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 3-3.4% for the manufacturing sector. Aggregate manufacturing CO_2 emissions decreased by about 31% between 1990 and 2015. Our estimated elasticities imply that firms' responses to carbon pricing accounted for 8 percentage points of this decrease.

Keywords: Carbon taxation, Emissions trading, Climate Policy, Climate change, Green growth, Tax policy

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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

[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 universe of Swedish manufacturing firms over the period 1990-2015.

We first document that only a small fraction of narrowly defined manufacturing sectors – including steel, cement, and refineries – 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 ended up having much lower (and sometimes even zero) marginal tax rates, despite facing a high average tax rate (that reduced their their pre-tax margins by more than 6 percentage points on average). Consistent with the reduced 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 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 the marginal carbon tax rate. Using data from about 4,000 manufacturing firms, covering 85-90% of Sweden's manufacturing CO_2 emissions over 1990-2015, we document a significant negative relationship between firm-level CO_2 emission intensity and the marginal cost of carbon emissions. In our main specification,

[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)).

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 3-3.4%.[6] This relationship is stable over the introduction of the EU ETS in 2005 and to the inclusion of different firm-level control variables. We estimate a stronger carbon pricing effect among firms in industries with lower pollution abatement costs and with a lower ability to move their 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. We use a standard decomposition technique from Grossman and Krueger (1993) and Levinson (2009) to separate emission reductions into scale, composition, and technique effects. The decomposition attributes 3 percentage points to a decrease in aggregate manufacturing output ("scale") and 10 percentage points to the changing composition of the Swedish manufacturing sector away from CO_2 emitting industries to less emitting ones.[7] By definition, the remaining 18 percentage points (58% of the total reduction) is attributed to changes in technology ("technique"). We then use our estimated carbon elasticities to calculate the contribution from carbon pricing on these reductions. Our calculations suggest that carbon pricing accounts for an 8 percentage point decrease in aggregate manufacturing CO_2 emissions since 1990, or close to half of the technique effect.

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 can

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

[7]In a related study, using similar firm data, Forslid et al. (2021) show that imports actually reduces emissions intensity in Swedish firms (and that this effect can not be explained by offshoring of dirty activities).

[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.

provide a valuable input for calibrating macroeconomic models of optimal climate policy, such as Golosov et al. (2014) and Acemoglu et al. (2016).

Our study should also be 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 reduced-form estimates ignore important general equilibrium effects, they confirm that firms do respond to the marginal cost of emitting CO_2, consistent with economic theory. Our results also suggest that Sweden could have achieved significantly larger reductions in CO_2 absent the various exemptions that reduced marginal carbon tax rates for the highest-emitting firms.

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 are indeed concentrated to a few sectors and just a few firms within these sectors, which will be disproportionally affected by carbon pricing. While governments may be tempting (or necessary) to reduce the tax burden on these firms, doing so through a scheme that combines constant marginal tax rates with lump-sum subsidies would be superior to a cap on maximum tax payments for high emitters.

2 Institutional setting

2.1 The design of the Swedish carbon tax

Energy taxation is a central environmental policy measure in many countries and is essentially a surcharge on fossil fuels in different forms, as a percentage of the energy sales price (ad-valorem taxes). Energy taxes on fuels and electricity were motivated by fiscal reasons (SEPA and SEA (2007)), and Sweden introduced energy taxation already in the 1920's.[10] In contrast with the energy tax, the introduction of carbon taxation in 1991 was

[10]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.

motivated by environmental concerns.

While the carbon tax is technically a type of energy tax, it specifically targets the CO_2-emissions resulting from burning fossil fuels. The Swedish carbon tax is levied on fossil fuels used either in combustion engines ("mobile emissions") or for heating ("stationary emissions"). The carbon tax on mobile emissions primarily affects road transportation and is included in the after-tax price of fuel "at the pump". Heating fuels are used for combustion in industrial (mostly manufacturing) processes. Furthermore, manufacturing production releases two types of emissions: heating and process CO_2 emissions. The carbon tax on stationary emissions is levied on emissions from heating only, while CO_2 released during production processes are exempt from the carbon tax.[11] 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.[12]

The tax facing a manufacturing plant is illustrated 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.[13] 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.[14]

[11] As an illustration, consider the example of steel production. 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 metal) into steel (World Coal Association (2019)). The emissions throughout these stages makes 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 emissions resulting from the heating of the coal and the coke.

[12] 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)).

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

[14] In 1991, one USD was roughly equal to 6.50 SEK. Over our sample period, the exchange rate fluctuated between 6 and 9 SEK per USD.

Already from its introduction, however, the Swedish carbon taxation incorporated multiple provisions and exemptions (summarized in Table 1) targeted at the highest-emitting firms . In 1991, the sum of carbon and energy taxes were capped at 1.7% of the firm's sales; a threshold that was subsequently 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 a quarter 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[15], whose carbon tax payments were still capped at 1.2% of their sales (the "1.2% rule").

In 1997, a new carbon tax threshold of 0.8% was introduced, above which the tax rate was reduced to one quarter of the statutory rate (the "0.8% rule"). As a result, 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.[16]

In 2005, the European Union introduced a cap-and-trade scheme for CO_2 emissions, the EU ETS (*European Union Emissions Trading System*), which had major implications for the Swedish carbon tax design. Installations covered by the EU ETS were gradually phased out of the Swedish carbon tax regulation during 2008-2011 (Government Bill 2007/2008:1 (2007)). 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.[17] 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 in the EU ETS is been mandatory for firms in the energy sector and in energy-intensive industries.In other sectors, only plants above a certain size are included in the trading system. Governments can exclude small installations from the system if

[15] These industries were considered particularly vulnerable to the costs of environmental taxation (Government Bill 1989/90:111 (1989), Government Bill 1991/92:150 (1991))

[16] 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.

[17] One unit of emission right allows a firm to emit greenhouse gases equivalent to one metric tonne of CO_2.

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.

In contrast, Swedish plants outside of the EU ETS experienced sharp carbon tax increases after 2011 (Hammar and Åkerfeldt (2011)). The 0.8% rule was replaced by a higher threshold of 1.2% in 2011, and then removed completely in 2015. Starting in January 2018, the special exemptions were removed, making all non-EU ETS plants subject to the economy-wide carbon tax rate (Ministry of Environment and Energy (2018)).

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 0f workers, sector classifications, 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). We obtain registry data for listed and unlisted Swedish corporations from *Upplysningscentralen* (UC) for the period 1990-1997 and from Bisnode Serrano for 1998-2015.[18]

In order to compute emission intensities we require our sample firms to have data on both sales and CO_2, resulting in roughly 50,000 firm-year observations. The fraction of firms with CO_2 emission data available changes during our sample period (see Table B.1), most notably in 1997-1999 and 2003-2006 when only emissions by larger plants were collected by SEPA. Since the largest emitters are always sampled, however, our sample consistently covers between 80-95% of aggregate manufacturing CO_2 emissions in any given year (autorefcoverage). Averaging across years, our sample covers 85% of aggregate CO_2 heating emissions and 87% of total (process plus heating) CO_2 emissions (Figure A.4) by the Swedish manufacturing sector during the period we study.

[18]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.

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) that was in place for each year of our sample. For the EU ETS period, we infer the fraction of emissions subject to the Swedish carbon tax from the difference between emissions reported in SEPA and the emission numbers in the The European Union Transaction Log, the official registry of the EU ETS.

For the regression analysis, we also require firms to have at least five consecutive observations to be included, which reduces the sample size to around 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 are provided in the appendix (subsection B.1 and subsection B.2) and in Sajtos (2020).

3.2 The effect of changing 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. Figure 6 illustrates the tax rates a hypothetical firm would face across different regimes. [19]

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. Taxes were capped at 1.7% of sales, which was further reduced to 1.2% in 1992, with firms above the threshold facing 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) were taxed at a constant rate of 0.08 SEK per kilogram. As a result, lower-emitting firms experienced a marginal tax decrease, while high-emitting firms (above the tax cap threshold) went from a zero to a positive marginal tax rate.

In 1997, the tax rate for manufacturing firms increased to 0.19 SEK per kg of CO_2 emitted.[20] At the same time, a new exemption was introduced for high-emitting firms,

[19] 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).

[20] 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

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 further raised in 2011, coupled 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.

Importantly for our identification, the numerous changes in carbon taxation gives rise to substantial variation in both the time-series and the cross-section. Figure 7 shows how the average, effective tax rate, computed as total carbon taxes paid divided by total CO_2 (heating) emissions (*Average tax*), and the the marginal tax rate for the next emitted unit of CO_2 (*Marginal tax*) evolves over time 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 **??**).

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

(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).

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 **??**, 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.5, 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.

3.3 Swedish manufacturing CO_2 emissions 1990-2015

Next, 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 four-digit industries each.

Table 3 presents summary statistics of emissions-to-sales ratios, shares of CO_2 emissions and shares of carbon tax payments by decile bin for the years 1990 (panel A), 2007 (panel B), and 2015 (panel C).[21] 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 only 18% of aggregate CO_2 emissions in 1990, despite accounting for more than 75% of manufacturing sales. 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 3.2). As a consequence, decile 10 firms only made up 54% of the carbon tax payments in 1991 despite emitting 72% of aggregate CO_2. In contrast, the share of tax payments exceeded the share of CO_2 emissions for the other nine deciles.

Panels B and C show that aggregate CO_2 emissions-to-sales decreased from 0.0084 to 0.0067 between 1990 and 2007 and remained at a similar level thereafter.[22] In 2007, changes in the tax system (that we describe 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

[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.

[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.

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 tax rate varied between 28 and 30% 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 sales.

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.

3.4 Firm-level responses to 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).[23] 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,

[23]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.

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 firms responding to the differential marginal cost changes reported in panel A. Also, following the 1993 tax change, firms that enjoyed exemptions in the 1991-1992 period display a decreasing emission intensity relative to firms without exemptions (a relative change of -0.059), which again is consistent the different marginal tax incentives in panel A. Panel C shows 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.

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.[24] Second, while we do have considerable time series and cross-sectional variation in marginal carbon tax rates, we there are no periods where one group being affected by a change and another unaffected. This means that we do not have a proper control group to derive

[24]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)).

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.

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

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 (per kg of CO_2 emissions) as the average marginal tax rate in a given firm-year under the Swedish carbon tax system (for the installations not under EU ETS) and the average market price of the emission trading permits in the corresponding year (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.

4.2 Baseline results

Table 6 presents baseline results from estimating Equation 1 with $q{=}0$ up to $q{=}3$ in columns 1-4 . In column 1, shows results without including any lags of τ.[25] 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

[25] 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. Whether we add one to the tax rate or not has a negligible impact on the estimates.

