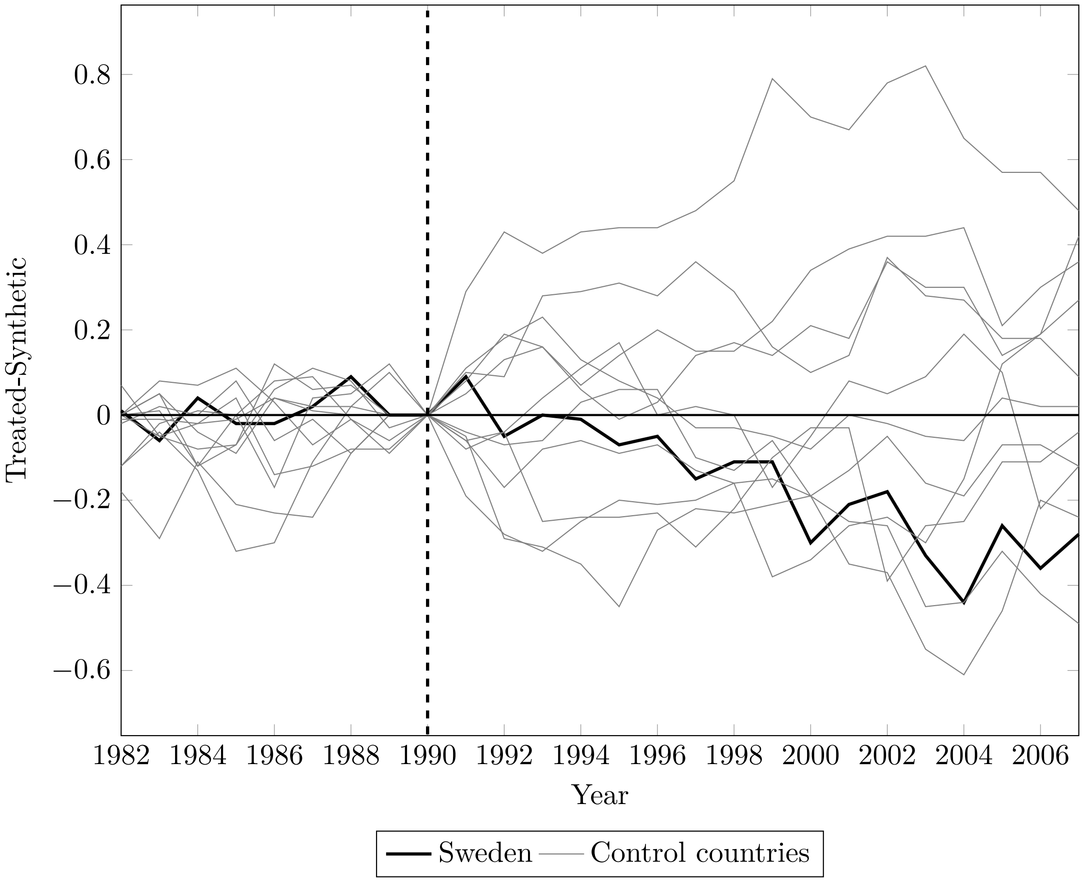

Figure A.9 reports the emission intensity gap for the lower-emitting sectors when the treatment is iteratively reassigned to every country in the donor pool, again using the synthetic control method to construct synthetic counterparts.

