Carbon Pricing and Investment*

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Abstract

How does carbon pricing affect firms' investment decisions? We study this question using unique data on capital investment and the firm-specific cost of emitting CO_2 for the Swedish manufacturing sector over the course of two decades. We document a positive connection between the price of carbon and firm investment spending. For firms in the most carbon-intensive sectors, a 10% increase in carbon pricing leads to a 2% increase in investment spending. High-emission firms also increase the share of investments focused specifically on abatement as well as green R&D in response to carbon pricing. Our results imply that pricing CO_2 emissions at a sufficiently high level incentivizes brown firms to make green investments.

Keywords: Carbon pricing, Climate policy, Investment, Environmental taxes
JEL codes: Q53, Q54, G31

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1 Introduction

Carbon pricing schemes are a crucial tool in the fight against climate change, offering a market-based approach to reducing greenhouse gas emissions. Several recent studies explore how carbon pricing and other environmental taxes impact emissions (e.g., Ahmadi et al., 2022, Bartram et al., 2022, Dechezleprêtre et al., 2023, Martinsson et al., 2024), but there is limited and inconclusive evidence on how these policies affect green investment in emitting firms. For example, whereas Colmer et al. (2024) find a positive investment response from regulated firms under the European Union Emissions Trading System (EU ETS), Jacob and Zerwer (2024) find that emissions taxes lead to less capital investment, particularly in firms with limited financial flexibility.

A more complete understanding of how carbon pricing affects abatement investment is important for multiple reasons. Most notably, to evaluate the effectiveness of carbon pricing schemes it is crucial to understand the mechanisms through which higher carbon prices lead to lower (local) emissions. In particular, if emitting firms primarily respond to higher carbon prices by relocating output to less regulated geographies or moving dirty assets to other parts of the economy (e.g., Bartram et al., 2022, Duchin et al., 2022), then the local emissions reductions documented in prior work will not necessarily translate into a global reduction in greenhouse gas emissions. On the other hand, evidence that emitting firms meaningfully respond to higher carbon prices by increasing abatement spending suggests that carbon pricing can incentivize firms to make the real investments that reduce emissions at the source.

Our study aims to shed new light on the consequences of carbon pricing for firm-level investment spending. We use unique data from Sweden, which allows us to combine detailed information on capital investment and the firm-specific cost of emitting CO_2 over the course of two decades (2000–2019). This setting is attractive not only because Sweden has been taxing carbon for decades, but also because Sweden has a high carbon tax that has sharply increased over time. The level of the tax is important because capital investment decisions in emitting firms are unlikely to be affected by small changes in carbon prices. Martinsson et al. (2024) estimate the sensitivity of CO_2 emission-to-output ratios to carbon pricing for Swedish manufacturing firms 1990–2015. They find that the carbon pricing elasticities are significantly lower for firms in the highest-emitting sectors – who account for more than 70% of emissions – compared to the lowest emitting ones. A likely explanation for this is that high-emitting sectors need to make substantial changes in production technology in order to reduce emissions. Such changes require large up-from capital investments, which are not positive NPV unless the carbon price is sufficiently high (Bolton et al., 2023). Firms in relatively low-emitting sectors, on the other hand, may be able to reduce a large fraction of their carbon emissions through relatively low-cost measures without any significant up-front investment (e.g., implementing energy cost-savings programs).[1]

Our sample covers around 9,000 firm-years in the Swedish manufacturing sector over the 2000–2019 period. First, we document that the marginal cost of emitting CO_2 is relatively constant in the first decade of our sample period, before increasing by over 250% over the subsequent ten year period up to 2019 (Figure 1). We find that aggregate manufacturing investment rates (relative to sales) increase only modestly following the sharp increase in carbon prices. Importantly, however, capital investment in the highest emitting manufacturing firms rise sharply, increasing by over 60% in the last decade of our sample (Figure 2).[2] This evidence suggests that carbon pricing spurred capital investment in high-emission firms.

We formalize this connection by estimating the elasticity of firm-level investment spending to the firms' (actual) marginal cost of emitting CO_2. The nature of the data allows us to include a highly saturated regression model including firm and four digit by year fixed effects. First, we establish a direct economic connection between carbon pricing and firm profitability. Specifically, there is a strong inverse relationship between between firm-level

[1] See Bustamante and Zucchi (2024) for a model along these lines.

[2] We consider a firm as high emitting if it is operating in four digit NACE sector in the top decile of carbon intensity. This measure is developed in Martinsson et al. (2024) and is based on the ratio of aggregate CO_2 emissions and PPI-adjusted sales for each four digit sector in 1990 (the year before the carbon is introduced). All sectors are ranked from highest to lowest w.r.t. carbon emissions to sales. The aggregate investment to sales increase for high emitting sectors and the relatively flat investment trajectory for other manufacturing firms leads to a relative increase of high emitting firms' capital expenditure out of manufacturing wide investment from about 30% in 2000 to over 40% by the end of the sample period.

operating margins and the level of carbon prices, with largest effects (by far) in the most emitting firms. This implies that firms were limited in their ability to pass through the carbon pricing to their customers through higher prices.

Second, we document a highly significant and positive investment-to-carbon pricing elasticity of 0.06 for the manufacturing sector. This implies that, on average, a 10% increase in the cost of emitting is associated with a 0.6% increase in capital investment. However, this elasticity varies greatly depending on how carbon intensive the firm is. The investment response in firms with low-emission production technologies is statistically insignificant and close to zero. For the most carbon-intensive firms, on the other hand, the investment-to-pricing elasticity is substantial: a 10% increase in pricing leads to an increase in capital investment of approximately 2%. This effect is slightly larger when we factor in a delay (up to three lags) in the investment response from annual carbon price changes.

We also have detailed information for a sub-set of the sample on environmental investments related specifically to emission abatement. With these data, we find that the response to carbon pricing is even stronger: in the highest emission firms, the investment-to-carbon price elasticity is almost 0.6. High-emission firms also substantially increase abatement investment as a fraction of total capital investment. We also document strong increases in R&D investment rates (both general and with abatement purposes) for high-emitting firms as carbon prices rise.

Finally, we investigate the importance of the EU Emissions Trading System (EUETS) compared to the Swedish carbon tax. After its introduction in 2007, Swedish firms could opt-in to have plants regulated under EUETS under certain conditions (e.g., depending on plant size and amount of emissions), in which case they would be exempt from Swedish carbon tax. Under EUETS, plants were allocated some emission rights for free, where the free quota depended on average emission intensities in the firm's industry.[3] As a result, relatively low-emitting firms would have excess emission allowances that they could sell in the market, while high-emitting firms would have to acquire additional allowances to cover their emissions. Whether switching from a tax to an emissions-trading system leads to

[3]The exact allocation rules changed throughout the different Phases of EUETS.

higher or lower abatement incentives is an open issue. Bustamante and Zucchi (2024), for example, argue on theoretical grounds that surplus allowances reduce a firm's incentives to cut emissions. The majority of EUETS-regulated firms in our sample turn out to have a surplus of allowances. In contrast to Bustamante and Zucchi (2024), we find a strong correlation between the value of surplus free emissions allowances and investment rates for firms regulated under EUETS.

We quantify the economic significance of our findings by relating the estimated elasticities to the aggregate investment increases for dirty manufacturing firms. If we multiply the carbon price increase during 2011–2019 (of 239%) with the elasticity estimate for the highest decile of emitting firms from Table 5 (of 0.19), our findings predict an increase in capital investment to sales of approximately 45%. The actual increase in capital investment to sales for this sub-set of the economy was 63%. Thus, the sharp increase in carbon pricing can explain approximately three quarters of the corresponding increase in capital investment in dirty manufacturing firms. Carbon rates in Sweden correspond to a price of about $125 per ton CO_2 (similar to estimates of the social cost of carbon (SCC) under certain discount rates EPA (2023)) which would suggest that carbon prices need to rise to levels nearer the SCC in order to seriously shift capital spending of the most CO_2 emitting firms.

We contribute to several related literatures on the real effects of climate policy. First, we advance the literature on the economic consequences of market-based emissions regulations (e.g., Martin et al., 2014, Fowlie et al., 2016, Bartram et al., 2022, Colmer et al., 2024). Most of this research focuses on how various climate policies affect emissions, energy use, or (aggregate) industry dynamics. In related work, Martinsson et al. (2024) show that higher carbon prices are associated with substantial reductions in CO_2 emissions in aggregate, but that sectors with higher abatement costs – which tend to be the highest-emitting industries – have a lower emission sensitivity to carbon pricing. Our work extends these findings by uncovering a direct micro-level mechanism through which carbon pricing reduces emissions: more abatement investment by high-emitting firms. These investments only took off towards the end of the sample, once carbon prices were sufficiently high. Moreover, these investments arguably take longer to implement before emission reductions are realized, which can explain the more modest carbon pricing elasticities documented in Martinsson et al. (2024).

In this way, our study provides new evidence on how environmental taxes impact firm-level investment decisions. There are surprisingly few studies on this topic and the studies that do exist provide mixed results. Jacob and Zerwer (2024) document a negative investment response to the introduction of emission taxes in Spain, France, and Ireland. They find no differential response to the tax based on the level of pollution; rather, they find that the investment decline is driven by factors related to tax incidence, including financial flexibility. On the other hand, Colmer et al. (2024) document an economically meaningful positive increase in the capital stock in Phase 2 of the EU ETS. Bolton et al. (2023) find no effect of higher carbon prices on capital investment during Phase 3 of the EU ETS, which they suggest could be due to firms having already increased investment in anticipation of carbon price increases. Our work shows that carbon pricing can have a substantial impact on capital (abatement) investment, particularly when the price is set sufficiently high and the emitting firms most exposed to the policy are not financially constrained. We are also able to measure investment spending and firm-specific emissions costs over decades, allowing us to compute more precise (long-run) estimates of the elasticity of investment to the price of carbon than is possible in other settings.

We also contribute to the literature on environmental taxes and investment in pollution abatement technologies. For example, Calel and Dechezleprêtre (2016) find that the EU ETS facilitated low-carbon innovation in regulated firms. Brown et al. (2022) find that higher pollution taxes lead to more R&D investment in high-pollution firms. We show that carbon-intensive firms in Sweden respond to higher carbon prices by substantially increasing R&D spending, including R&D spending directly related to pollution abatement.