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.[26] 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

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

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

In column 1 in Table 7, the *EU/ETS* indicator takes the value of zero for all firms prior to 2005; from 2005 and onwards it takes the value of one for the firms that have at least one plant covered by the EU ETS, and zero otherwise.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 the coefficients for all firm-years outside

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

EU ETS is -5.142 and considerably larger than the baseline result in reported in Table 6. The sum of coefficients for EU ETS firm-years is -3.403 and also statistically significant.

In column 2, we let the EU ETS indicator variable equal 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 by the firms regulated under EU ETS having a systematically different response to carbon pricing.[27] The uninteracted *EU-ETS* variable drops out in column 2 due to the inclusion of firm fixed effects. It turns out that the result in column 2 is very similar to the result presented in column 1 suggesting it is not the introduction of the EU ETS that leads to a lower carbon pricing elasticity for these firms. Overall, we conclude that our estimated carbon pricing elasticities reported in Table 6 are stable over the entire time period and do not change with 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).[28] 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 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, under the assumption that abatement costs are primarily a function of production technologies and 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.[29] We

[27] The firms who have plants regulated under EU ETS are certainly different in terms of their characteristics, including emission levels.

[28] The choice of control variables follows Brännlund et al. (2014).

[29] 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

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. While the statistical power is reduced due to smaller sample sizes, we estimate a larger carbon pricing response among low-PACE sector firms compared to those in high PACE sectors, largely due to a larger contemporaneous response for low-PACE firms compared to high-PACE firms. The sum of σ's (in column 1) is twice the size as the baseline result in Table 6. In contrast, the sum of σ's for high-PACE firms is slightly smaller than the baseline estimate. These results suggests that firms with lower abatement costs respond more quickly, and at a lower cost, to a change in carbon pricing, as would be expected.

We also consider how the geographic mobility of assets impacts firms operating in low- and high-PACE sectors. Firms with high mobility would be able to move their production facilities to other countries in order to avoid paying Swedish carbon tax (commonly referred to as "carbon leakage"). 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)).[30] As was the case with the PACE data, we lose a large number of observations in the process of converting 1987 SIC codes to 2007 SNI codes. We define firms above (below) the median in plant fixed costs as having low (high) mobility. Results for low- (high-) PACE industries divided by low versus high mobility are shown in columns 3 (5) and 4 (6) (in Table 8). There are two main takeaways from this analysis. 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.

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.

[30] Specifically, plant fixed costs is measured as the ratio between the real structures capital stock and the value of shipments. We do not have fixed costs available at the plant level in our Swedish data.

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).[31] 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.[32] We compute the "scale" effect by plotting hypothetical emissions by multiplying the average 1990 emission intensity with PPI-adjusted, total sales for Swedish manufacturing, normalized to 100 in 1990 (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 compared to 1990 levels. Line (2) in Figure 8 plots the actual aggregate CO_2 emissions for Swedish manufacturing over the same period. The level of overall CO_2 emissions in 2015 was 31% lower than in 1990, representing the combined scale, composition and technique effects. 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 the annual PPI-adjusted sales of that industry. In other words, line (3) represents what total CO_2 emissions would have been each year if each manufacturing sub-sector had produced emissions at the rate of their 1990 production technologies but their output shares would

[31] 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).

[32] 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.

have evolved as in the data. 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 9) 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 9 (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 9 (Panel B)).[33]

Finally, the technology effect is the difference between lines (2) and (3) in Figure 8. Out of a total reduction in CO_2 emissions of 31%, scale and composition (line (3)) accounted for 13%. Accordingly, the technique effect, defined as the residual, amounts to an 18% drop in emissions (column (5) in Table 9 (Panel A)). This decomposition then indicates that almost two thirds of the scale-adjusted reduction in CO_2 emissions can be attributed to changes in production technology (column (2) in Table 9 (Panel B)).[34]

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

Finally, we try to calibrate how much of the 31% CO_2 emissions decrease in Swedish manufacturing that can be attributed to carbon pricing. Since we have not estimated a general equilibrium model (in contrast with e.g. Shapiro and Walker 2018), the estimates from this calibration are very much subject to the Lucas critique and should be viewed as partial equilibrium estimates at best. For example, changes in output and composition are

[33]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).

[34]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. Moreover, while we adjust sales using each industry's PPI, our estimates are sensitive to relative price changes over the period we study. This problem, which could have been addressed if we had access to actual output (rather than sales) data, is shared with much of the productivity literature (see Syverson 2011).

assumed held constant as we change the carbon tax in our calibration, while it is likely that those would have evolved differently absent carbon pricing. Still, we believe this exercise is informative in assessing the economic significance of the carbon pricing elasticity we have estimated.

To perform this calibration, we start with our predicted estimates from Equation 1, using specification (1) of Table 6 (i.e. without lagged tax rates). Using these estimates we can calculate predicted emission intensities under the assumption that the tax rate had been zero and output had been the same as in 1990. We then apply these estimated intensities to the sales of each firm to get predicted emissions in the absence of the tax. Since sample size varies over time, we use a balanced sample of firms, where we have observations for every year in the sample to avoid mechanical year-by-year changes (see Figure A.3 for annual sample coverage).[35] Since the balanced sample still includes all large emitters, the aggregate carbon emissions in this sample is very close to the full sample.

Finally, we convert the counterfactual emissions 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. Naturally, the changes in this index will coincide with changes in the carbon tax, such as in 1991 (the year the Swedish carbon tax was introduced), 1997 (when the doubling manufacturing carbon tax rate doubled), 2008 (the year Swedish installations started phasing into EU ETS) and 2015 (when there was a large increase in carbon tax rates and firm exemptions were abolished). We estimate that 8 percentage points of the 31 percentage point decrease in manufacturing CO_2 emissions (i.e. roughly 25% of the total) can be attributed to carbon pricing. We summarize the results from Figure 8 and Figure 9 in Table 9.

6 Conclusions and Implications

As one of the first countries in the world, Sweden introduced a carbon tax in 1991, which remains the world's highest carbon price. We assemble a comprehensive dataset of Swedish manufacturing firms and track firm-level CO_2 emissions during 1990-2015. Our panel includes more than 4,000 firms and covers almost all CO_2 emissions in the

[35]Estimating Equation 1 on the balanced sample yield very similar results as estimating for the full sample in column 1 in Table 6.)

Swedish manufacturing sector over this period. We document a statistically robust and economically meaningful inverse relationship between CO_2 emissions and the marginal carbon cost of emitting CO_2. We estimate the CO_2 emissions-to-carbon pricing elasticity to be between 3-3.4% for the manufacturing sector. 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, a simple calibration using our estimated carbon pricing elasticity attributes 8 of the 31 percentage point decrease in aggregate manufacturing CO_2 emissions to carbon pricing.

6.1 Implications for climate policy

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 Lessons for carbon pricing design

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 does not attempt to account for general equilibrium effects (as in Shapiro and Walker 2018), 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 (Åhman et al. (2018)), which we believe is an interesting example of a sector-specific policy solution with the potential to significantly lower manufacturing greenhouse gas emissions. While it is hard to tell whether this initiative would 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.

References

Acemoglu, D., Aghion, P., Bursztyn, L., and Hemous, D. (2012). The environment and directed technical change. *American economic review*, 102(1):131–66.

Acemoglu, D., Akcigit, U., Hanley, D., and Kerr, W. (2016). Transition to clean technology. *Journal of Political Economy*, 124(1):52–104.

Aghion, P., Dechezleprêtre, A., Hemous, D., Martin, R., and Van Reenen, J. (2016). Carbon taxes, path dependency, and directed technical change: Evidence from the auto industry. *Journal of Political Economy*, 124(1):1–51.

Åhman, M., Olsson, O., Vogl, V., Nyqvist, B., Maltais, A., Nilsson, L. J., Hallding, K., Skånberg, K., and Nilsson, M. (2018). Hydrogen steelmaking for a low-carbon economy. *Stockholm: Stockholm Environment Centre and Lund University.*

Andersson, J. J. (2019). Carbon taxes and co_2 emissions: Sweden as a case study. *American Economic Journal: Economic Policy*, 11(4):1–30.

Becker, R., Gray, W., and Marvakov, J. (2013). Nber-ces manufacturing industry database: Technical notes. *NBER Working Paper*, 5809.

Bond, S. and Xing, J. (2015). Corporate taxation and capital accumulation: Evidence from sectoral panel data for 14 oecd countries. *Journal of Public Economics*, 130:15–31.

Bovenberg, A. L. and De Mooij, R. A. (1994). Environmental levies and distortionary taxation. *The American Economic Review*, 84(4):1085–1089.

Brännlund, R., Lundgren, T., and Marklund, P.-O. (2014). Carbon intensity in production and the effects of climate policy—evidence from swedish industry. *Energy Policy*, 67:844–857.

Burke, M., Craxton, M., Kolstad, C. D., Onda, C., Allcott, H., Baker, E., Barrage, L., Carson, R., Gillingham, K., Graff-Zivin, J., et al. (2016). Opportunities for advances in climate change economics. *Science*, 352(6283):292–293.

Calel, R. and Dechezlepretre, A. (2016). Environmental policy and directed technological change: evidence from the european carbon market. *Review of economics and statistics*, 98(1):173–191.

Copeland, B. R. and Taylor, M. S. (1994). North-south trade and the environment. *The quarterly journal of Economics*, 109(3):755–787.

Copeland, B. R. and Taylor, M. S. (2004). Trade, growth, and the environment. *Journal of Economic literature*, 42(1):7–71.

Dai, A. (2013). Increasing drought under global warming in observations and models. *Nature climate change*, 3(1):52–58.

Dell, M., Jones, B. F., and Olken, B. A. (2014). What do we learn from the weather? the new climate-economy literature. *Journal of Economic Literature*, 52(3):740–98.

Ederington, J., Levinson, A., and Minier, J. (2005). Footloose and pollution-free. *Review of Economics and Statistics*, 87(1):92–99.

Environmental Charges Commission (1989). Ekonomiska styrmedel i miljöpolitiken : energi och trafik : delbetänkande.
https://lagen.nu/sou/1989:83#S2.

European Commission (2004). Memo/04/43 kyoto protocol.
https://ec.europa.eu/commission/presscorner/detail/en/MEMO_04_43.

European Commission (n.d.). Phase 1 and 2 (2005-2012).
https://ec.europa.eu/clima/policies/ets/pre2013_en.

Eurostat (2008). Nace rev.2. statistical classification of economic activities in the european community.
https://ec.europa.eu/eurostat/documents/3859598/5902521/KS-RA-07-015-EN.PDF.

Eurostat (2016). Glossary: Statistical classification of economic activities in the european community (nace).
https://ec.europa.eu/eurostat/statistics-explained/index.php/Glossary:Statistical_classification_of_economic_activities_in_the_European_Community_(NACE).