Figure A.10: Leave-one-out test for the high-emitting sectors

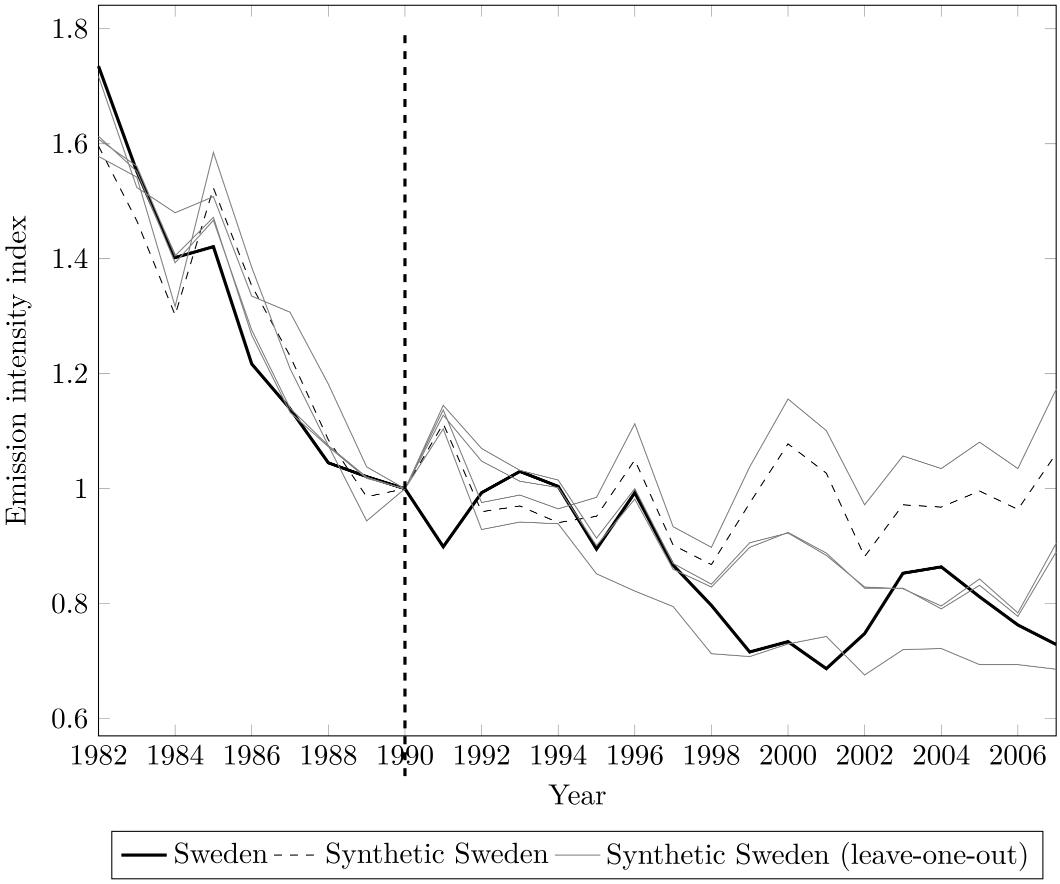

Figure A.10 reports the path of emission intensity indices in the high-emitting sectors for Sweden and its counterfactual when we iteratively eliminate one of the control countries with positive weight.