2 Carbon Pricing and Investment

2.1 Carbon pricing in the Swedish manufacturing sector

Sweden introduced a tax on carbon dioxide (CO_2) emissions in 1991. There have been numerous changes to the carbon tax regime; both in terms of the rate and also through various exemptions that have come and gone. The largest manufacturing plants were phased out from the Swedish carbon tax and in to the European Union Emission Trading System (EU ETS) during 2008–2011.[4]

Figure 1 plots the marginal and average carbon price separately for the firms only taxed by the Swedish carbon tax, and for the firms that eventually become regulated under EU ETS. For firms only facing the Swedish carbon tax (solid and dashed gray lines) the average tax rate (what they pay) and the marginal tax rate (the cost for the next kilogram of emitted CO_2) is virtually the same. For firms regulated under EU ETS, the average tax rate is always higher than the marginal tax rate (dotted black line always above the solid black line) during the period that all of their emissions are in the Swedish carbon tax regime (2000–2007). After 2008, the marginal carbon price for these firms increases and is consistently above the average carbon price (i.e., the actual carbon tax payments relative to emissions). The reason for this is the free allocation of emission allowances under EU ETS. To the the extent that a firm can cover its emissions through the free allocation, there is no tax expense incurred, even though the marginal cost of emitting is still positive and equal to the market price of emission rights (also for firms with a surplus, since excess allowances can be sold in the market).

The sharp increase in the marginal carbon price after 2014 is driven by the phasing out of a general carbon tax exemption for manufacturing firms in the Swedish carbon tax system. Because firms in the Swedish carbon regime have all their emissions priced under the Swedish system, they experience a much larger increase in the marginal price of carbon (gray solid line). The EU ETS firms, on the other hand, have some of their emissions fall under the EU ETS (prices in the EU ETS start to increase later in 2017), so their weighted marginal carbon price is lower.

[4] We refer to a firm as regulated under EU ETS if at least one plant is in the EU ETS. We compute the carbon price for a firm in the EU ETS as the weighted sum of the emissions in EU ETS regulated plant x the EUA price and the emissions falling under the Swedish carbon tax x the Swedish carbon tax rate. For a detailed discussion on the carbon pricing in Sweden see Martinsson et al. (2024).

2.2 Sample construction

We construct the main sample from five different data sets. The key data source is the annual capital investment survey conducted by Statistics Sweden which covers the time period 2000–2019. We then merge this data with: i) CO_2 emissions data at the firm and plant level from the Environmental Protection Agency (SEPA), ii) abatement investment information from the Environmental protection expenditure survey maintained by Statistics Sweden, iii) data on investment in research and development (R&D) at the group level from consolidated accounts (from Statistics Sweden) and, finally iv) firm balance sheet and income statement information using from the Serrano dataset. See section A for a detailed description of each of the datasets. We consolidate the firm-level information to the group level.

Our main sample, which is the intersection of the capital investment data, CO_2 emissions and firm fundamentals data, includes just under 10,000 observations during 2000–2019. The abatement investment data starts in 2002 and covers fewer companies (with a focus on emitting firms that actually have abatement investment), which reduces the sample size to about 2,000 observations. Finally, the R&D sample comprises around 5,200 firm-years.

Table 1 reports summary statistics for the key variables in this study. The first four columns in Table 1 report statistics for the full sample of firms. In the last three columns we report sub-sample means, as well as differences in means, for the highest emitting firms (top decile) compared to all other firms in the sample. Overall, Swedish manufacturing firms invest more in capital than for abatement purposes or R&D, and they are quite old (average (median) age is 57 (53) years). The highest emitters invest more in capital and in abatement (both capital and R&D), are larger and older, while at the same time investing less in R&D, having less long-term bank debt, and slower grow. EBIT margins and cash flows are similar for high- and low-emitting firms.

2.3 Emissions and economic performance in the manufacturing sector

In this sub-section we show how carbon pricing, investment and the broader manufacturing sector has developed over time. We follow Martinsson et al. (2024) and sort all firms in to deciles based on the carbon emissions intensity of their four-digit NAC industry (around 200 industries in total). Specifically, we sort sectors from highest (most emitting) to lowest (least emitting) based on the ratio between aggregated CO_2 emissions and producer-price adjusted sales in 1990 (the year before Sweden introduced carbon pricing). Since PPI-deflating removes the impact of average 4-digit sector prices on sales, this ratio is an approximation of emissions relative to unit of output.[5]

2.3.1 Carbon Prices and Aggregate Investment

In Figure 2 we plot aggregate capital investment to sales ratios (as a three-year moving average) for the manufacturing sector (grey dashed line), the most emitting firms (firms in decile 10 sectors; black solid line) and the other manufacturing firms (from deciles 1–9; black dashed line). We also report the average carbon price (also smoothed over a three year period) for each year (grey dotted line; measured on the right hand vertical axis).

The carbon price hovers around 0.22–0.25 SEK per kilogram CO_2 in the first decade of the sample period (2000-2010). The average carbon price rises slightly in 2011–2014 (to around 0.35), then increases sharply after 2014 (up to about 1.15 SEK/KG). The price increases by almost 300% from 2011 to 2019.

During the first part of the sample period when carbon prices are relatively low and non-increasing there is general decrease in capital investment-to-sales ratios (using PPI-deflated sales) for the manufacturing sector as a whole. The trends for high- and low-emitting firms are similar during this period. The investment ratio declines by about 25% for the manufacturing sector as a whole (-17% for decile 10 highest-emitting firms, and -27% for the lower-emitting firms).

[5] PPI-deflating sales is important to ensure that emission ratios are not simply driven by firms changing output prices. Most of the manufacturing firms are exporters and their revenues are heavily affected by fluctuations in both world market prices and exchange rate movements.

However, coinciding with the steep carbon price increase after 2014, investment in high emitting firms incrases sharply. As carbon prices rise, the investment ratio for emitting firms (who are most exposed to the higher carbon prices) increases by over 60% (from about 0.03 to 0.05). At the same time, lower emitting manufacturing firms only increase investment relative to sales by about 20% (0.02 to 0.025). This *differential* change in investment between high- and low-emitting firms is a primary focus of our more formal tests later in the paper.

2.3.2 Emissions, Investment, and Internal Finance Over Time

After documenting the steep increase in carbon prices in the second half of the sample period and a concurrent investment surge for high emitting firms, Table 2 summarizes some additional, aggregate patterns for the Swedish manufacturing sector between 2000 and 2019. We focus on three sub-samples of firms based on emission-intensity: low emitters (deciles 1–4), medium emitters (deciles 5–8), and high emitters (both as deciles 9–10 together, and decile 10 on its own). Panels A and B in Table 2 report averages for the first and last three years of the sample. Panel C reports changes in these average values.

We first confirm that sorting firms based on a 1990 ranking of low to high CO_2 emissions is stable. The share of CO_2 from the top decile of firms is 0.85 in the beginning of the sample period, and rises to about 0.88 at the end of the period. The CO_2 emissions to PPI adjusted sales ratio is low (under 0.001) and decreasing for firms in deciles 1–8. Decile 10 firms have 200 (20) times higher CO_2 emission to sales ratio than low (medium) emitting firms in 2000–2002. Both low- and high-emitting firms have a sizable reduction in emission intensity during the sample period. Despite the reduction in emission intensity, decile 10 firms have almost 45 times higher emissions intensity in the final sample years compared to the lower emitting firms.

In the final three rows in the panels we report how capital investment to sales and internal finance (measured as cash flow to sales) evolve over the sample period. Consistent with Figure 2, the investment intensity in high emitting firms increases, whereas for low and medium emitting firms the investment ratio is lower in the final years of the sample period compared to in the beginning. Next we relate the investment changes to how cash flows have evolved over time. Aggregate cash flow to sales is higher for both low and medium emitting firms in 2017–2019 compared to 2000–2002. While high emitting firms have considerably higher cash flows relative to the low emitting firms, this ratio is 22% lower in the 2017–2019 compared to 2000–2002. It is noteworthy that cash flows are consistently higher than capital investment expenditures. Finally, we relate aggregate capital investment directly to internal finance. For high emitting firms, investment spending is about one third of cash flows in the beginning of the sample period and rises to over 50% in the final years. In contrast, lower emitting firms invest less in relation to cash flows over the sample period.

3 Carbon Pricing and Firm Investment

3.1 Baseline specification

We evaluate the relationship between the cost of emitting carbon and investment by following similar approaches as Shapiro and Walker (2018) and Martinsson et al. (2024) do for estimating CO_2-to-carbon price elasticities.

$$ln(Inv)_{i,t} = \alpha + \sum_{s=0}^{q} \beta_{\mathrm{s}} \cdot ln(C)_{i,t-s} + \gamma \mathrm{X}_{\mathrm{i,t\text{-}1}} + \eta_i + \eta_{j,t} + \epsilon_{i,t}. \tag{1}$$

where *Inv* is capital expenditure divided by sales for firm i in year t. C is the marginal cost of emitting a unit of CO_2 times total emissions divided by PPI-deflated sales for firm i in year t-s.[6] The lagged terms of C allow for a delayed investment response to carbon price changes. η_i captures firm-specific time-invariant factors that could impact the relation between investment and carbon pricing. $\boldsymbol{X}$ is a vector of lagged firm level control variables comprising cash flow, the natural logarithm of total assets, long term debt, firm age (in logs) and (PPI adjusted) sales growth. $\eta_{i,t}$ absorbs changes in *Inv* that are common to all firm in the same four digit sector in a given year and controls for (narrowly defined) industry investment trends unrelated to carbon pricing.

[6] As discussed in Cropper and Oates (1992), firms' should mostly depend on the marginal abatement cost and we therefore measure the carbon price at the margin.