Fazzari, S., Hubbard, R. G., and Petersen, B. (1988). Investment, financing decisions, and tax policy. *The American Economic Review*, 78(2):200–205.

Forslid, R., Akerman, A., and Prane, O. (2021). Imports and the co2 emissions of firms. *Center for Economic Policy Research Discussion Paper Series*, DP16090.

Golosov, M., Hassler, J., Krusell, P., and Tsyvinski, A. (2014). Optimal taxes on fossil fuel in general equilibrium. *Econometrica*, 82(1):41–88.

Government Bill 1989/90:111 (1989). Government bill 1989/90:111. regeringens proposition 1989/90:111 reformerad mervärdesskatt m.m.
http://www.riksdagen.se/Webbnav/index.aspx?nid=37&dok$_$id=GD03111.

Government Bill 1991/92:150 (1991). Regeringens proposition 1991/92:150 med förslag om slutlig reglering av statsbudgeten för budgetåret 1992/93, m.m., bilaga i:5. http://www.riksdagen.se/Webbnav/index.aspx?nid=37&dok$_$id=GF03150.

Government Bill 2007/2008:1 (2007). Budgetpropositionen för 2008. https://www.regeringen.se/49bb06/contentassets/0cea7c72952947a7825d8c9e75abe51d/forslag-till-statsbudget-for-2008-inklusive-finansplan.

Greenstone, M. (2002). The impacts of environmental regulations on industrial activity: Evidence from the 1970 and 1977 clean air act amendments and the census of manufactures. *Journal of political economy*, 110(6):1175–1219.

Griffin, P. and Heede, C. R. (2017). The carbon majors database. *CDP carbon majors report 2017*, page 14.

Grossman, G. and Krueger, A. B. (1993). Environmental impacts of a north american free trade agreement, the us-mexico free trade agreement. *MA: MIT Press, Cambridge.*

Grossman, G. M. and Krueger, A. B. (1991). Environmental impacts of a north american free trade agreement. Technical report, National Bureau of Economic Research.

Hammar, H. and Åkerfeldt, S. (2011). CO_2 taxation in sweden: 20 years of experience and looking ahead. *Fiscalidad Verde en Europa-Objetivo 20/20*, 20.

Hassler, J., Krusell, P., and Olovsson, C. (2012). Energy-saving technical change. Technical report, National Bureau of Economic Research.

Hoegh-Guldberg, O., Jacob, D., Taylor, M., Bindi, M., Brown, S., Camilloni, I., Diedhiou, A., Djalante, R., Ebi, K. L., Engelbrecht, F., et al. (2018). Impacts of 1.5 ºc global warming on natural and human systems. In *Global Warming of 1.5° C: An IPCC Special Report on the impacts of global warming of 1.5° C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. IPCC.

III, I. W. G. (2014). *Climate Change 2014-Mitigation of Climate Change: Summary for Policymakers*. Intergovernmental Panel on Climate Change.

Jaffe, A. B., Newell, R. G., and Stavins, R. N. (2002). Environmental policy and technological change. *Environmental and resource economics*, 22(1-2):41–70.

Jiborn, M., Kander, A., Kulionis, V., Nielsen, H., and Moran, D. D. (2018). Decoupling or delusion? measuring emissions displacement in foreign trade. *Global Environmental Change*, 49:27–34.

Knutson, T. R., McBride, J. L., Chan, J., Emanuel, K., Holland, G., Landsea, C., Held, I., Kossin, J. P., Srivastava, A., and Sugi, M. (2010). Tropical cyclones and climate change. *Nature geoscience*, 3(3):157–163.

Lans, A. (1996). Optimal environmental taxation in the presence of other taxes: General-equilibrium analyses. *THE AMERICAN ECONOMIC REVIEW*.

Levinson, A. (2009). Technology, international trade, and pollution from us manufacturing. *American Economic Review*, 99(5):2177–92.

Martin, R., De Preux, L. B., and Wagner, U. J. (2014a). The impact of a carbon tax on manufacturing: Evidence from microdata. *Journal of Public Economics*, 117:1–14.

Martin, R., Muûls, M., De Preux, L. B., and Wagner, U. J. (2014b). On the empirical content of carbon leakage criteria in the eu emissions trading scheme. *Ecological Economics*, 105:78–88.

Metcalf, G. E. and Stock, J. H. (2020). The macroeconomic impact of europe's carbon taxes. Technical report, National Bureau of Economic Research.

Ministry of Environment and Energy (2018). Sweden's draft integrated national energy and climate plan.
https://ec.europa.eu/energy/sites/ener/files/documents/sweden_draftnecp.pdf.

Newell, R. G., Jaffe, A. B., and Stavins, R. N. (1999). The induced innovation hypothesis and energy-saving technological change. *The Quarterly Journal of Economics*, 114(3):941–975.

Nicholls, R. J. and Cazenave, A. (2010). Sea-level rise and its impact on coastal zones. *science*, 328(5985):1517–1520.

Nordhaus, W. D. (1993). Optimal greenhouse-gas reductions and tax policy in the" dice" model. *The American Economic Review*, 83(2):313–317.

Pindyck, R. S. (2013). Climate change policy: What do the models tell us? *Journal of Economic Literature*, 51(3):860–72.

Popp, D. (2002). Induced innovation and energy prices. *American economic review*, 92(1):160–180.

Ritchie, H. and Roser, M. (2017). CO_2 and greenhouse gas emissions. *Our world in data*.

Rockström, J., Gaffney, O., Rogelj, J., Meinshausen, M., Nakicenovic, N., and Schellnhuber, H. J. (2017). A roadmap for rapid decarbonization. *Science*, 355(6331):1269–1271.

Sajtos, L. (2020). *Essays on Environmental Regulation*. PhD thesis, Stockholm School of Economics.

Scharin, H and Wallström, J (2018). The swedish co2 tax–an overview. http://www.enveco.se/wp-content/uploads/2018/03/Anthesis-Enveco-rapport-2018-3.-The-Swedish-CO2-tax-an-overview.pdf.

SEPA and SEA (2007). Economic instruments in environmental policy.

Shah, A. and Larsen, B. (1992). *Carbon taxes, the greenhouse effect, and developing countries*, volume 957. World Bank Publications.

Shapiro, J. S. and Walker, R. (2018). Why is pollution from us manufacturing declining? the roles of environmental regulation, productivity, and trade. *American Economic Review*, 108(12):3814–54.

Statistics Sweden (2003). Meddelanden i samordningsfrågor för sveriges officiella statistik-sni 2002 standard för svensk näringsgrensindelning 2002. http://share.scb.se/ov9993/data/publikationer/statistik/ov/ov9999/2003m00/x71op0301.pdf.

Stern, N. (2008). The economics of climate change. *American Economic Review*, 98(2):1–37.

Sterner, T., Barbier, E. B., Bateman, I., van den Bijgaart, I., Crépin, A.-S., Edenhofer, O., Fischer, C., Habla, W., Hassler, J., Johansson-Stenman, O., et al. (2019). Policy design for the anthropocene. *Nature Sustainability*, 2(1):14–21.

Stott, P. A., Stone, D. A., and Allen, M. R. (2004). Human contribution to the european heatwave of 2003. *Nature*, 432(7017):610–614.

Swedish National Audit Office (2013). Energieffektivisering inom industrin– effekter av statens insatser. https://www.riksrevisionen.se/download/18.78ae827d1605526e94b300b8/1518435473932/Bilaga%205.pdf.

Swedish Tax Authority (2012). Taxes in sweden. https://www.skatteverket.se/download/18.3684199413c956649b57c66/1361447643691/10413.pdf.

Syverson, C. (2011). What determines productivity? *Journal of Economic Literature*, 49(2):326–365.

U.S. Bureau of the Census (1990). Pollution abatement costs and expenditures. https:https://www.epa.gov/sites/production/files/2016-08/documents/pace_1990.pdf.

World Bank (2020). State and trends of carbon pricing 2020. https://openknowledge.worldbank.org/handle/10986/33809.

World Coal Association (2019). How is steel produced. https://www.worldcoal.org/coal/uses-coal/how-steel-produced.

Figure 1: Carbon and energy taxation of an industrial plant

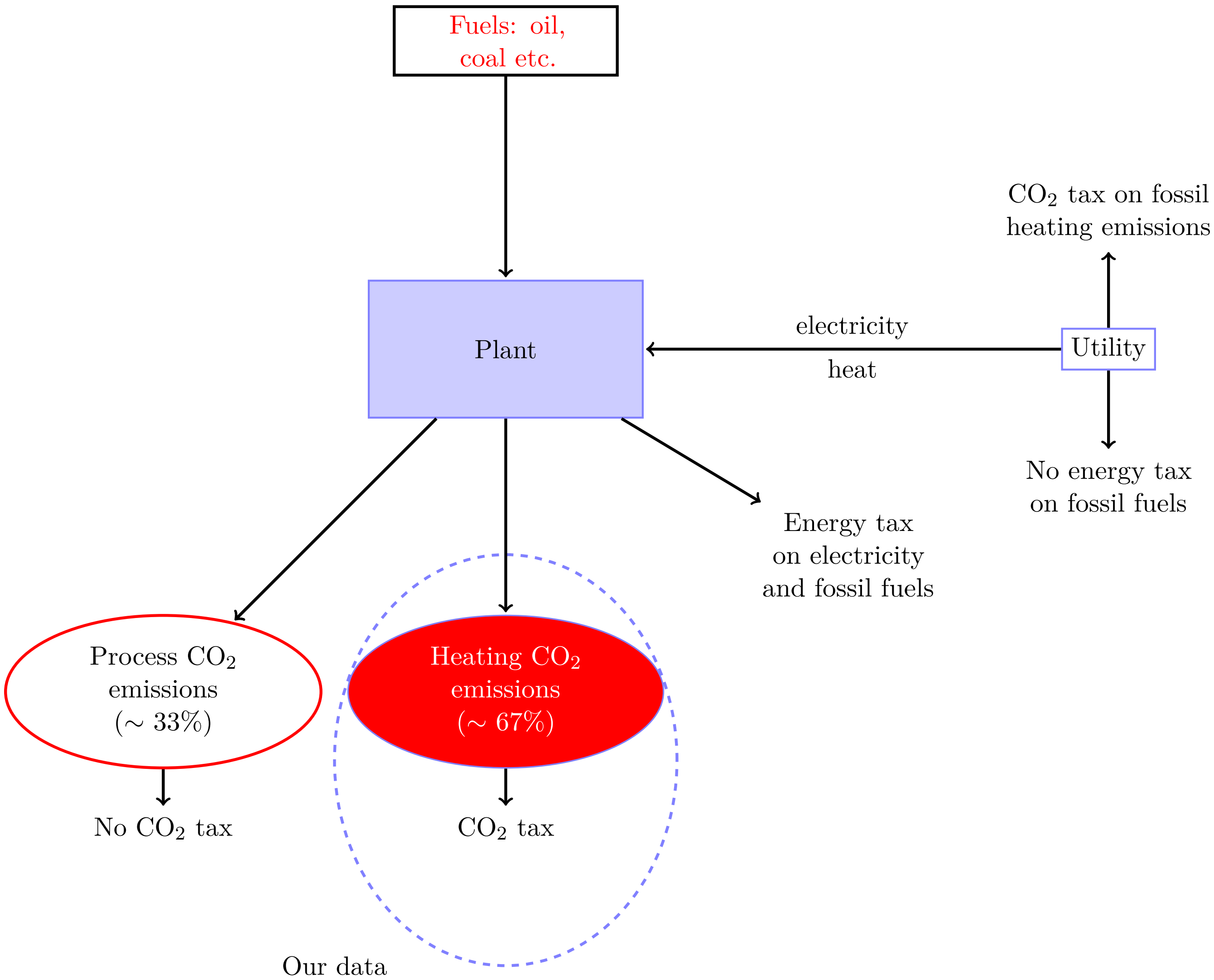

Figure 1 illustrates the carbon and energy taxation for a manufacturing plant in Sweden in 2019. *Heating CO_2 emissions* refers to the emissions released from the combustion of fossil fuels. *Process CO_2 emissions* refers to the carbon dioxide emissions released in the actual manufacturing process (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