Figure A.11: Leave-one-out test for the low-emitting sectors

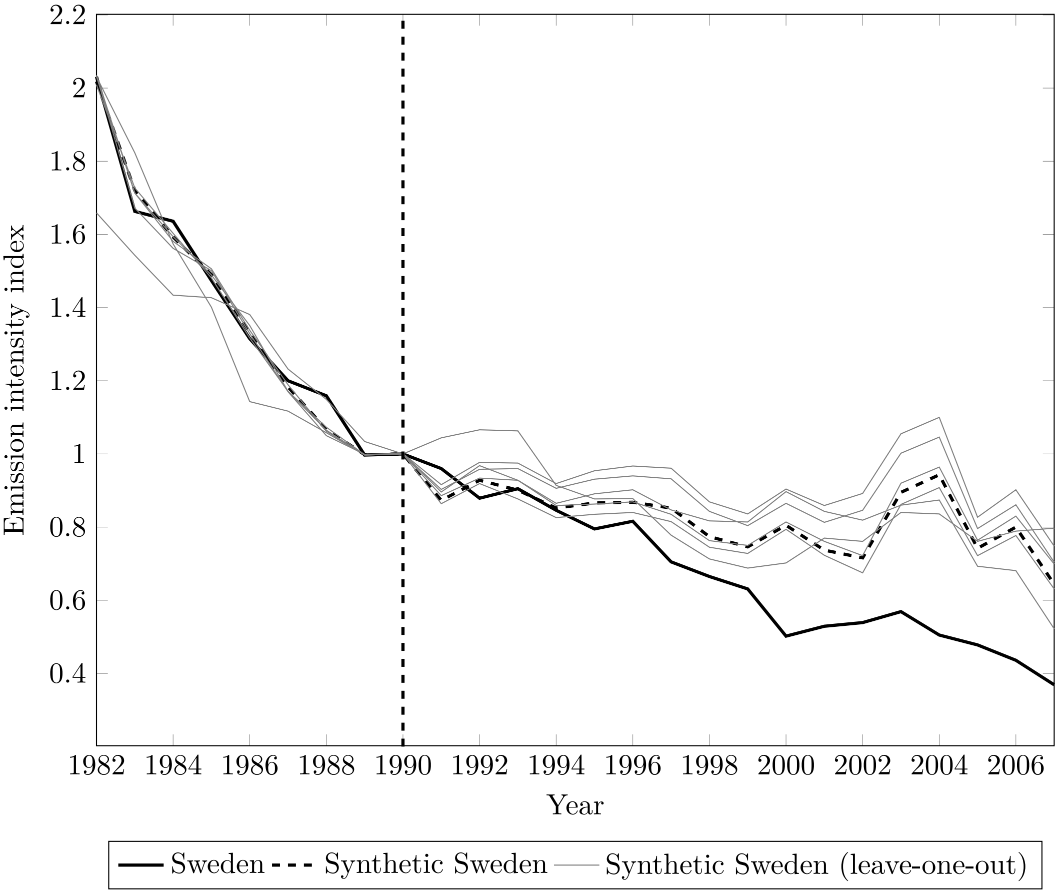

Figure A.11 reports the path of emission intensity indices in the low-emitting sectors for Sweden and its counterfactual when we iteratively eliminate one of the control countries with positive weight.