3.2 Do carbon prices impact firm profit margins?

Before we turn to the baseline investment results we test whether there is a direct effect from the price of CO_2 on firm profitability. Specifically, we use a firm's operating margin, measured as EBIT relative to sales, as dependent variable and estimate a version of Equation 1 considering only *s=0*. Results are reported in Table 3. There is a highly statistically significant relationship between changes in carbon pricing and firm operating margins as reported in column 1 (-0.005). We do not measure EBIT to sales in logarithms (due to the occurrence of negative realizations) and therefore we cannot interpret the coefficient in Table 3 as elasticities. Instead, for a 10% increase of carbon prices (which is the average annual increase during the sample period), the -0.005 point estimate in column 1 is associated with a 0.0005 reduction in operational performance, or 1.2% relative to the sample mean (0.041). However, there are annual changes of 36% (in 2011), 40% (in 2016) and even up to 100% (in 2015). Increases of 40 and 100% would instead imply reductions of EBIT margins of 5 up to 12%.

The results for the manufacturing sector as a whole suggests that very large increases in carbon pricing translate in to economically meaningful profitability reductions. However, emission intensities vary greatly across different parts of the manufacturing sector. Indeed, as we show in Table 2 above, emissions to sales for low emitting sectors (deciles 1–4) is 0.0001 compared to 0.03 for the high emitting sectors (decile 10). We proceed and re-estimate the EBIT margin regressions across sub-samples of firms in low, medium and high emitting sectors. The relationship between carbon prices and operating margins is close to zero and far from statistically significant for firms in low emitting sectors (column 2). The estimated coefficient for medium emitting sectors is slightly larger than reported in column 1. Further, for firms in the highest emitting sectors the coefficient is almost three times as large than for the manufacturing sector as a whole.

The economic significance of carbon price changes is considerably larger for high emitting firms. If we consider the sample average price increase of 10%, there is a 6% decrease in EBIT to sales. However, in years with large price increases of 40% to 100%, operating margins deline by 13–32% for the high emitting firms.

The results in Table 3 show two important things. First, it is important to account for differences in emission intensity across sectors with different production technologies (as measured by groups of narrowly defined industry emission intensities). Some (high-emitting) industries are much more affected by carbon pricing. Second, for firms in high emitting sectors, increases in carbon prices have economically meaningful effects on operating margins.

3.3 Baseline investment results

Table 4 reports baseline results of Equation 1 with $s=0$ in the first four columns and then with lagged values up to $s=3$ in the remaining three columns. We begin in the first column and report a highly statistically significant elasticity of 0.11 using only year fixed effects. This implies that the suggestive relationship between changes in carbon prices and manufacturing-wide capital investment in Figure 2 translates over to the firm level. We proceed in next four columns by adding firm fixed effects, four-digit industry by year fixed effects and the $\mathbf{X}$ vector of control variables. When we estimate the full specification (while only considering the case with $s=0$) the elasticity is about 0.06 (or about half relative to column 1). This result implies that a 10% increase in carbon prices is associated with 0.6% increase in investment. In the final three columns we add lags progressively up to $s=3$ in column 7. There remains a highly statistically significant contemporaneous relationship between investment and carbon pricing. However, the sum of the coefficients are almost twice large as the contemporaneous in the case of three lags included in column 7 (0.075 compared to 0.130).

We report a set of robustness in Table B.1. First, in columns 1 and 2 we consider measuring the firm level marginal cost of emitting CO_2 in two alternative ways. Our preferred measure used in the paper calculates the marginal cost based on the highest emitting plant the (consolidated) firm owns. In column 1 (2) we instead calculate the marginal cost based on sales (fixed assets) weighting the plants. The results are very similar if we consider these alternative approaches. We provide similar results when we scale investment and the emissions cost by total assets in column 3 and un-scaled in column 4. Finally, in column 5 we consider the plant level relationship, i.e., the unconsolidated data, and find similar results.

3.4 Investment results across emission intensity groups

Next we re-estimate Equation 1 across sub-samples of firms based on the emission intensity of their production technology. In Table 3 we show that carbon prices impact firm operating margins and that it is only for the highest emitting firms that the impact is economically meaningful. It is therefore reasonable to assume that the impact of carbon prices on capital investment also should be largest for the most emitting firms. Table 5 reports results for firms in deciles 1–4 (columns 1–2), deciles 5–8 (columns 3–4), deciles 9–10 (columns 5–6) and decile 10 only (columns 7–8) when $s=0$ in odd numbered columns and the full lag structure in even numbered.

The estimated elasticities are close to zero and far from statistically significant across the first four columns, considering low to medium emitting sectors. This result is in line with the aggregate investment pattern presented in Figure 2 and consistent with carbon prices being less costly to low emitting firms. In sharp contrast, the estimated elasticities in the final four columns are up to three times larger than the baseline estimate in Table 4 for the average manufacturing firm. The elasticity in column 7 for high emitting firms (in decile 10) is 0.19 and highly statistically significant. There are also delayed responses as reported in column 8 which results in a larger effect of 0.25 compared to the contemporaneous effect of 0.19.[7] Finally, we report similar results as for the decile sorts in Table B.3 when we consider an alternative measure to capture the different emission intensity of sectors by adopting the so called carbon leakage list that is used categorize sectors in the EU ETS.[8]

[7] We report results in Table B.2 with the contemporaneous marginal cost regressions (odd numbered columns in Table 5) using the same sample as in the even numbered columns to attain comparability.

[8] European Commission (2009) includes the initial carbon leakage list. Firms in a given four digit industry can be considered at risk of carbon leakage if it has i) high costs of carbon pricing (i.e., sectors with high emission intensity ("Emission"), ii) high level of international competition (i.e., high levels of trade outside of the EU ("Trade only") or, iii) being exposed to both of these factors.

3.5 Abatement investment

For a subset of the manufacturing firms we also have data on abatement investment.[9] This data is from the annual environmental protection expenditure survey carried out by Statistics Sweden. We consider capital expenditure in emissions treatment equipment and air emissions prevention equipment and call this variable *Abate Inv*. We re-estimate a version Equation 1 with *Abate Inv* as dependent variable and s=0. As the sub-sample of firms with abatement investment data are generally more emission intensive than the average manufacturing firm we re-estimate the first four columns in Table 4 on this sample for comparison reasons and report the results in Table B.4. The baseline capital investment to carbon pricing elasticity is 0.16 for the abatement sample compared to 0.06 for the full manufacturing sample.

The results with *Abate Inv* as dependent variable are reported in Table 6. In columns 1 and 2 we present estimates without and with the set of firm control variables respectively. The abatement investment to pricing elasticity is between 0.22 and 0.3. In other words twice as large as the general capital investment elasticity of 0.16. Although the abatement investment sample is more heavily tilted toward the high emitting sectors we interact the marginal cost variable with an indicator variable (*D10*) taking on the value one if the firm is operating in a decile 10 industry. The estimated coefficient for the interaction term is 0.58 compared to a non-significant 0.04 for non-decile 10 sectors. In other words, a 10% increase in carbon price is associated with an almost 6% increase in abatement investment. These results suggest that the documented investment response is almost exclusively driven by abatement investment in the most emitting firms.

In the next columns we relate abatement investment as a fraction of total capital expenditures and report results for all firms in column 4 and with the *D10* interaction term in column 5. The results in column 5 show that abatement investment increase more than other non-abatement investment as carbon prices go up. Finally, we consider the non-abatement capital investment relative to sales in columns 6 and 7. Non-abatement investment is

[9]The purpose of this survey is to capture environmental expenditures and therefore the sub-sample of firms covered are more emitting than the average manufacturing firm. Also, this survey begins in 2002 which means 2000 and 2001 are omitted from this test.

significantly related to changes in carbon prices (in column 6) but not significantly more so for high emitting firms (in column 7). This result can be driven by multiple factors including that i) some abatement investment lead to non-abatement investment needs in emitting firms as well as in the less emitting firms and, ii) some investment that is targeted to abate emissions is falls outside the classification abatement expenditures in the survey.

Overall, the results in Table 6 show that there is a more than as large investment to pricing elasticity for abatement (0.30) relative to non-abatement investment (0.14) for the manufacturing as a whole. And, for the most emitting firms the elasticity is almost 0.60, or more than four times the non-abatement elasticity, which also leads to the share of abatement investment in total investment for these firms to increase sharply.

3.6 R&D investment results

We use R&D investment to sales (*R&D*) (in columns 1–3) and R&D abatement investment to sales (*Abate R&D*) (in columns 4–6) as dependent variables and report the results in Table 7. The sample coverage for the both R&D variables is considerably weaker. The relationship between carbon pricing and the broad R&D variable is close to zero and far from statistically significant. We do note that high emitting firms, who are most treated by a carbon price, invest significantly less in R&D compared to lower emitting firms (see Table 1). However, in column 3 when we interaction the marginal cost variable with an indicator variable equal to one if the firm operates in a decile 10 (high-emitting) industry (*D10*) we find a positive and highly statistically effect. A 10% increase in carbon prices is associated with a 3.6% increase in R&D investment for high emitting firms.

In the final three columns we consider R&D abatement investment. These tests have rather weak statistical power as the sample only includes between 150–200 firm-years. However, the estimated elasticity between R&D abatement investment and carbon price changes is 0.49 (columns 4 and 5) for the average firm and 0.89 for high emitting firms in decile 10 (column 6). The results in Table 7 show that high emitting firms invest more in R&D as carbon prices increase (the elasticity is 0.36 compared to the capital abatement investment elasticity of 0.58), and suggestive evidence points to an even larger effect on R&D

with the purpose of emissions abatement.

3.7 EU ETS compared to the carbon tax

We generally consider the combined carbon price effect from both the Swedish carbon tax and the EU ETS. However, there are important differences between the two carbon emission regulation mechanisms. One is that the Swedish carbon tax rate differs from the EU ETS price (which we have accounted for in all our tests through the marginal cost variable). Another difference is that a large fraction of the emissions allowances are supplied for free to companies. In this sub-section we measure the value of a surplus of emissions allowance (so called EU allowances, EUA) and to what extent this is related to investment.[10] Specifically, we take for each firm-year, the number of free EUAs minus the amount of EU ETS regulated emissions and multiply this value by the EUA price (and relate this value to sales). We name this variable *Value allowances*.[11] If a firm has more (less) free allowances than emissions it can sell these (must buy) allowances.