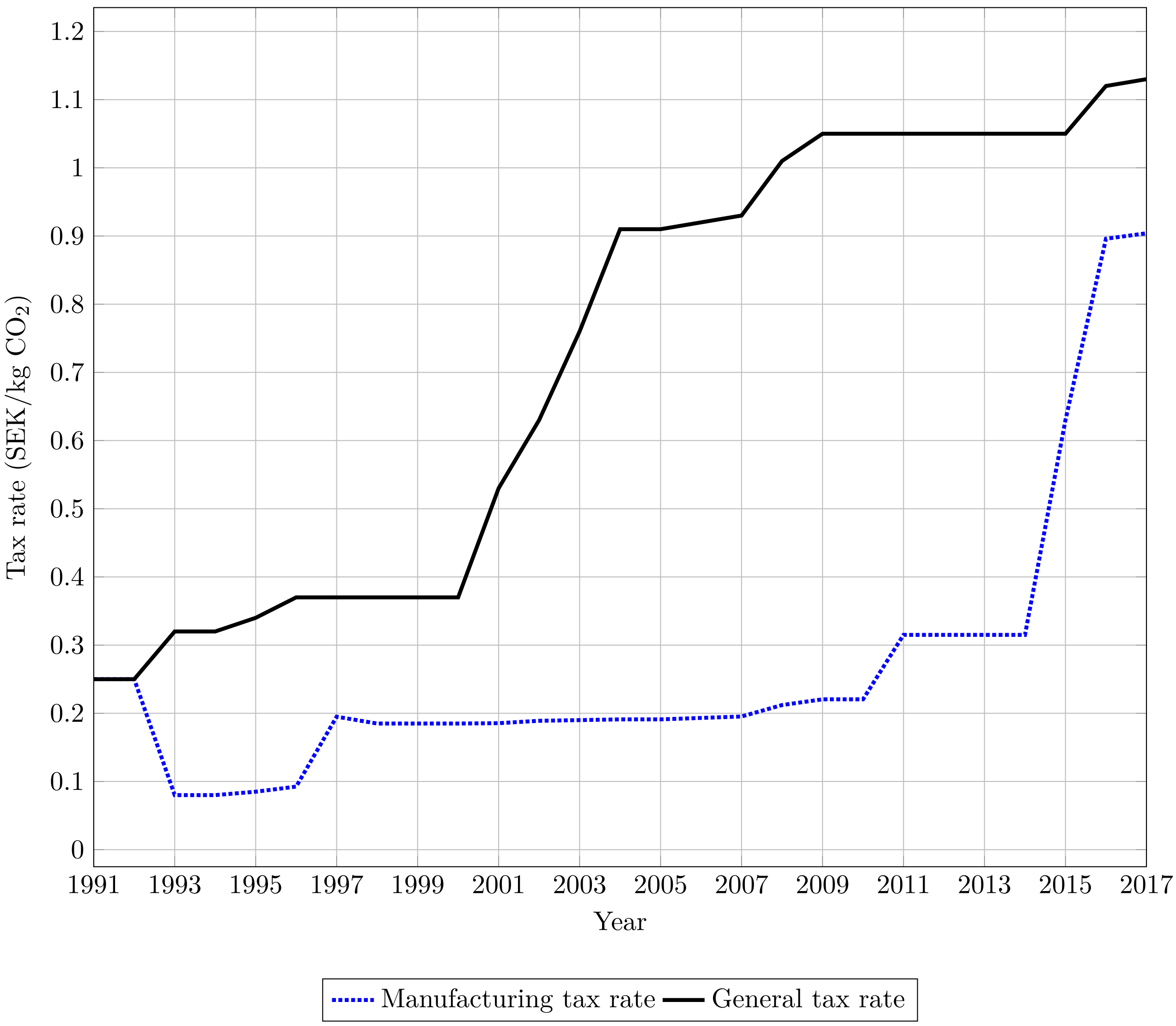

Figure 2 displays the nominal carbon tax rates (Swedish krona per kilogram of emitted carbon dioxide) for Sweden from 1991 to 2017. *Manufacturing tax rate* refers to the tax rate for the manufacturing sector (SNI 10-33 in the SNI2007 nomenclature), while *General tax rate* refers to the tax rate for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

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

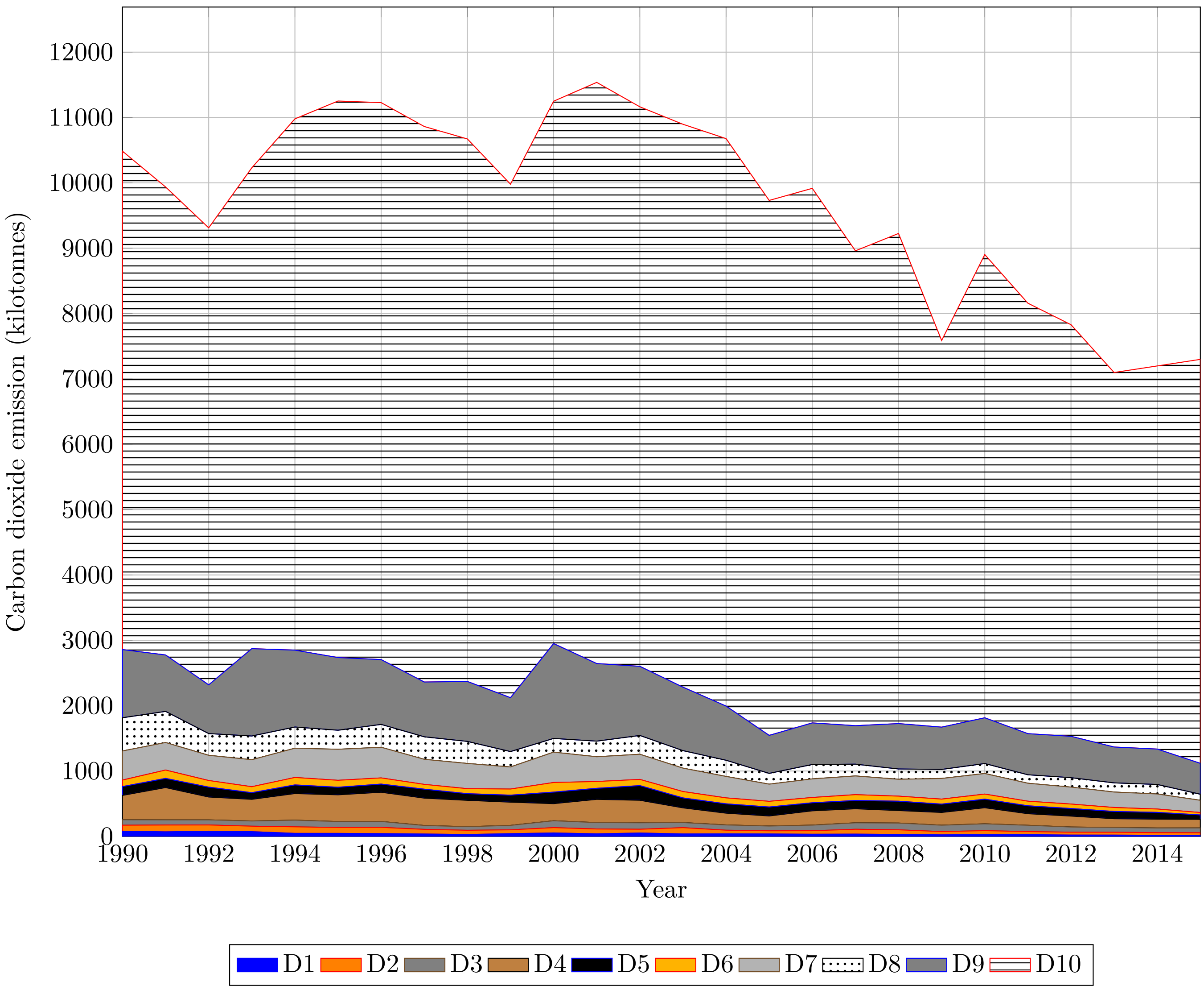

Figure 3 reports the distribution of CO_2 emissions in the Swedish manufacturing sector. The sample is divided into ten deciles based on the firms' carbon intensity (i.e. CO_2 emissions over sales) in 1990.