Figure A.11

Figure A.12: Confidence interval- most emitting sectors

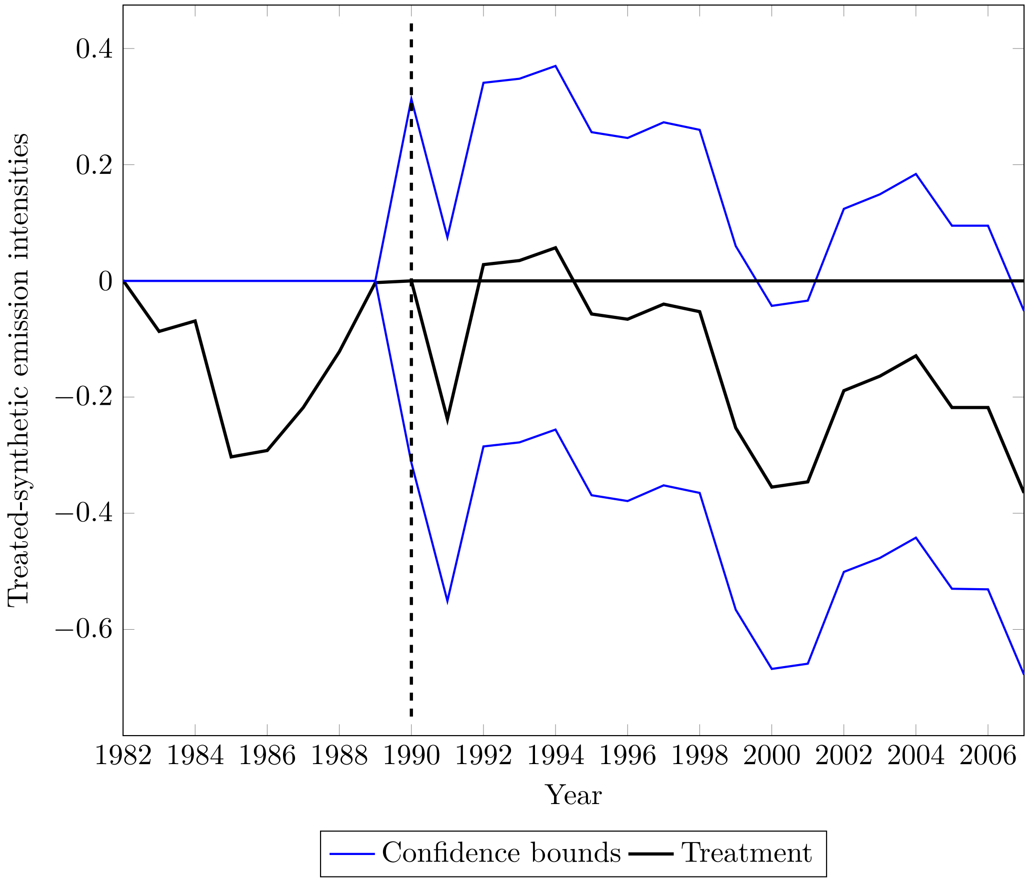

Figure A.12 reports the difference in emission intensity indices between Sweden and synthetic Sweden for the highly emitting manufacturing sector. The confidence bound is constructed as in Firpo and Possebom (2016).

Figure A.13: Confidence interval- rest of the manufacturing sector

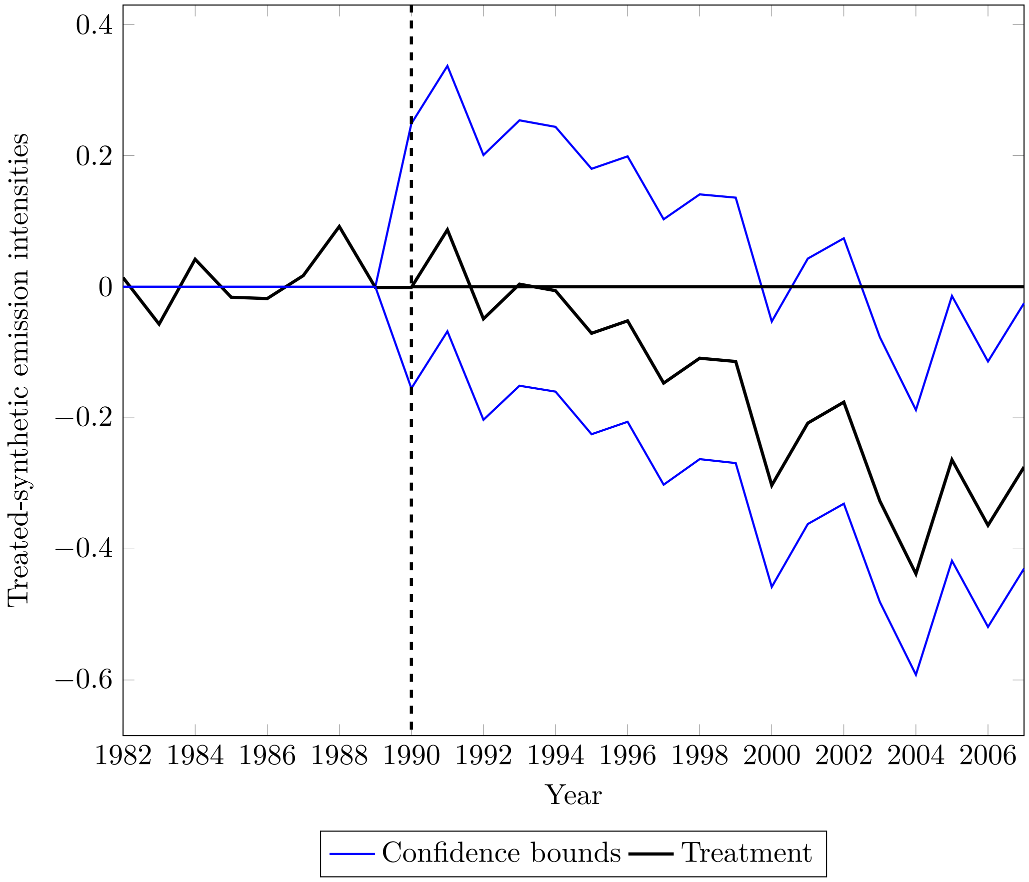

Figure A.13 reports the difference in emission intensity indices between Sweden and synthetic Sweden for the low-emitting manufacturing sector. The confidence bound is constructed as in Firpo and Possebom (2016).