We report results from an augmented version Equation 1 with *Value allowances* only in year t (odd numbered columns) and the full lag structure (even numbered columns) in Table 8. Results for the full manufacturing sector are reported in columns 1–2 and for the high emitting firms only in 3–4. There is a significant and positive relationship between the value of emissions allowances a firm has and investment. As expected the result is considerably stronger in the high emitting sectors.[12] These results suggest an independent channel through which the value of emission allowances affect capital investment in high emitting firms.

[10] It is not obvious that surpluses or deficits in emission allowances should be associated with investment policy. Firms might simply pay out or save surplus revenues from the sale of excess emissions allowances or absorb deficits by reducing profit margins.

[11] This approach is inspired by Bolton et al. (2023).

[12] This in part expected as the vast majority of all EU ETS regulated plants are owned by firms in decile 10. However, not all firms in decile 10 have EU ETS plants.

4 Quantifying Economic Importance of Estimated Elasticities

The estimation results in section 3 show a strong relationship between increases in carbon prices and and capital investment in high emitting firms. In this section we assess the plausibility and economic magnitude of the estimated elasticities relative to the aggregate increases of capital investment in Figure 2. The sample period can be divided into two carbon pricing regimes; one characterized flat or weakly increasing prices (2000-2010) and one with sharply increasing prices (2011–2019). The average marginal cost per emitted unit of CO_2 increased by 8% in the first period, and by almost 240% in the second period.

Capital investment relative to sales decreased similarly for both high emitting firms (decile 10) and firms outside of decile 10. However, aggregate investment to output increased by 63% between 2011 to 2019 for high emitting firms compared to only 20% for other manufacturing firms (arguably less impacted by a price on carbon). If we multiply the 239% increase in average marginal cost during 2011-2019 with the estimated investment elasticity for high emitting firms (column 7 in Table 5) our results predict 45% higher investment (column 3, top row). This would imply that about three quarters of the observed investment increase for high emitting manufacturing firms can be attributed to the increase in carbon prices (column 5, top row). We also show how much larger the investment increase could have been if all Swedish manufacturing CO_2 emissions would have been regulated by the higher Swedish carbon tax (second row) and how much lower it would have been had all firms had the same average marginal cost as the EU ETS regulated firms (bottom row).[13]

Finally, we convert the Swedish carbon prices in to US dollar per ton and relate the price levels to estimates of social cost of carbon (SCC) (Figure 3). The gray line is the marginal cost for non EU ETS regulated firms. In 2019 these firms faced a marginal cost of emitting carbon equivalent of $125 per ton. The same for firms also having some of their plants regulated under EU ETS is $82 per ton. We also highlight the estimated SCC from EPA (2023) for 2020 with a 2.5% (blue short dashed line, lowest) and 2% (blue long dashed line,

[13]This comparison omits a multitude of important features and differences between the Swedish carbon tax and the EU ETS regulation. Perhaps most importantly in the context of capital investment the fact that a tax represent cash flowing out of the firm that could otherwise be used versus the EU ETS case of a positive marginal cost and the majority of emissions allowances received for free.

highest) discount rates respectively for comparison. This suggests that the carbon prices that non EU ETS regulated manufacturing firms face in Sweden is in a similar region as some estimates of SCC. It is also clear from Figure 3 that EU ETS regulated almost consistently face a lower carbon price. We also include the average, annual EUA price (in 2020 USD per ton) to highlight that the sharp increase in EU ETS starts after our sample period.

5 Conclusion

A primary goal of carbon pricing and other emission taxation schemes is to encourage abatement investment in high-emission firms. But the extent to which these policies affect firms' investment spending is an open question, both theoretically and empirically. We provide new evidence on this issue by estimating the investment response to CO_2 prices in a broad sample of Swedish manufacturing firms. We document a positive capital investment-to-carbon price elasticity, with differentially stronger effects in the high-emission firms most affected by higher carbon pricing. We also find that carbon pricing leads high-emission firms to substantially increase spending on investments focused specifically on pollution abatement. Our results suggest that with a sufficiently high carbon tax, the incentives to increase investment to reduce emissions at the source overcome any potential negative effect the higher tax burden may have on capital investment.

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Figure 1: Average and Marginal carbon price 2000–2019

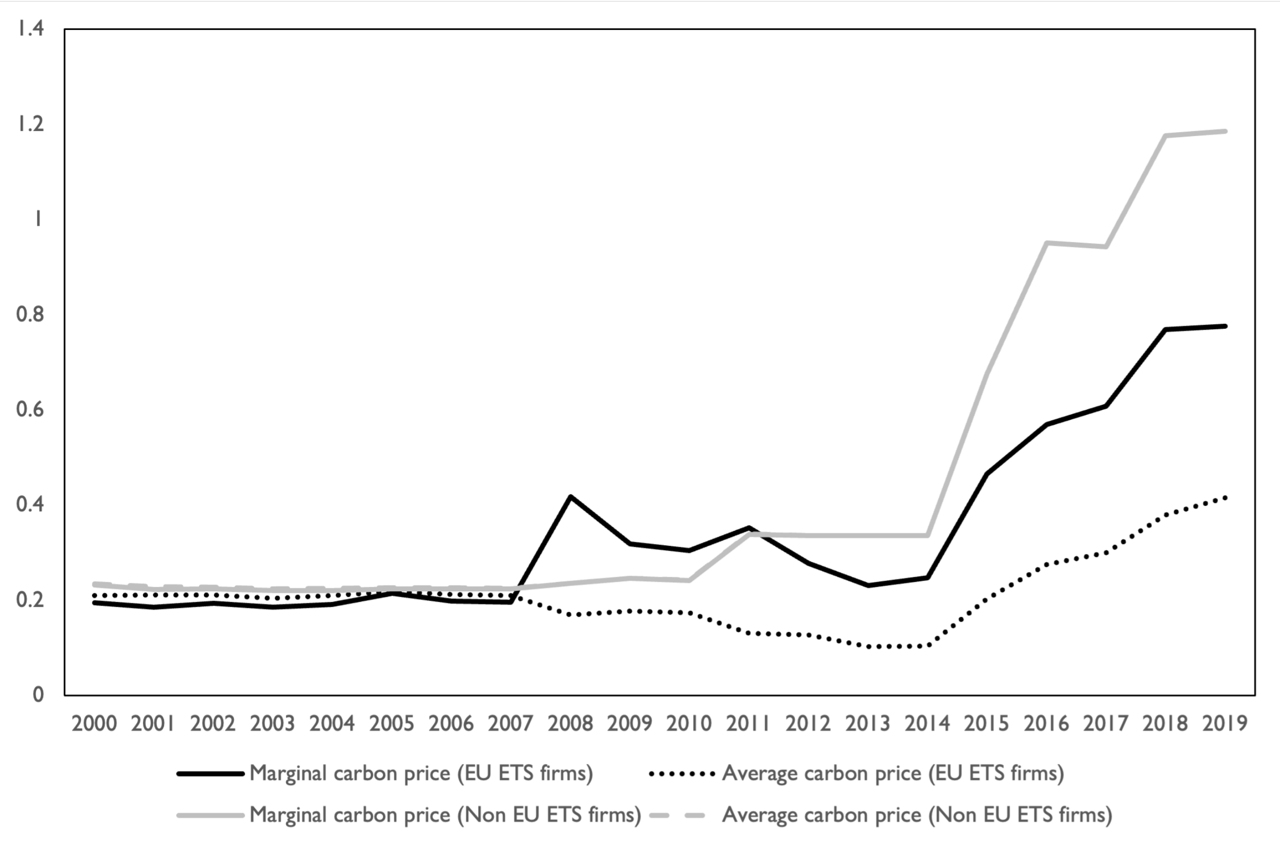

Figure 1 displays the marginal carbon price (solid black line) and average carbon price (dotted black line) for firms regulated by the EU ETS. Before EU ETS firms enter EU ETS the price refers to the Swedish carbon tax rate. The marginal carbon price (solid gray line) and average carbon price (dashed gray line) for firms only taxed under the Swedish carbon tax.

Figure 2: Capital investment in the manufacturing sector

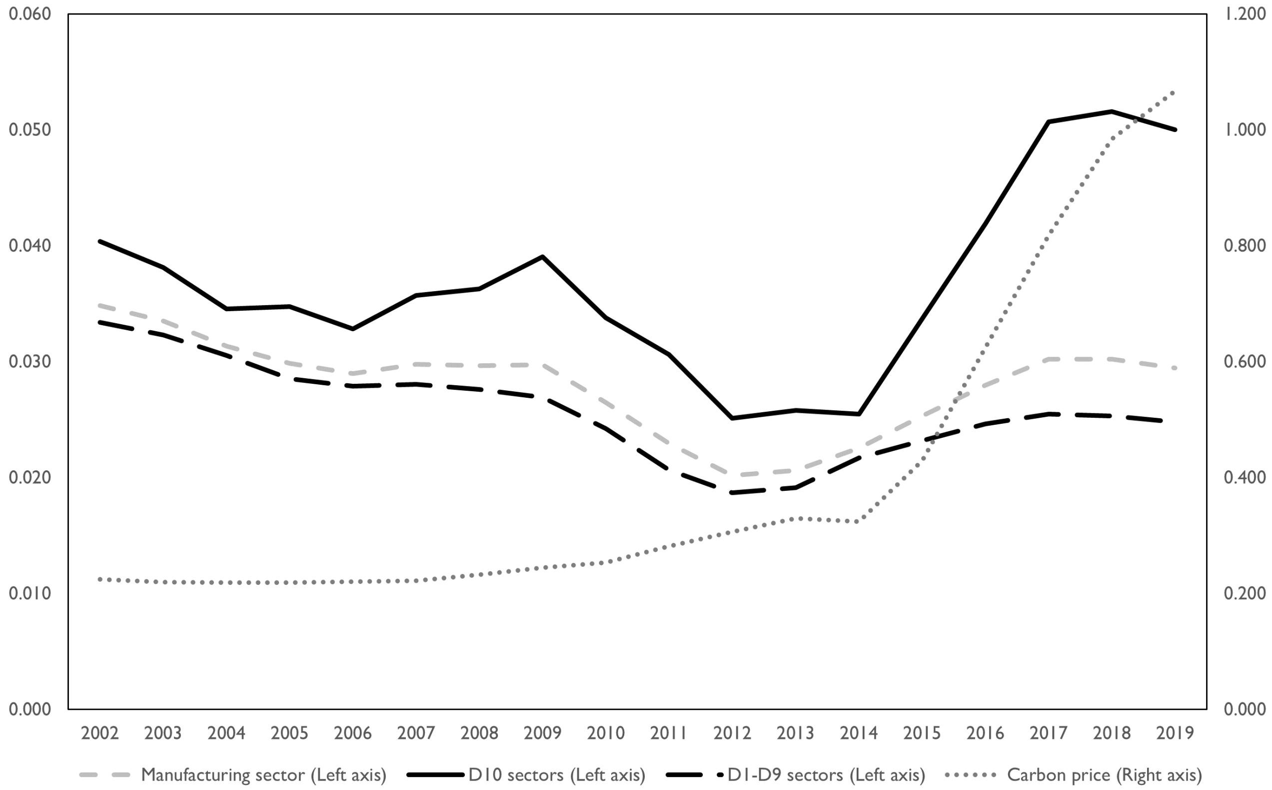

Figure 2 displays the aggregate capital investment to sales ratio for the manufacturing sector (dashed gray line), for decile 10 sectors, D10 (solid black line), for decile 1-9 sectors, D1-D9 (dashed black line) and the average carbon price (dotted grey line). All time series are expressed as a rolling moving average from t to t-2 for the time period 2000–2019.