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

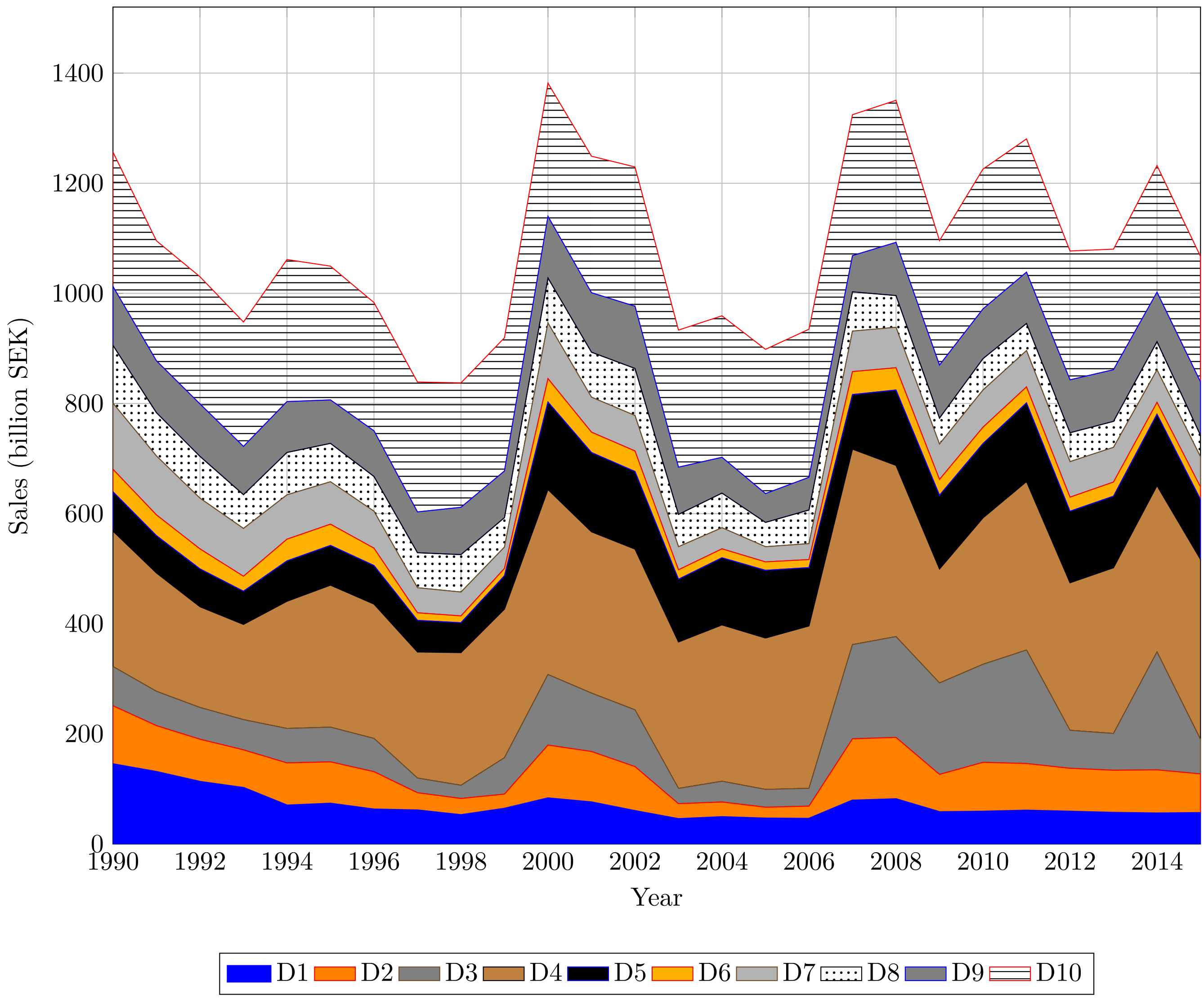

Figure 4 reports the distribution of PPI-adjusted sales in the Swedish manufacturing sector. The sample is divided into ten deciles based on the firms' carbon intensity (i.e. CO_2 emissions over sales) in 1990.

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

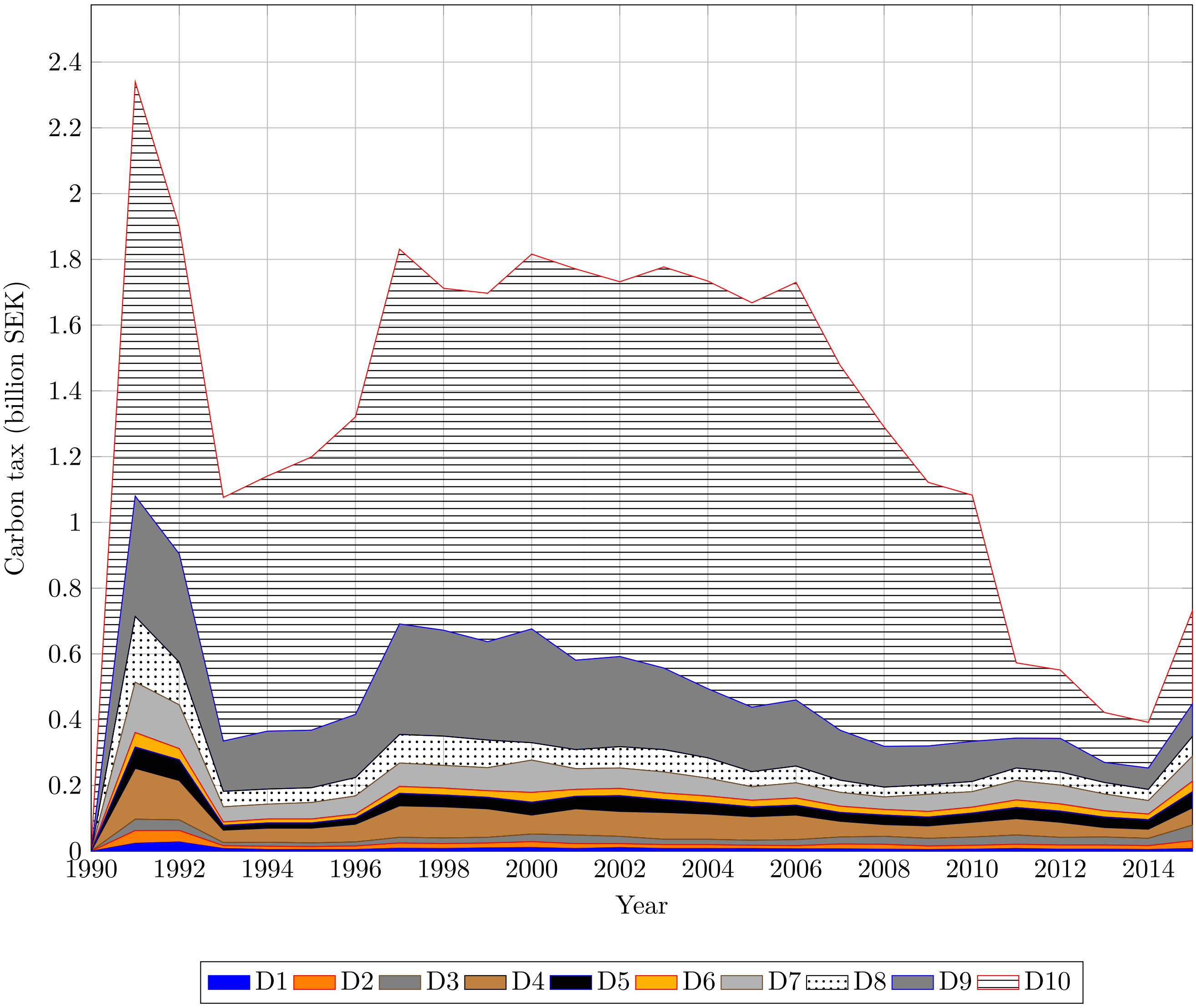

Figure 5 reports the distribution of carbon tax payments in the Swedish manufacturing sector. The sample is divided into deciles based on the firms' carbon intensity (i.e. CO_2 emissions over sales) in 1990.

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

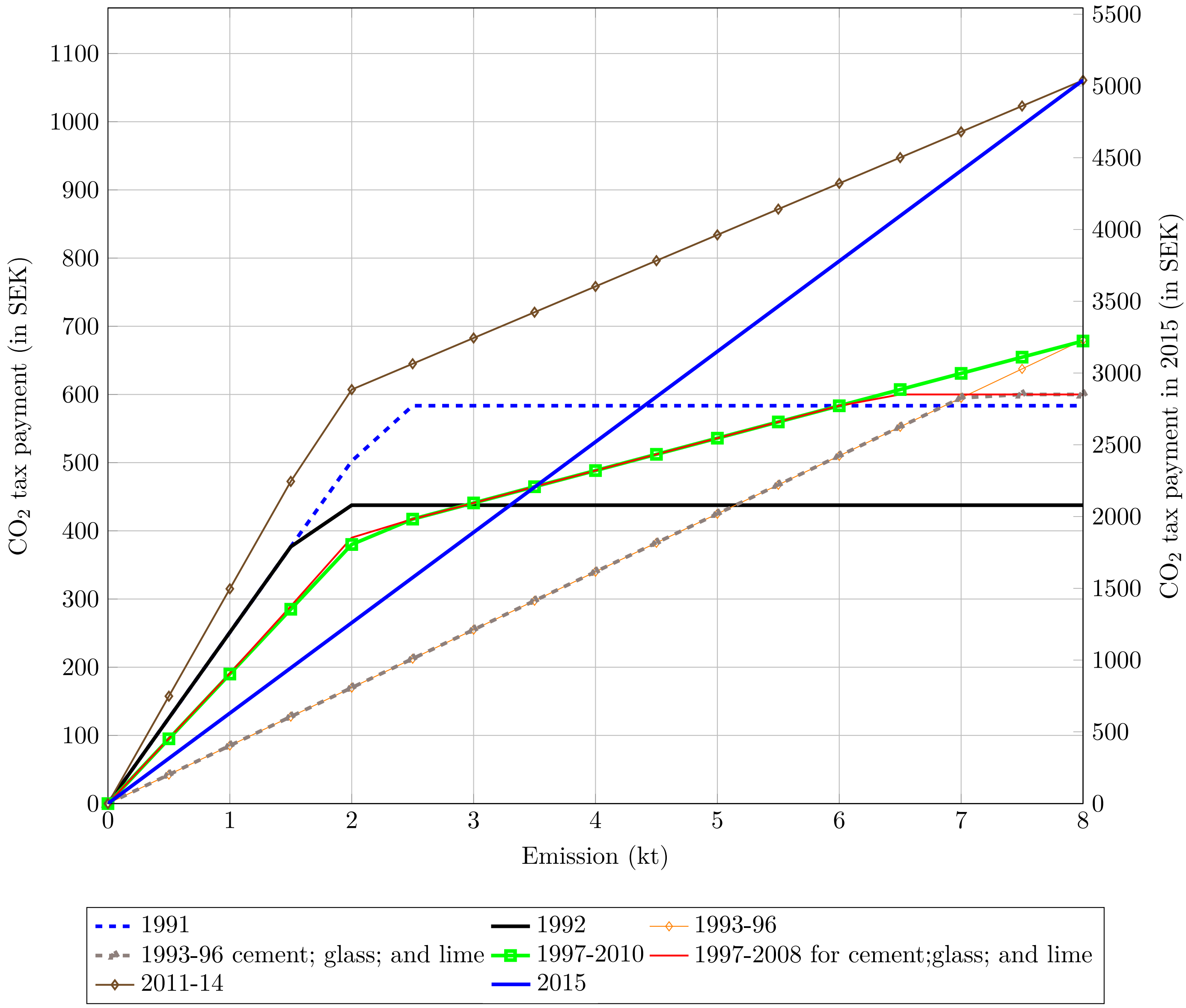

Figure 6 compares the carbon tax payments under the different regimes through a representative manufacturing firm. The hypothetical firm earns 50,000 SEK each year, and assumed to burn only coal in 1991 and 1992. All carbon tax payments with the exception of 2015 are shown on the vertical axis on the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