Table B.2: Emission intensities and PACE

	Emissions-to-sales	**Emissions-to-cost**	**PACE-to-sales**	**PACE-to-cost**
All	0.0084	0.0133	0.0021	0.0032
D10	0.0313	0.0486	0.0088	0.0109
D9	0.0097	0.0133	0.0031	0.0045
D8	0.0048	0.0053	0.0006	0.0009
D7	0.0037	0.0042	0.0022	0.0033
D6	0.0024	0.0040	0.0006	0.0011
D5	0.0019	0.0029	0.0004	0.0005
D4	0.0015	0.0016	0.0010	0.0015
D3	0.0012	0.0022	0.0012	0.0018
D2	0.0008	0.0010	0.0010	0.0017
D1	0.0006	0.0010	0.0009	0.0015

	Emissions-to-sales	**Emissions-to-cost**	**PACE-to-sales**	**PACE-to-cost**
Emissions-to-sales	1.0000			
Emissions-to-cost	0.9979	1.0000		
PACE-to-sales	0.9765	0.9778	1.0000	
PACE-to-cost	0.9640	0.9636	0.9973	1.0000

Table B.2 reports aggregate CO_2 emissions scaled by sales, PACE expenditures scaled by sales, and total costs by decile and in the overall manufacturing sector.

Table B.3: CO_2 elasticity

SNI 2007 industries		$\frac{CO_2\text{emissions (kg)}}{\text{cost (SEK)}}$	CO_2emissions elasticity	Coefficient	Std error	T	OBS
10-33	Total manufacturing	0.0133	0.0190	52.60	7.26	7.24	23 593
10-12	Food, beverages and tobacco products	0.0072	0.0543	18.43	13.66	1.35	2 994
13-15	Textiles, apparel and leather products	0.0067	0.0125	80.15	28.03	2.86	813
16	Wood and products of wood	0.0021	0.0156	64.21	22.77	2.82	1 485
17	Paper and paper products	0.0202	0.0274	36.53	13.00	2.81	1 513
18	Printing and reproduction of recorded media	0.0025	0.0031	327.12	84.24	3.88	452
19	Coke and refined petroleum products	0.0948	0.0542	18.44	9.32	1.98	122
20-21	Chemicals and Pharmaceuticals products	0.0164	0.0474	21.09	6.40	3.29	1 245
22	Rubber and plastic products	0.0023	0.0111	89.80	37.13	2.42	1 129
23	Other non-metallic mineral products	0.0447	0.0245	40.83	11.62	3.51	1 240
24	Basic metals	0.0190	0.0396	25.25	17.14	1.47	1 500
25	Fabricated metal products	0.0040	0.0143	69.90	43.60	1.60	4 412
26-27	Computer, electronic, optical products and electrical equip.	0.0017	0.0040	252.47	108.69	2.32	863
28	Machinery and equipment n.e.c.	0.0013	0.0036	278.89	52.31	5.33	2 570
29	Motor vehicles, trailers and semi-trailers	0.0032	0.0061	165.02	65.89	2.50	1 048
30	Other transport equipment	0.0021	0.0070	142.12	173.43	0.82	359
31-33	Furniture, other and recycling	0.0016	0.0100	99.93	42.23	2.37	1 847

Table B.3 reports the CO_2 elasticities for the manufacturing sector.