Figure 3: Swedish carbon prices and Social Cost of Carbon estimates

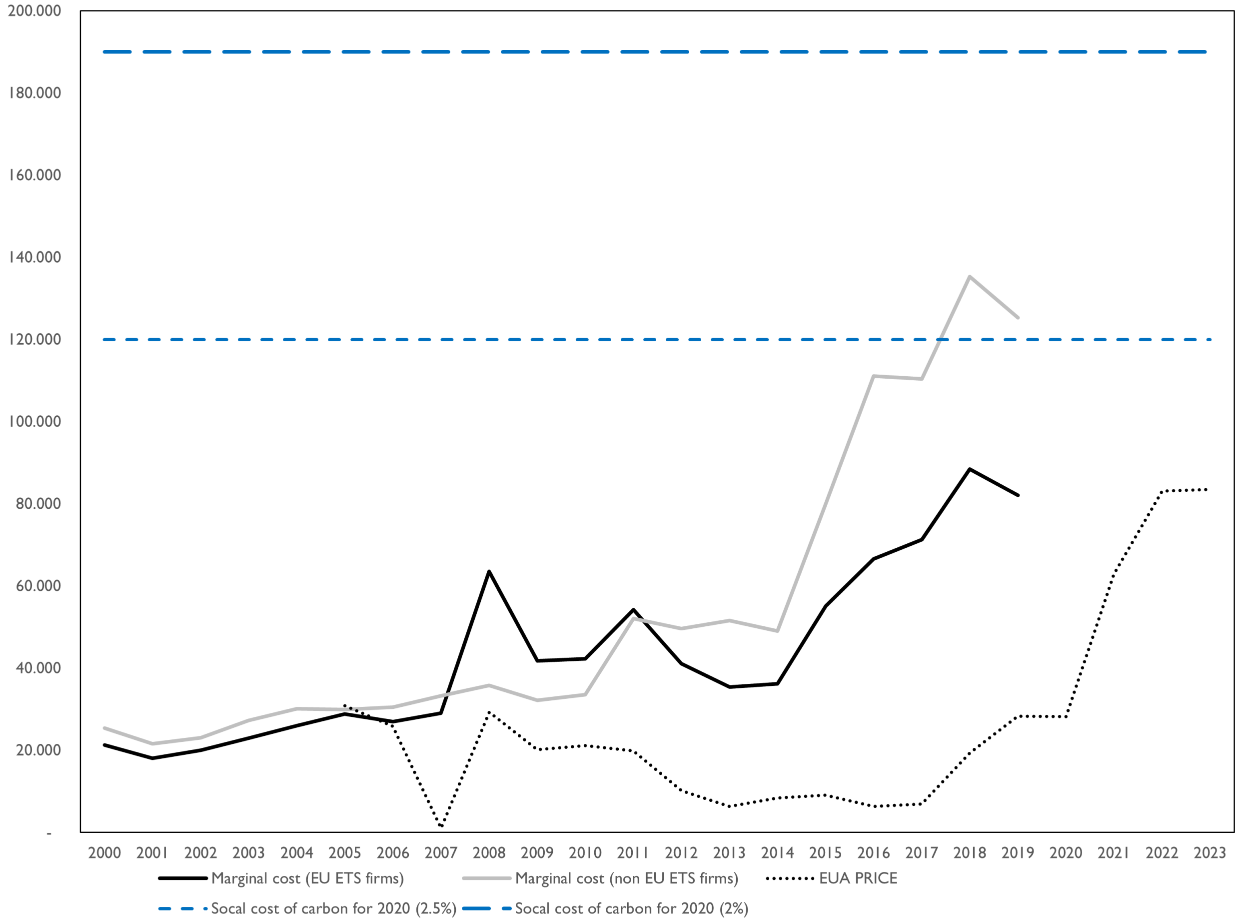

Figure 3 displays the marginal carbon price (solid black line) for firms regulated by the EU ETS converted to US dollar per ton emission (before EU ETS firms enter EU ETS the price refers to the Swedish carbon tax rate). The marginal carbon price (solid gray line) for firms only taxed under the Swedish carbon tax converted to US dollar per ton emission. The EUA price, EU allowances price in constant 2020 US dollars. Social cost of carbon for 2020 (2.5%) (blue short dashed line, lowest) is the reported social cost for 2020 with a 2.5% discount rate from EPA (2023). Social cost of carbon for 2020 (2%) is from the same source but with a 2% discount rate (blue long dashed line, highest).

Table 1: Summary Statistics

	OBS	Mean	Median	St Dev	Mean (D10)	Mean (D1–D9)	Difference
Inv	9,839	0.031	0.017	0.047	0.041	0.030	0.011***
C	9,839	0.0011	0.0003	0.0021	0.0030	0.0008	0.0022***
Abate Inv	2,046	0.002	0.001	0.005	0.005	0.002	0.004***
Non-abate Inv	2,046	0.031	0.020	0.040	0.044	0.027	0.017***
Share Abate Inv	2,046	0.127	0.030	0.283	0.185	0.111	0.074***
R&D Inv	5,267	0.011	0.000	0.033	0.006	0.012	-0.006***
Abate R&D Inv (x 10)	2,046	0.0004	0.0000	0.0014	0.0009	0.0002	0.0006***
EBIT	9,839	0.041	0.044	0.183	0.045	0.041	0.004
Cash flow	9,185	0.121	0.097	0.208	0.111	0.122	-0.012
Total assets (BSEK)	9,839	3.469	0.237	18.800	9.495	2.781	6.714***
Long term debt	9,810	0.118	0.034	0.168	0.101	0.140	-0.039***
Firm age	9,839	57	53	33	70	55	14***
Sales gwth	8,992	0.133	0.022	0.911	0.108	0.185	-0.077*

Table 1 reports summary statistics of the key variables used in this study. The sample comprises Swedish manufacturing firms (NACE: 1000–3300) with capital expenditure and CO_2 emissions data during 2000–2019. Prices are expressed in constant 2020 Swedish Krona (sek). *Inv* is the capital expenditure to sales ratio. *C* is the marginal cost of emitting CO_2 (Marginal cost x total CO_2 emissions) divided by sales. *Abate Inv* is the abatement capital expenditure to sales ratio. *Non Abate Inv* is the non-abatement capital expenditure to sales ratio. *Share Abate Inv* is the share of abatement capital expenditure out of total capital investment. *R&D* is the research and development (R&D) expenditure to sales ratio. *Abate R&D* is the abatement R&D expenditure to sales ratio. *EBIT* is the earnings before interest and taxes to sales ratio. *Cash flow* is cash flow divided by total assets. *Total assets* is the book value of total assets. *Long term debt* is long term bank debt divided by total assets. *Age* is the number of years since incorporation. *Sales gwth* is the annual log difference in PPI-adjusted sales. ***, **, and * indicate significance at the 1%, 5%, and 10% levels.

Table 2: Stats across deciles and over time

	D1–D4	D5–D8	D9–D10	D10
	Panel A: Ratios 2000–2002			
Share CO_2 emissions	0.039	0.079	0.877	0.849
CO_2 emissions to sales	0.0001	0.001	0.023	0.029
Investment to sales	0.026	0.037	0.035	0.040
Cash flow to sales	0.060	0.093	0.113	0.123
Investment to cash flow	0.437	0.399	0.313	0.327
	Panel B: Ratios 2017–2019			
Share CO_2 emissions	0.023	0.061	0.915	0.877
CO_2 emissions to sales	0.000	0.000	0.013	0.015
Investment to sales	0.023	0.025	0.045	0.050
Cash flow to sales	0.077	0.098	0.094	0.095
Investment to cash flow	0.303	0.253	0.479	0.521
	Panel C: Change ratios			
Share CO_2 emissions	-0.016	-0.018	0.038	0.029
CO_2 emissions to sales	0.000	-0.001	-0.010	-0.014
Investment to sales	-0.003	-0.012	0.010	0.009
Cash flow to sales	0.017	0.005	-0.019	-0.028
Investment to cash flow	-0.134	-0.147	0.166	0.194

Table 2 reports aggregate shares and ratios across deciles and time in panels A and B and the difference in shares and ratios in panel C. *Share CO_2 emissions* is the aggregate CO_2 emissions for a given decile group in 2000–2002 (2017–2019) in panel A (B) divided by total CO_2 emissions in the Swedish manufacturing sector in 2000–2002 (2017–2019). *CO_2 emissions to sales* is the ratio between aggregate CO_2 emissions and PPI adjusted sales for a given decile group in 2000–2002 (2017–2019) in panel A (B). *Investment to sales* is the ratio between aggregate capital investment and sales for a given decile group in 2000–2002 (2017–2019) in panel A (B). *Cash flow to sales* is the ratio between aggregate cash flow and sales for a given decile group in 2000–2002 (2017–2019) in panel A (B). *Investment to cash flow* is the ratio between aggregate capital investment and cash flow for a given decile group in 2000–2002 (2017–2019) in panel A (B).