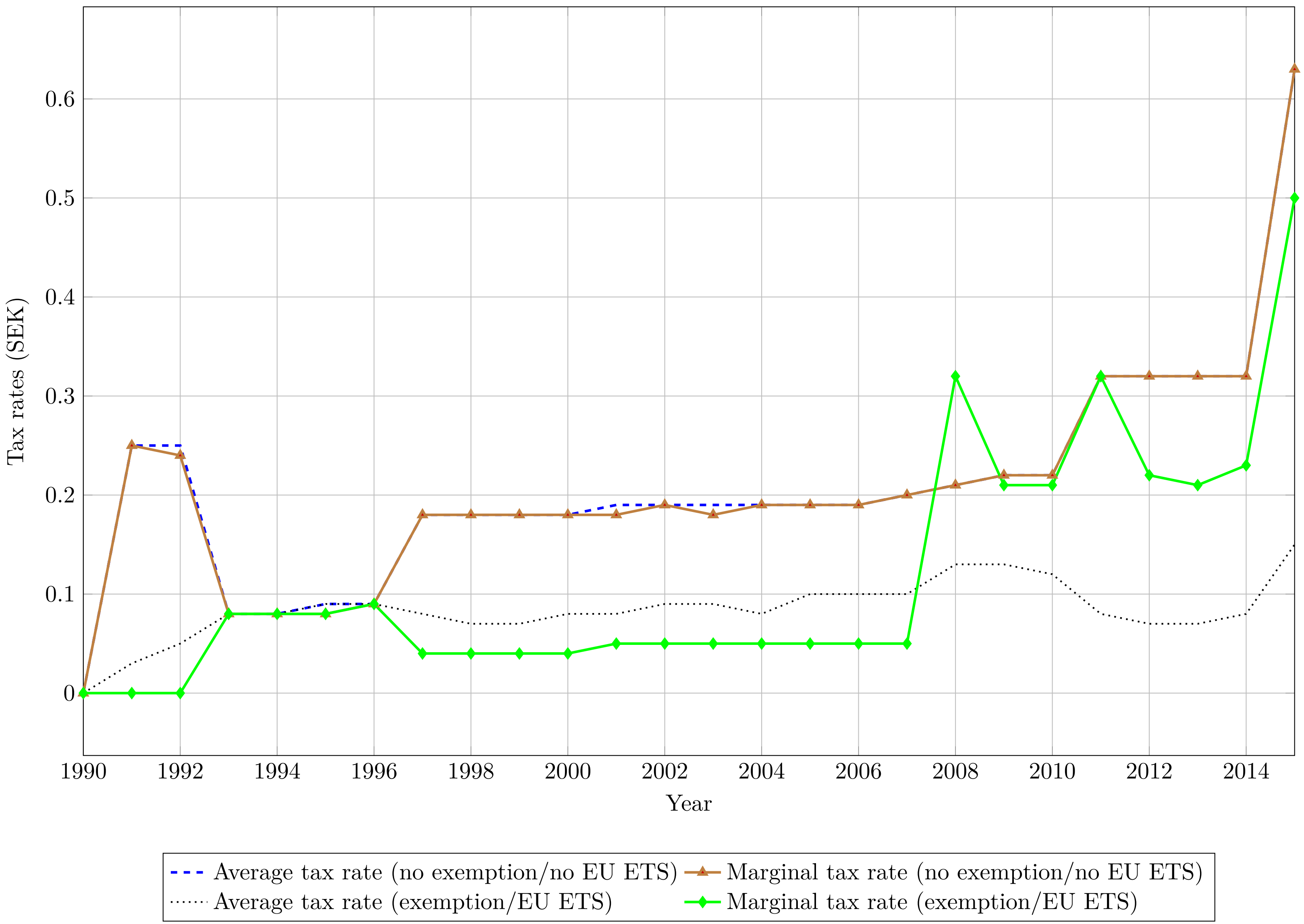

Figure 7 displays the average and marginal tax rates depending on whether the firm is eligible for carbon tax exemptions and covered by the EU ETS. *no exemption/no EU ETS* denotes firms that are not regulated by the EU ETS and are not entitled to carbon tax cut, *exemption/EU ETS* refers to the firms 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)

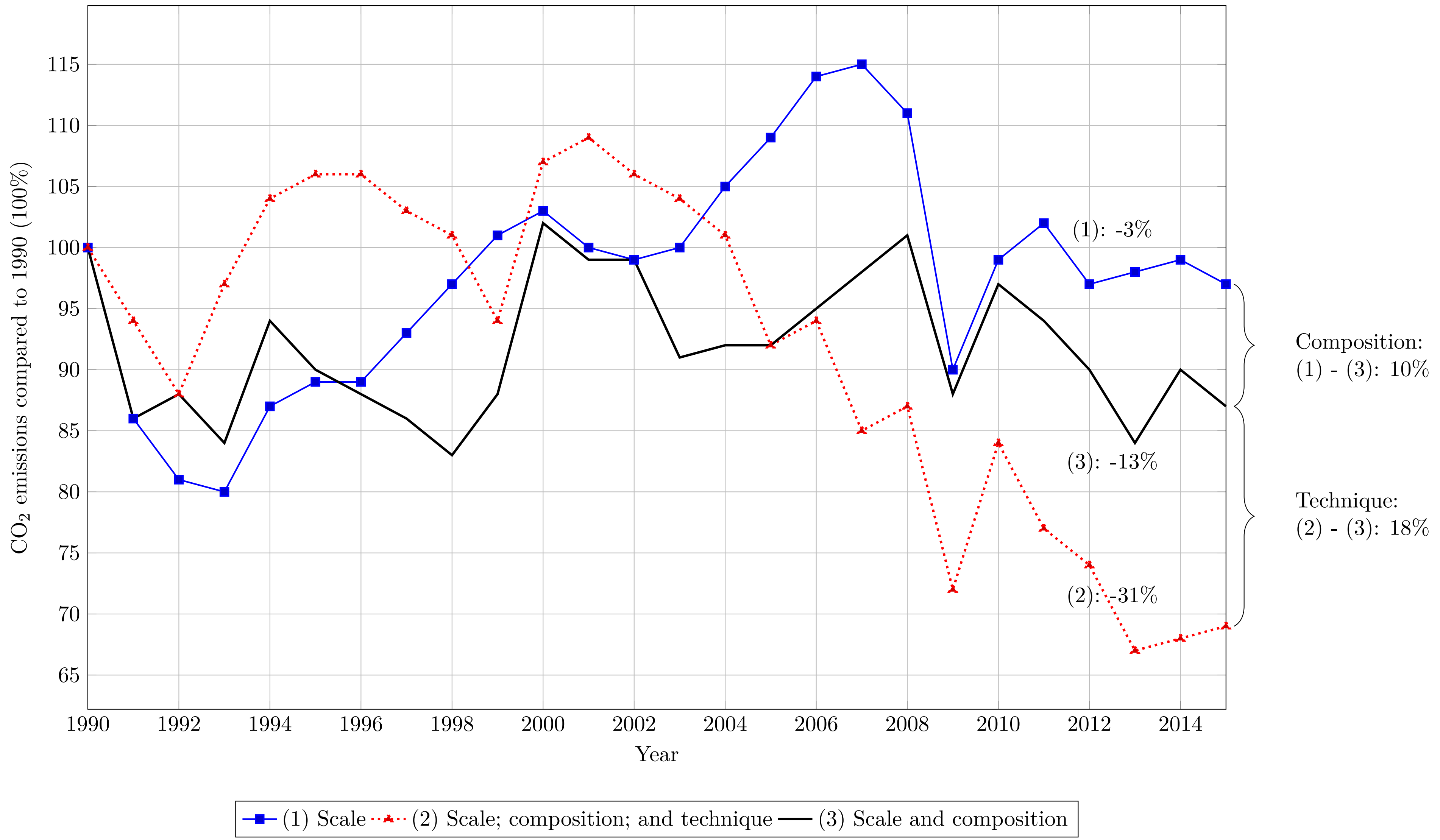

Figure 8 displays the decomposition of the Swedish carbon dioxide emission reduction. *Scale* captures how emissions would have evolved without tangible technological progress and structural changes in the manufacturing sector. *Composition* refers to the change in industry composition (e.g. booming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