Table B.4: Synthetic control method: predictors and weights

Panel A

Predictor	Overall economy		High-emitting sectors		Low-emitting sectors	
	Treated	Synthetic	Treated	Synthetic	Treated	Synthetic
GDP per capita	31632.98	28765.33	31632.98	28686.31	31632.98	27444.34
Manufacturing value added	3696.79	4059.91	3696.79	4122.91	3696.79	3976.34
Total factor productivity	0.82	0.85	0.82	0.85	0.82	0.84
Composition	-	-	0.47	0.47	0.54	0.54
EI index (1982)	1.74	1.75	1.74	1.60	2.03	2.02
EI index (1989)	1.01	1.01	1.02	1.05	1.00	1.00

Panel B

Country	Overall economy	High-emitting sectors	Low-emitting sectors
Australia	0.426	0.569	0.162
Austria	0.165	0	0.108
Belgium	0	0	0.338
Canada	0	0	0
France	0	0	0
Germany	0.141	0.217	0.095
Iceland	0.172	0.109	0.192
Ireland	0.097	0.105	0.106
Italy	0	0	0
Japan	0	0	0
New Zealand	0	0	0
Portugal	0	0	0
Spain	0	0	0
United Kingdom	0	0	0

Table B.4 reports the predictor balance (i.e. actual and counterfactual values) and the weights assigned to the control countries. All variables except lagged emission intensities are averaged for the period 1982– 1989. GDP per capita is measured in 2015 dollars.

Table B.5: Ratio of MSPE values

Panel A

Country	post-MSPE	pre-MSPE	RMSPE
Canada	0.01	0.00	4.56
Portugal	0.02	0.01	3.29
Ireland	1.59	0.49	3.26
Italy	0.10	0.04	2.55
UK	0.08	0.03	2.24
Belgium	0.02	0.01	2.09
Iceland	1.16	0.69	1.69
Sweden	0.04	0.03	1.29
Spain	0.01	0.01	1.00
Germany	0.02	0.03	0.64
France	0.01	0.01	0.60
Japan	0.02	0.04	0.58
Austria	0.00	0.02	0.15
New Zealand	0.03	0.23	0.12
Australia	0.00	0.04	0.10

Panel B

Country	Post-MSPE	Pre-MSPE	RMSPE
Italy	0.33	0.00	1291.31
France	0.08	0.00	31.62
Sweden	0.05	0.00	26.12
Austria	0.06	0.00	13.88
Germany	0.09	0.01	11.44
Canada	0.04	0.01	7.95
New Zealand	0.04	0.01	6.86
Japan	0.01	0.00	6.43
Portugal	0.12	0.03	3.79
Spain	0.01	0.00	2.58
UK	0.01	0.01	1.48
Australia	0.04	0.04	1.14
Belgium	0.06	0.06	1.06
Ireland	0.03	0.07	0.40
Iceland	0.31	1.35	0.23

Table B.5 reports the mean sqaured prediction errors (MSPE) post- (1991-2007) and pre-treatment (1982-1989) as well as their ratios for the countries in the donor pool.

Table B.6: Correspondence of IEA industry classification and NACE

IEA data	NACE classification
Iron and steel	Manufacture of basic metals, except casting of light metals and other non-ferrous metals Manufacture of basic metals except basic precious and other non-ferrous metals
Chemical and petrochemical	Manufacture of chemicals and chemical products Manufacture of basic pharmaceutical products Manufacture of pharmaceutical preparations
Non-ferrous metals	Manufacture of basic precious and other non-ferrous metals Casting of light metals and other non-ferrous metals
Non-metallic minerals	Manufacture of other non-metallic mineral products
Transport equipment	Manufacture of motor vehicles, trailers and semi-trailers Manufacture of other transport equipment
Machinery	Manufacture of fabricated metal products, except machinery and equipment Manufacture of computer, electronic and optical products Manufacture of electrical equipment Manufacture of machinery and equipment n.e.c.
Food and tobacco	Manufacture of tobacco products and textiles
Paper, pulp and printing	Manufacture of paper and paper products Printing and reproduction of recorded media
Textile and leather	Manufacture of textiles, wearing apparels, leather and related products
Wood and wood products	Manufacture of wood and of products of wood and cork, except furniture Manufacture of articles of straw and plaiting materials
Non-specified industry	Manufacture of rubber and plastic products Manufacture of furniture and other manufacturing

Table B.6 reports the correspondence between the industries covered by the IEA and the Swedish emission sample.