Table 3: Carbon pricing and operating margins

	(1)	(2)	(3)	(4)	(5)
	All	**D1–D4**	**D5–D8**	**D9–D10**	**D10**
$\ln(\mathrm{C_{i,t}})$	-0.005***	-0.002	-0.007**	-0.012**	-0.013**
	(0.002)	(0.002)	(0.003)	(0.005)	(0.006)
Firm fixed effects	Yes	Yes	Yes	Yes	Yes
Industry x Year effects	Yes	Yes	Yes	Yes	Yes
Firm controls	Yes	Yes	Yes	Yes	Yes
Observations	6,242	2,693	2,457	1,084	643
Adjusted R^2	0.797	0.777	0.850	0.100	0.149

Table 3 reports OLS estimates of Equation 1. $EBIT_{i,t}$ is the dependent variable, where *EBIT* is the earnings before interest and taxes to sales ratio for firm i in year t. C is the cost of emitting CO_2 divided by sales for firm i in year t. The sample comprises Swedish manufacturing firms (NACE: 1000-3300) with capital expenditure and CO_2 emissions data during 2000–2019. D1-D4 include firms from the four-digit industries with emissions to sales in 1990 in the lowest 40%, D5-D8 from four-digit industries from the 5th to the 8th decile in terms of emissions intensity, D9-D10 include firms from the highest 20% (i.e., the two highest deciles) and D10 include firms from the highest 10% (i.e., the highest decile). All regressions include firm and four digit industry-year fixed effects and the following firm control variables: *Cash flow*$_{i,t-1}$, *ln(Total assets)*$_{i,t-1}$, *Long term debt*$_{i,t-1}$, *ln(Age*$_{i,t-1}$*)* and *Sales gwth*$_{i,t-1}$. The standard errors are clustered at the firm level. ***, **, and * indicate significance at the 1%, 5%, and 10% levels.

Table 4: Carbon pricing and firm level capital investment

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
$\ln(C_{i,t})$	0.111***	0.046***	0.061***	0.059**	0.080***	0.087***	0.075**
	(0.013)	(0.016)	(0.022)	(0.025)	(0.029)	(0.030)	(0.035)
$\ln(C_{i,t-1})$					0.000	0.005	0.019
					(0.029)	(0.033)	(0.038)
$\ln(C_{i,t-2})$						0.020	0.029
						(0.028)	(0.032)
$\ln(C_{i,t-3})$							0.007
							(0.035)
Cash $\text{flow}_{i,t-1}$				0.488***	0.641***	1.336***	1.508***
				(0.165)	(0.205)	(0.371)	(0.368)
ln(Total $\text{assets}_{i,t-1}$)				0.018	0.021	-0.009	0.063
				(0.043)	(0.075)	(0.073)	(0.084)
Long term $\text{debt}_{i,t-1}$				-0.762***	-0.809***	-0.710***	-0.803***
				(0.208)	(0.218)	(0.223)	(0.495)
$\ln(\text{Age}_{i,t-1})$				-0.736**	-0.576	-0.497	-0.727
				(0.352)	(0.378)	(0.393)	(0.495)
Sales $\text{gwth}_{i,t-1}$				-0.026	-0.050*	-0.053	-0.155***
				(0.021)	(0.027)	(0.064)	(0.059)
$\sum$ ln(C)					0.080**	0.112***	0.130**
					(0.015)	(0.006)	(0.021)
Firm fixed effects	No	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	No	No	No	No	No
Industry x Year effects	No	No	Yes	Yes	Yes	Yes	Yes
Firm controls	No	No	No	Yes	Yes	Yes	Yes
Observations	9,839	9,043	7,869	6,242	5,477	4,681	3,653
Adjusted R^2	0.040	0.453	0.443	0.449	0.459	0.478	0.481

Table 4 reports OLS estimates of Equation 1. *ln(Inv)*$_{i,t}$ is the dependent variable. *Inv* is the capital expenditure to sales ratio for firm i in year t. C is the cost of emitting CO_2 divided by sales for firm i in year t. The sample comprises Swedish manufacturing firms (NACE: 1000–3300) with capital expenditure and CO_2 emissions data during 2000–2019. Regressions in columns 2–7 include firm fixed effects. Regressions in columns 1–2 include year fixed effects and columns 3–7 include four digit industry-year fixed effects. Regressions in columns 4–7 include the following firm control variables: *Cash flow*$_{i,t-1}$, *ln(Total assets)*$_{i,t-1}$, *Long term debt*$_{i,t-1}$, *ln(Age*$_{i,t-1}$*)* and *Sales gwth*$_{i,t-1}$. The standard errors are clustered at the firm level. $\sum \Delta\ln(C)$ present an F-test of joint significance. ***, **, and * indicate significance at the 1%, 5%, and 10% levels.

Table 5: Carbon pricing and firm level capital investment: By decile

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	D1–D4		**D5–D8**		**D9–D10**		**D10**	
$\ln(C_{i,t})$	0.046	0.066	0.018	-0.002	0.149***	0.200***	0.189***	0.186***
	(0.036)	(0.047)	(0.040)	(0.058)	(0.056)	(0.065)	(0.056)	(0.070)
$\ln(C_{i,t-1})$		-0.004		0.034		0.066		0.018
		(0.056)		(0.050)		(0.082)		(0.085)
$\ln(C_{i,t-2})$		0.026		-0.019		0.082**		0.085**
		(0.053)		(0.067)		(0.036)		(0.034)
$\ln(C_{i,t-3})$		-0.032		0.075		-0.043		-0.038
		(0.058)		(0.054)		(0.069)		(0.082)
$\sum \ln(C)$		0.056		0.088		0.305***		0.251**
		(0.569)		(0.252)		(0.002)		(0.023)
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry x Year effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Firm controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	2,693	1,495	2,457	1,401	1,084	757	643	481
Adjusted R^2	0.419	0.437	0.474	0.502	0.480	0.548	0.486	0.513

Table 5 reports OLS estimates of Equation 1. $ln(Inv)_{i,t}$ is the dependent variable. *Inv* is the capital expenditure to sales ratio for firm i in year t. C is the cost of emitting CO_2 divided by sales for firm i in year t. The sample comprises Swedish manufacturing firms (NACE: 1000–3300) with capital expenditure and CO_2 emissions data during 2000–2019. D1–D4 include firms from the four-digit industries with emissions to sales in 1990 in the lowest 40%, D5–D8 from four-digit industries from the 5th to the 8th decile in terms of emissions intensity, D9–D10 include firms from the highest 20% (i.e., the two highest deciles) and D10 include firms from the highest 10% (i.e., the highest decile). All regressions include firm and four digit industry-year fixed effects and the following firm control variables: $Cash\ flow_{i,t-1}$, $ln(Total\ assets)_{i,t-1}$, $Long\ term\ debt_{i,t-1}$, $ln(Age_{i,t-1})$ and $Sales\ gwth_{i,t-1}$. The standard errors are clustered at the firm level. $\sum \Delta\ln(C)$ present an F-test of joint significance. ***, **, and * indicate significance at the 1%, 5%, and 10% levels.

Table 6: Carbon pricing and firm level abatement investment

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
		Abate Inv		Share Abate Inv		Non Abate Inv	
$\ln(C_{i,t})$	0.220**	0.297***	0.039	0.175	-0.121	0.137***	0.091
	(0.088)	(0.101)	(0.112)	(0.107)	(0.136)	(0.044)	(0.060)
ln(C) X D10			0.578***		0.550***		0.085
			(0.158)		(0.179)		(0.087)
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry x Year effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Firm controls	No	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1,239	1,025	1,025	815	815	795	795
Adjusted R^2	0.369	0.375	0.389	0.260	0.272	0.477	0.477

Table 6 reports OLS estimates of Equation 1. *ln(Abate Inv)*$_{i,t}$ is the dependent variable in columns 1–3, where *Abate Inv* is the abatement capital expenditure to sales ratio for firm i in year t. *ln(Share Abate Inv)*$_{i,t}$ is the dependent variable in columns 4–5, where *Abate Inv* is the share of abatement capital investment out of total capital investment for firm i in year t. *ln(Non Abate Inv)*$_{i,t}$ is the dependent variable in columns 4–5, where *Non Abate Inv* is the non abatement capital investment to sales ratio for firm i in year t. *MC* is the cost of emitting CO_2 divided by sales for firm i in year t. *D10* is an indicator variable taking on the value one if the firm is located in a four-digit industry with emissions to sales in 1990 in the highest 10% (i.e., the highest decile). The sample comprises Swedish manufacturing firms (NACE: 1000–3300) with capital expenditure, abatement investment and CO_2 emissions data during 2002–2019. All regressions include firm and four digit industry-year fixed effects and the following firm control variables: *Cash flow*$_{i,t-1}$, *ln(Total assets)*$_{i,t-1}$, *Long term debt*$_{i,t-1}$, *ln(Age*$_{i,t-1}$*)* and *Sales gwth*$_{i,t-1}$. The standard errors are clustered at the firm level. ***, **, and * indicate significance at the 1%, 5%, and 10% levels.