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

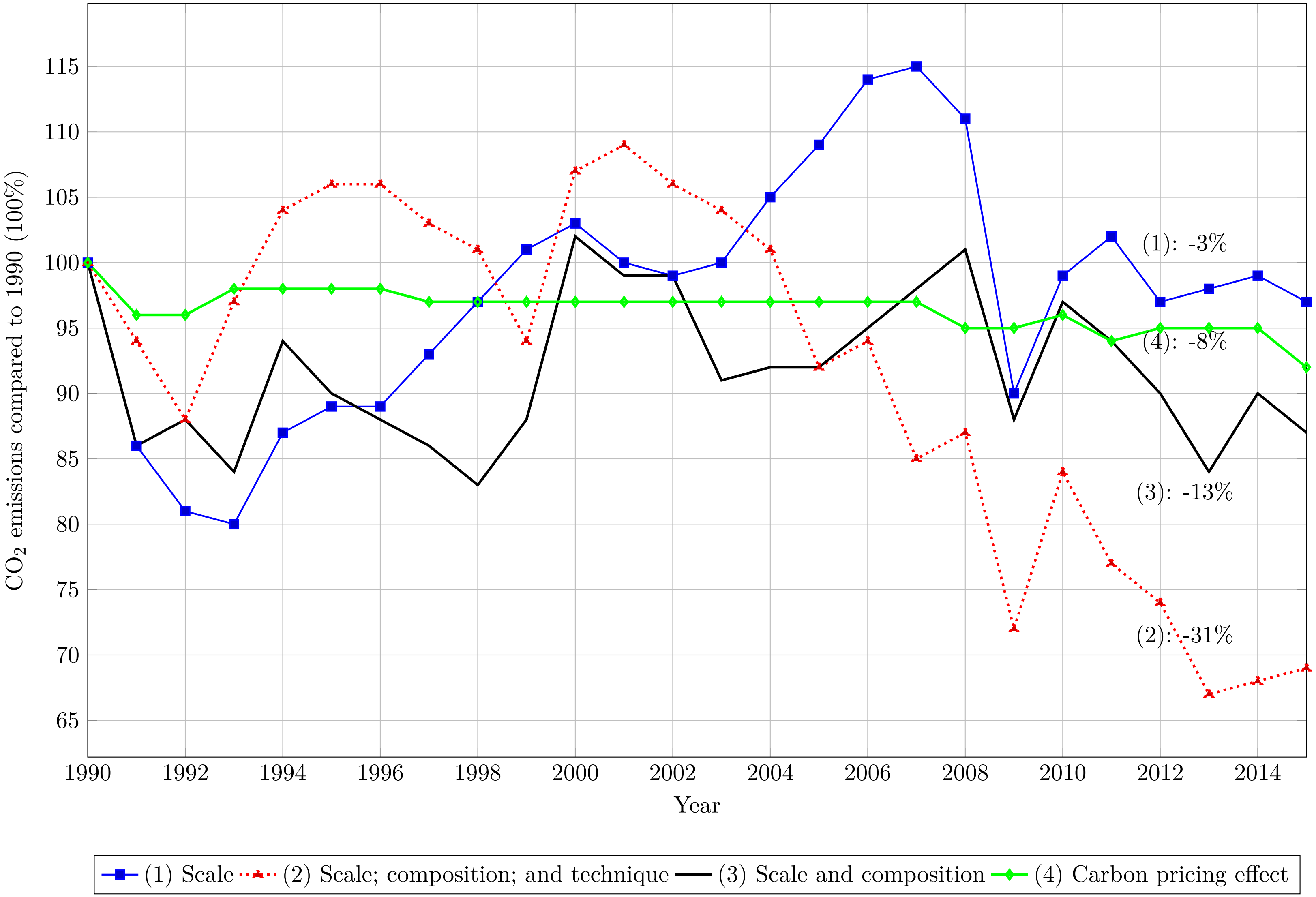

Figure 9 displays the decomposition of the Swedish carbon dioxide emission reduction. *Scale* captures how the emission would have evolved without tangible technological progress and structural changes in the manufacturing sector. *Composition* refers to the change in industry composition (e.g. booming 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)

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		

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	5.000	0.093	53.000	0.000	N/A	32,345	8.000	0.140	66.000	0.000	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	0.000	0.122	32,345	0.007	0.002	0.018	0.000	0.141
Carbon taxes paid (2010, MSEK)	50,501	0.589	0.016	7.000	0.000	394.000	32,345	0.886	0.025	8.000	0.000	394.000
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	0.000	0.702	32,345	0.200	0.212	0.128	0.000	0.702
Average tax rate	50,501	0.190	0.191	0.119	0.000	1.000	32,345	0.196	0.195	0.124	0.000	1.000
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	0.000	5.000	31,976	0.519	0.316	0.870	0.003	6.000

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 F-test	-2.758 (0.000)***	-3.335 (0.000)***	-3.410 (0.000)***	-3.403 (0.000)***	-4.622 (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	-1.686	-21.425	0.326	-2.812	-1.367
	(1.816)**	(0.663)***	(3.919)***	(1.491)	(1.258)**	(1.077)
log (1 + marginal tax rate) (i,t-1)	-1.385	-0.453	-5.802	-1.766	-0.556	-0.846
	(1.042)	(0.366)	(2.308)**	(1.294)	(0.618)	(0.645)
log (1 + marginal tax rate) (i,t-2)	-0.596	0.055	-2.797	-1.206	-0.102	0.424
	(0.914)	(0.361)	(1.942)	(2.091)	(0.691)	(0.602)
log (1 + marginal tax rate) (i,t-3)	-1.485	0.051	-4.853	-4.909	0.021	-0.241
	(1.217)	(0.403)	(1.343)***	(1.766)***	(0.718)	(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: 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 9 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.[36] 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.[37] 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

[36] 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.

[37] 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.[38] 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[39] 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[40]) 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

[38]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.

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

[40]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.

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

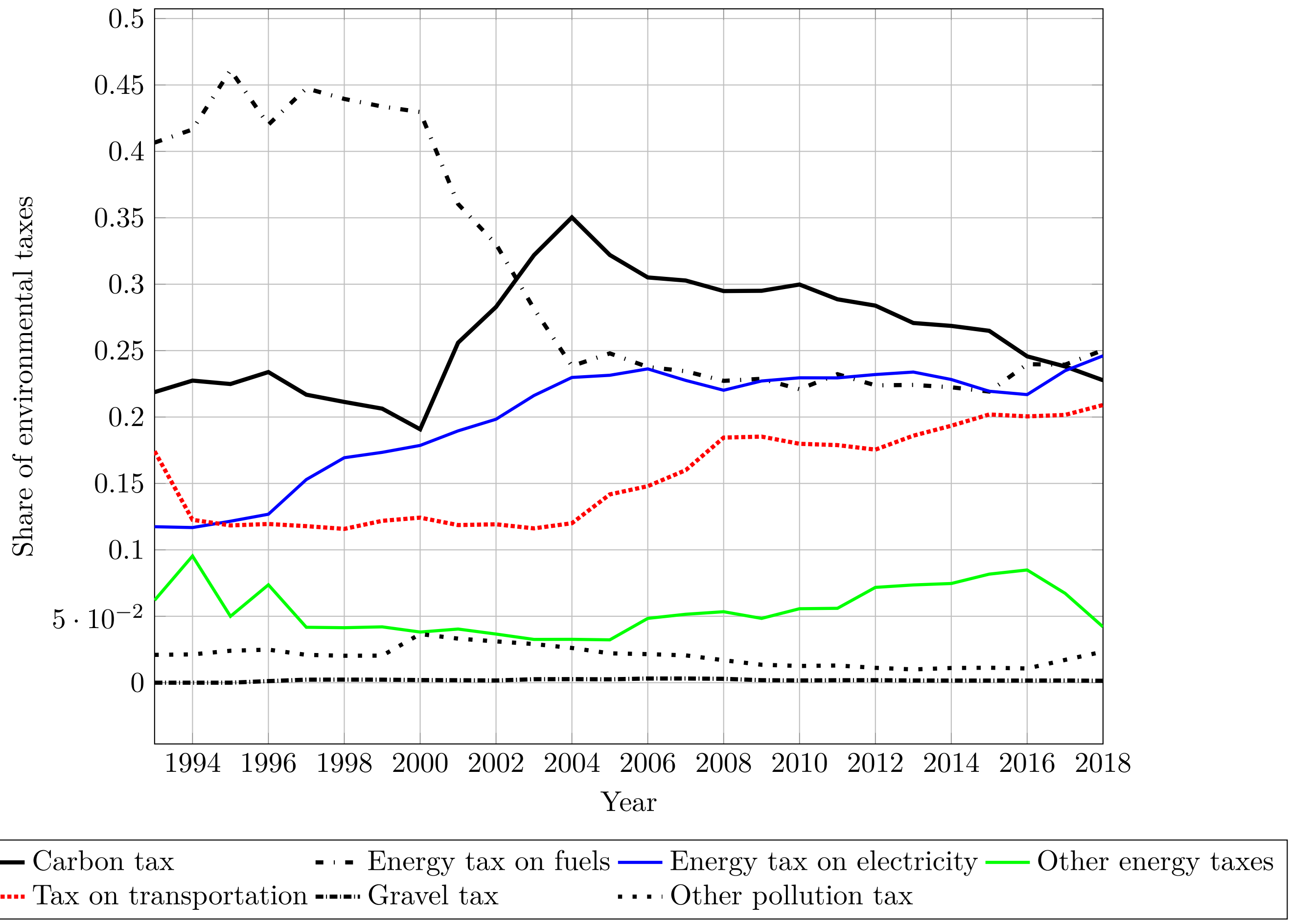

Figure A.1 displays distribution of the Swedish environmental tax payments in the overall economy (including households) from 1993 to 2018.

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

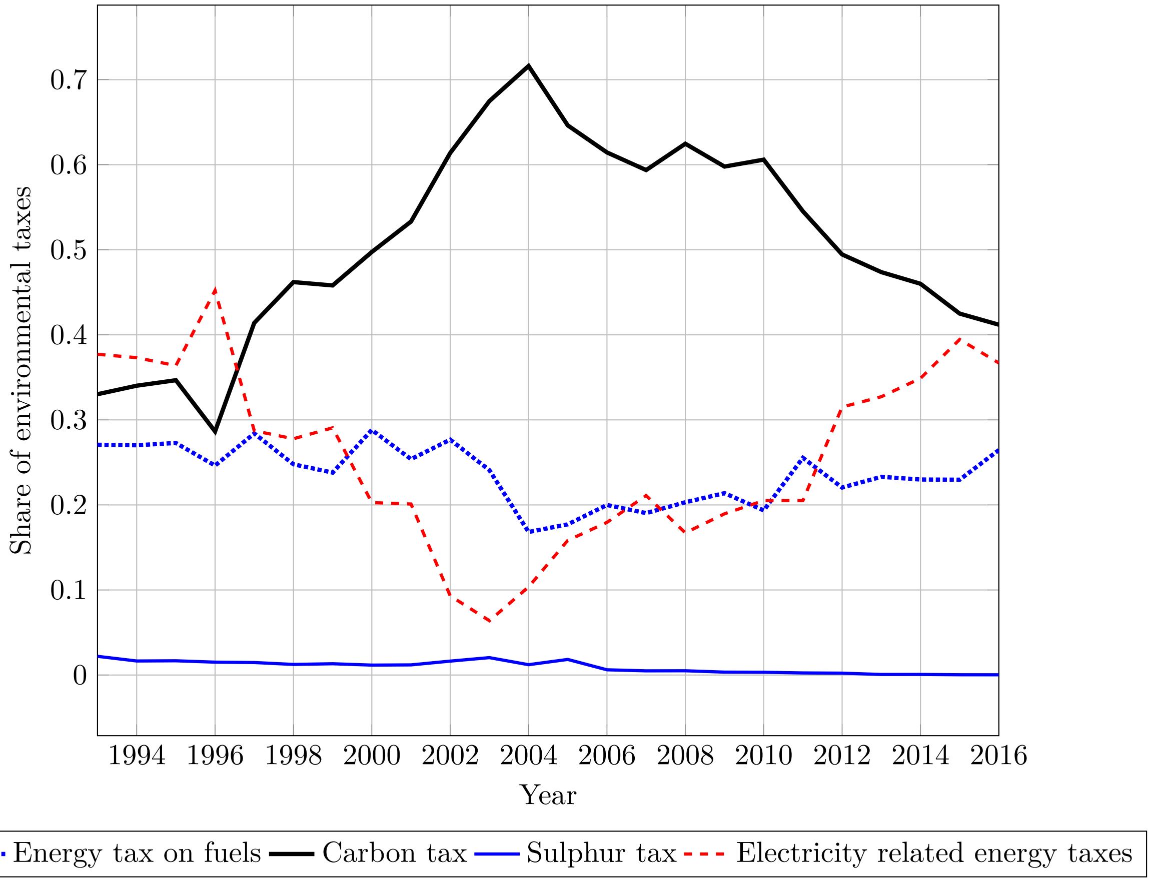

Figure A.2 displays the distribution of the Swedish environmental tax payments in the manufacturing sector (i.e. SNI 10-33 in the SNI2007 nomenclature) from 1993 to 2016.

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

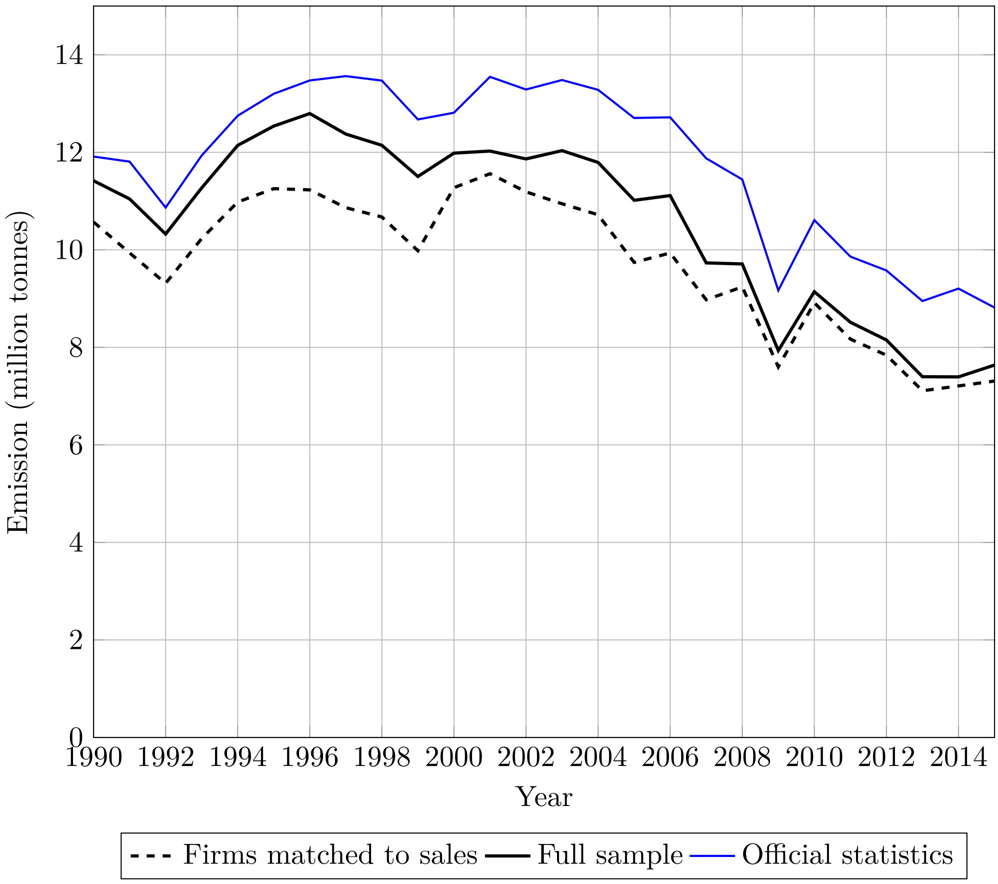

Figure A.3 compares heating emissions calculated from our full sample (*Full sample*) with the official tax payments registered by the responsible authorities and government agencies (*Official statistics*) and with that subsample that has observable sales (*Firms matched to sales*).

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

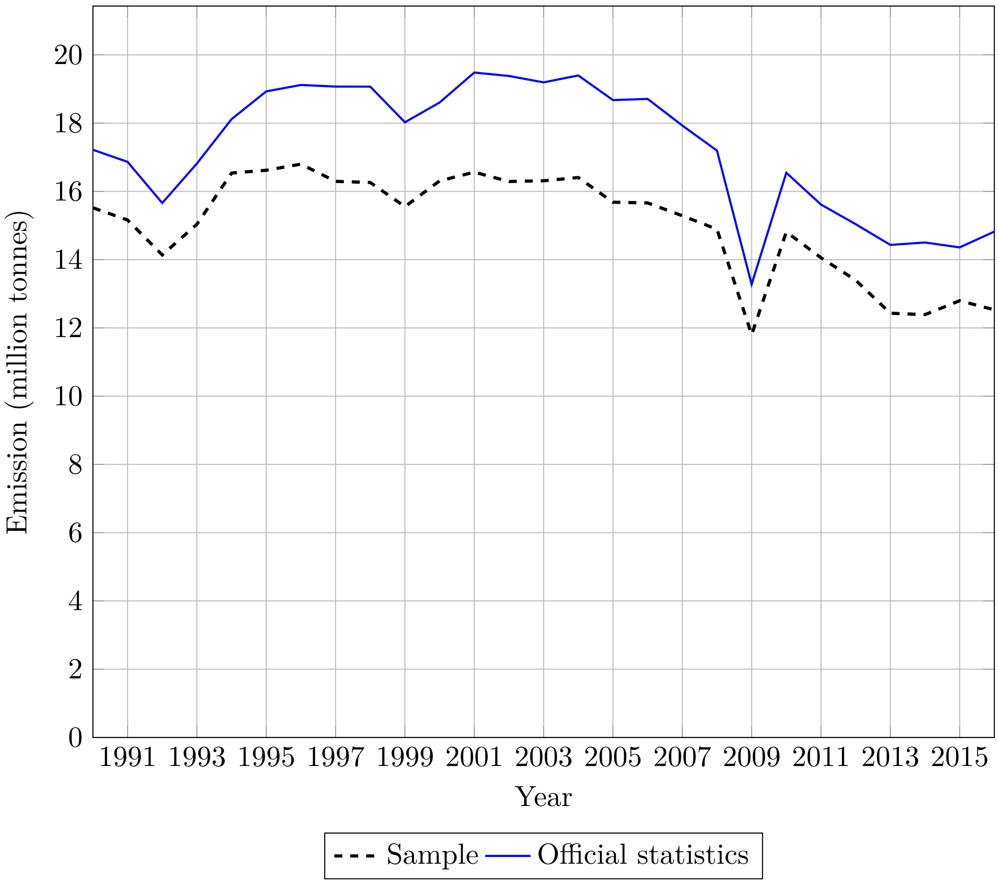

Figure A.4 compares the total emissions (i.e. heating plus process) calculated from our sample (*Sample*) with the official tax payments registered by the responsible authorities and government agencies (*Official statistics*).

Figure A.5: Distribution of sales, carbon dioxide emissions, and carbon tax payments

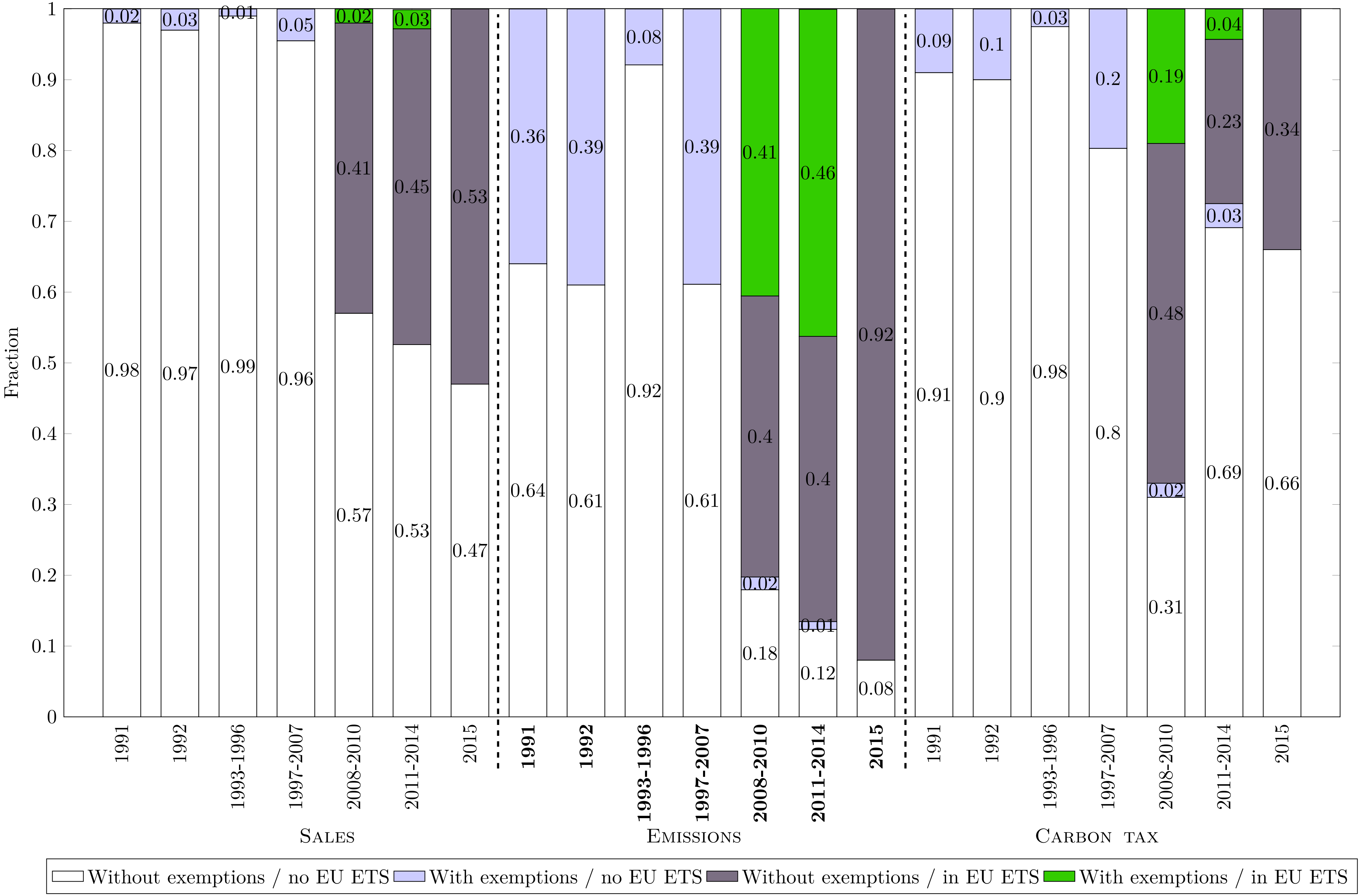

Figure A.5 displays the distribution of sales, carbon dioxide emissions, and carbon taxes paid under different tax regimes. For a description of *Without (with) exemptions/no (in) EU ETS*, see Figure 7.

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.