Table 7: Carbon pricing and R&D investment

	(1)	(2)	(3)	(4)	(5)	(6)
	R&D Inv			Abate R&D Inv		
$\ln(C_{i,t})$	-0.033	0.034	-0.007	0.485**	0.496	-0.197
	(0.049)	(0.048)	(0.048)	(0.237)	(0.304)	(0.271)
ln(C) X D10			0.364***			0.890**
			(0.108)			(0.478)
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Industry x Year effects	Yes	Yes	Yes	Yes	Yes	Yes
Firm controls	No	Yes	Yes	Yes	Yes	Yes
Observations	1,200	830	830	181	152	152
Adjusted R^2	0.771	0.834	0.838	0.761	0.720	0.730

Table 7 reports OLS estimates of Equation 1. $ln(R\&D)_{i,t}$ is the dependent variable in columns 1–3, where *R&D* is the R&D to sales ratio for firm i in year t. $ln(Abate\ R\&D)_{i,t}$ is the dependent variable in columns 4–6, where *Abate R&D* is the abatement R&D expenditure to sales ratio for firm i in year t. C is the cost of emitting CO_2 divided by sales for firm i in year t. *D10* is an indicator variable taking on the value one if the firm is located in a four-digit industry with emissions to sales in 1990 in the highest 10% (i.e., the highest decile). The sample comprises Swedish manufacturing firms (NACE: 1000–3300) with R&D and CO_2 emissions data during 2000–2019 in columns 1–3 and with abatement R&D and CO_2 emissions data during 2002–2019 in columns 4–6. All regressions include firm and four digit industry-year fixed effects and the following firm control variables: $Cash\ flow_{i,t\text{-}1}$, $ln(Total\ assets)_{i,t\text{-}1}$, $Long\ term\ debt_{i,t\text{-}1}$, $ln(Age_{i,t\text{-}1})$ and $Sales\ gwth_{i,t\text{-}1}$. The standard errors are clustered at the firm level. ***, **, and * indicate significance at the 1%, 5%, and 10% levels.

Table 8: Carbon pricing and firm level capital investment: Value of EU ETS allowances

	(1)	(2)	(3)	(4)
	All		D10	
$\ln(C_{i,t})$	0.059**	0.074**	0.183***	0.171**
	(0.025)	(0.035)	(0.055)	(0.068)
$\ln(C_{i,t-1})$		0.019		0.025
		(0.038)		(0.083)
$\ln(C_{i,t-2})$		0.030		0.068*
		(0.032)		(0.034)
$\ln(C_{i,t-3})$		0.008		-0.060
		(0.035)		(0.075)
ln(Value allowances$_{i,t}$)	0.002	0.011	5.899*	8.708***
	(0.006)	(0.014)	(3.251)	(2.125)
ln(Value allowances$_{i,t-1}$)		0.041***		4.783
		(0.013)		(3.429)
ln(Value allowances$_{i,t-2}$)		0.049**		-1.362
		(0.019)		(3.144)
ln(Value allowances$_{i,t-3}$)		0.094**		0.763
		(0.042)		(4.046)
$\sum$ ln(C)		0.131**		0.204**
		(0.020)		(0.038)
$\sum$ (Value allowances)		0.195***		12.892**
		(0.007)		(0.027)
Firm fixed effects	Yes	Yes	Yes	Yes
Industry x Year effects	Yes	Yes	Yes	Yes
Firm controls	Yes	Yes	Yes	Yes
Observations	6,242	3,653	643	481
Adjusted R^2	0.449	0.481	0.490	0.527

Table 8 reports OLS estimates of Equation 1. *ln(Inv)*$_{i,t}$ is the dependent variable. *Inv* is the capital expenditure to sales ratio for firm i in year t. C is the cost of emitting CO_2 divided by sales for firm i in year t. *Value allowances* is (nr of free emissions allowances - EU ETS regulated CO_2 emissions) x EUA price divided by sales for firm i in year t. The sample comprises Swedish manufacturing firms (NACE: 1000–3300) with capital expenditure and CO_2 emissions data during 2000–2019. All regressions include firm and four digit industry-year fixed effects and the following firm control variables: *Cash flow*$_{i,t-1}$, *ln(Total assets)*$_{i,t-1}$, *Long term debt*$_{i,t-1}$, *ln(Age*$_{i,t-1}$*)* and *Sales gwth*$_{i,t-1}$. The standard errors are clustered at the firm level. $\sum$ ln(C) present an F-test of joint significance. ***, **, and * indicate significance at the 1%, 5%, and 10% levels.

Table 9: Quantification of estimation results

	(1)	(2)	(3)	(4)	(5)	(6)
	Percent change in marginal cost		**Predicted percent change**		**Predicted change to actual change**	
	2000-2010	**2011-2019**	**D10**	**D1–D9**	**D10**	**D1–D9**
Actual marginal cost for average sample firm	8%	239%	45%	9%	72%	44%
Marginal cost had all firms faced Swedish carbon tax	4%	250%	47%	9%	75%	46%
Marginal cost had all firms faced carbon price as EU ETS firms	56%	120%	23%	4%	36%	22%

Table 9 reports the percent change in marginal cost for the average sample firm between 2000–2010 (in column 1) and between 2011–2019 (in column 2). The predicted percent change is product between the increase reported in column 2 and the estimated elasticity of decile 10 firms (in column 3) and for deciles 1–9 firms (in column 4). The predicted change to actual change is the ratio between the predicted change in column 3 (4) and the actual percent increase in investment sales for decile 10 (decile 1–9) firms. The actual, aggregate investment to sales increase for decile 10 (decile 1–9) firms is 63% (20%). The first row uses the actual marginal cost changes for the average sample firm. The second row considers the scenario if all sample firms faced the same marginal cost as the firms that only face the Swedish carbon tax. And, the third row consider the case if all firms would have faced the marginal cost of the EU ETS firms.

A Appendix

We build our sample data based on several sources. The study is based on administrative data on manufacturing Swedish limited liability companies (Swedish: Aktiebolag) from 1999 to 2020. The Swedish Companies Registration Office (SCRO) (Swedish: Bolagsverket) assigns each Swedish limited liability company an unique and permanent identifier entitled organization number. We link the data using the unique identifier by years. Due to privacy policy, all real identifiers related to micro objects are removed, the data is anonymized and handled by Statistics Sweden (SCB).

Firm-level financial data: First, we get accounting data of Swedish limited liability companies from Bisnode Serrano database. This database integrates financial information from balance sheets, income statements, bankruptcy records, as well as NACE Rev.2 industrial classifications from 1998 to 2020. All variables are converted into the respective calendar year. Since firms can switch industrial sectors during our research period, we take the latest 5-digit industrial classification codes (NACE Rev.2) to make it consistent across time.

We build a consolidated dataset at the group and year level by integrating the accounting variables within the same group. We merge accounting variables with corporate structure data from the knc file of serrano database. Each firm identity in a specific year is linked to a unique parent company identifier. In the absence of a group identity, we replace it with the firm's organization number and consider it as an independent entity. We establish coherent NACE Rev.2 for group using the classification of the subsidiary with the most sales or employees. If no entity provides NACE2007 information based on sales or employees, we choose the most recent one among the group. All required values are deflated by Consumer Price Index (CPI), and Swedish Producer Price Index (PPI) at four-digit NACE Rev.2 level with the base year of 2020. For a stand-alone firm, the consolidated figure will be its own value; for firms matched with corporate structure file, we aggregate figures of all subsidiaries within the same group.

General investments data: We have firm-level general investment data from the survey conducted by Statistics Sweden (SCB). This data contains information on implemented and planned general investments from 2000 to 2019, which is aligned with the European System of Accounts (ESA) framework. The investments are categorized into (a) buildings and facility, (b) machinery and equipment, and (c) housing for only real estate companies (NACE Rev.2 sector 68). Table A.2 provides an overview of the sample selection criteria over time based on data description documents from SCB. Table A.3 provides information on sample size with observable investments, which is between 4,100 and 4,900, with an average of 4,600 firms. Figure A.1 displays the coverage of micro data to the aggregated public investments in manufacturing sectors provided by Statistics Sweden.

Environmental investments data: We obtain firm-level environmental expenditures from the survey conducted by Statistics Sweden (SCB), which adheres to EU Regulation [14] and utilizes the accounting system for environmental protection expenditure defined by Eurostat. This dataset consists of firms' environmental investment statistics from 2002 to 2019. The survey includes all firms with 250 or more employees and a selection of firms with 50-249 employees. Surveyed firms are required by law to provide data to SCB (Lag (2001:99) om den officiella statistiken, 7 §). Accordingly on average,

[14] Regulation (EU) No 691/2011 of the European Parliament and of the Council of 6 July 2011 on European environmental economic accounts, https://eur-lex.europa.eu/eli/reg/2011/691/oj

88.5 % of the surveyed firms in the years 2002-2019 complete the survey.[15] Environmental investments encompass expenditures aimed at reducing or treating pollution. This includes the total expenditure when the sole purpose or direct function is environmental protection (e.g., end-of-pipe equipment or the environmental adaptation of existing equipment). Partial expenditures are considered when a part of the equipment or machinery serves an environmental function and can be separately identified; in such cases, only the cost for that specific part is classified as an environmental investment (e.g., a catalytic converter in a car). Marginal costs related to environmental benefits of an investment are included when a decision has been made to purchase more expensive, environmentally beneficial equipment compared to standard alternatives. The additional cost attributable to these environmental benefits is regarded as part of the environmental investment. If the primary purpose of the equipment is environmental protection but the environmental component cannot be separately estimated, total costs are used as a proxy for environmental investment. Conversely, expenditures are excluded from environmental protection investment if the primary purpose is not environmental protection and the environmental component cannot be estimated separately.[16]

R&D expenditures: The data of business R&D expenses are derived from two sources. i. we have annual total R&D expenses of firms using functional accounting, from the bokslut file in Serrano database; ii. we get biennial R&D data for business sectors from the survey conducted by Statistics Sweden (SCB). The R&D questionnaire contains various components, such as external and internal costs, different funding sources, usages, and anticipated R&D values. This survey ranges from 1997 to 2021. Table A.6 shows the selection thresholds over time, we have around 460 manufacturing firms with valid R&D expenses on yearly average. Figures A.2 and A.3, which are segmented by internal and outsourced R&D expenses, illustrate how our sample data compares to the publicly available aggregated data released by SCB.

To get observable values for even years, we assume that the total external and internal R&D expenditures follow linear trends within the same firm in adjacent years. We generate imputed values by filling in the gaps with the average values of adjacent years when the values are either 0 or missing. We solve fewer than fifty percent of the value gaps by this approach, since larger firms exist the entire time, while smaller ones are rolling depending on the selection cut-off. Additionally, we consider values from accounting type F and K3 firms as benchmarks. If a firm with F(K3) accounting type has a zero total external or internal R&D expense and a missing R&D value from the questionnaire, we replace the missing value with zero. Figure A.2 displays the process of establishing imputed values for data from the questionnaire. Table A.7 exhibits the sample size with observable R&D expenses (both raw and imputed), we have more than 10,000 firms including estimated values on yearly average, which covers around 75% of aggregated R&D expenses of Swedish manufacturing sectors.

The R&D variables at firm level apply functional accounting, which is comparable to the sum of external and internal R&D expenditures from the questionnaire. However, the number of firms using functional accounting declined dramatically since 2014, According to Swedish Annual Accounts Act (Årsredovisningslag) Justitiedepartementet L1 (b) and Accounting Board's Guidance

[15]The detailed information the survey, including lapse can be found here [in Swedish]: https://www.scb.se/hitta-statistik/statistik-efter-amne/miljo/miljoekonomi-och-hallbar-utveckling/miljoskyddskostnader/. An example of the web survey used for abatement investments in year 2019 can be found here [in Swedish] https://www.scb.se/contentassets/5c671de894c247a7aa6560cdb0b06e34/mi1302_staf_2019_ml_201014.pdf

[16]For a decision tree see: https://www.scb.se/contentassets/f7af32625bdd49f6be7b747299c23d3e/tf_off2000.pdf

(Bokföringsnämndens vägledninga, 2012:1 Justitiedepartementet L1 (a)) , the updated accounting framework entitled K3 has been made obligatory for larger companies since January 1, 2013.[17] Firms are defined as larger at current year if two of the same conditions have been fulfilled in the last two consecutive years: (i. the average number of employees are at least 50; (ii. the average balance sheet total (Balansomslutning, common name for total assets in Swedish) are at least 40 million SEK; (iii. the average sales are at least 80 million SEK (Bokföringsnämndens vägledninga, 2012:1 Justitiedepartementet L1 (a)). We consider K3 firms which fulfill these criteria as F firms to solve the drastically decreased sample.

Emission data: We acquire annual CO2 emissions at installation level from 1990 to 2021 from Environmental Protection Agency (SEPA). We also have CO2 emissions and allowances at installation level from EU emissions trading system (EU ETS) since 2005. Below we describe our steps to process the emission data.

1. Firstly, we collect Swedish carbon tax rates and generate primary carbon tax payments by multiplying applicable tax rate with corresponding carbon emissions. We measure average cost and marginal cost incurred by firms when emitting an extra unit of CO2 using the summarized tax scheme and approach developed by Martinsson et al. (2024). In our research period, manufacturing sectors were subjected to the "0.8% rule" from 1997 to 2006, which indicated that firms paid carbon tax with a maximum of 0.8% of their sales, and 25% of the initial marginal tax rate was applied to the exceeding part of the payments. Subsequently, the exemption cap was raised from 0.8% to 1.2% during 2011 to 2014, and then was eliminated in 2015. While for high-emitting sectors as cement and glass lime, the highest possible payment is 1.2% of sales until 2007, see Table 1 by Martinsson et al. (2024) for details.

2. The European Union Emissions Trading Scheme (EU ETS) comprises four distinct phases. We assess if the firm qualifies for EU ETS exemptions for each phase in accordance with the established rules specific to industrial sectors. We acquire EU ETS emissions and free allowances data since 2005 from the European Union Transaction Log and link it with our sample data. We develop a dummy identifier to track firms that have ever been part of the EU ETS. At the consolidated-group level, we consider the group under EU ETS if at least one subsidiary belongs to the system. The marginal costs of emissions for installations under EU ETS align with the sum of the carbon tax rate and allowance prices since 2008. Then we aggregate total CO2 emissions, EU ETS emissions and sum of allowances, CPI-deflated carbon tax payments, weighted marginal costs and allowance prices by sales and tangible fixed assets at group level.

3. As SEPA only collects emissions on bigger installations from 2003 to 2006, we have relatively fewer observations during this period (see Table A.9). We follow the same approach as we developed for R&D expenditure to solve this issue. With the assumption that the emission intensity within a firm between 2002 and 2007 is linear, we interpolate missing values if there are at least two observable emissions, i.e., neither missing or zero during this period. We further multiply the imputed emission intensity by deflated sales to scale the imputed emissions. Finally,

[17] If a company prepares fiscal annual report including information of year 2014, it needs to adopt the new accounting standards and principles starting from January 1, 2013, to ensure consistency in the presentation of comparable statistics. The implementation date has been extended to January 1, 2014 for smaller firms which have no need to modify comparative values (Bokföringsnämndens vägledninga, 2012:1 Justitiedepartementet L1 (a)).

we integrate data on specific sectors identified as being at a high risk of carbon leakage, and produce decile dummy variables based on ascending-sorted emission intensity in 1990 at four-digit industrial level, see Martinsson et al. (2024) for details.

Finally, We link data of general investments, environmental investments, biennial R&D expenditures, accounting R&D expenses and accounting values for all manufacturing firms by organization numbers and years. Our sample data is from 1999 to 2020 and at unit of firm and year level.

A.1 Additional Tables and Figures

Table B.1: Some robustness

	(1)	(2)	(3)	(4)	(5)
	Inv		Inv Scaled TA	Inv unscaled	Uncons-olidated
$\ln(C_{i,t}$ - Sales weighted)	0.065***				
	(0.023)				
$\ln(C_{i,t}$ - Fixed assets weighted)		0.072***			
		(0.021)			
$\ln(C_{i,t}$ - Scaled by Total assets)			0.063**		
			(0.025)		
$\ln(C_{i,t})$				0.050*	
				(0.029)	
$\ln(C_{i,t}$ - Unconsolidated)					0.044***
					(0.017)
Firm fixed effects	Yes	Yes	Yes	Yes	Yes
Industry x Year effects	Yes	Yes	Yes	Yes	Yes
Firm controls	Yes	Yes	Yes	Yes	Yes
Observations	6,242	6,154	6,242	6,242	10,621
Adjusted R2	0.450	0.435	0.461	0.802	0.401

Table B.1 reports OLS estimates of Equation 1. *ln(Inv)*$_{i,t}$ is the dependent variable in columns 1–2, where *Inv* is the capital expenditure to sales ratio for firm i in year t. *ln(Inv Scaled TA)*$_{i,t}$ is the dependent variable in column 3, where *Inv Scaled TA* is the capital expenditure to total assets ratio for firm i in year t. *ln(Inv unscaled*$_{i,t}$ is the dependent variable in column 4, where *Inv unscaled* is the capital expenditure for firm i in year t. *C - Sales weigthed* is the unconsolidated firm sales weighted cost of emitting CO_2 divided by sales for firm i in year t. *C - Fixed assets weigthed* is the unconsolidated firm fixed assets weighted cost of emitting CO_2 divided by sales for firm i in year t. *C - Scaled by TA* is the cost of emitting CO_2 divided by total assets for firm i in year t. The sample comprises Swedish manufacturing firms (NACE: 1000–3300) with capital expenditure and CO_2 emissions data during 2000–2019. All regressions include firm and four digit industry-year fixed effects and the following firm control variables: *Cash flow*$_{i,t-1}$, *ln(Total assets)*$_{i,t-1}$, *Long term debt*$_{i,t-1}$, *ln(Age*$_{i,t-1}$) and *Sales gwth*$_{i,t-1}$. The standard errors are clustered at the firm level. ***, **, and * indicate significance at the 1%, 5%, and 10% levels.

Table B.2: Carbon pricing and firm level capital investment: Robustness deciles

	(1)	(3)	(5)	(7)
	D1–D4	**D5–D8**	**D9–D10**	**D10**
$\ln(C_{i,t})$	0.067	0.021	0.236***	0.205***
	(0.050)	(0.055)	(0.056)	(0.059)
Firm fixed effects	Yes	Yes	Yes	Yes
Industry x Year effects	Yes	Yes	Yes	Yes
Firm controls	Yes	Yes	Yes	Yes
Observations	1,495	1,401	757	481
Adjusted R^2	0.439	0.502	0.547	0.514

Table B.2 reports OLS estimates of Equation 1. $ln(Inv)_{i,t}$ is the dependent variable. *Inv* is the capital expenditure to sales ratio for firm i in year t. C is the cost of emitting CO_2 divided by sales for firm i in year t. The sample comprises Swedish manufacturing firms (NACE: 1000–3300) with capital expenditure and CO_2 emissions data during 2000–2019 and with firm-years in C in four consecutive years. D1–D4 include firms from the four-digit industries with emissions to sales in 1990 in the lowest 40%, D5–D8 from four-digit industries from the 5th to the 8th decile in terms of emissions intensity, D9–D10 include firms from the highest 20% (i.e., the two highest deciles) and D10 include firms from the highest 10% (i.e., the highest decile). All regressions include firm and four digit industry-year fixed effects and the following firm control variables: $Cash\ flow_{i,t-1}$, $ln(Total\ assets)_{i,t-1}$, $Long\ term\ debt_{i,t-1}$, $ln(Age_{i,t-1})$ and $Sales\ gwth_{i,t-1}$. The standard errors are clustered at the firm level. ***, **, and * indicate significance at the 1%, 5%, and 10% levels.

Table B.3: Carbon pricing and firm level capital investment: EU Leakage list

	(1)	(2)	(3)	(4)
	Leakage list		Leakage list Yes	
	No	Yes	Trade only	Emission
$\ln(C_{i,t})$	0.045	0.072**	0.054	0.107**
	(0.035)	(0.035)	(0.049)	(0.044)
Firm fixed effects	Yes	Yes	Yes	Yes
Industry x Year effects	Yes	Yes	Yes	Yes
Firm controls	Yes	Yes	Yes	Yes
Observations	3,349	2,893	2,175	718
Adjusted R^2	0.439	0.467	0.446	0.384

Table B.3 reports OLS estimates of Equation 1. $ln(Inv)_{i,t}$ is the dependent variable. *Inv* is the capital expenditure to sales ratio for firm i in year t. C is the cost of emitting CO_2 divided by sales for firm i in year t. The sample comprises Swedish manufacturing firms (NACE: 1000–3300) with capital expenditure and CO_2 emissions data during 2000–2019. All regressions include firm and four digit industry-year fixed effects and the following firm control variables: *Cash flow*$_{i,t\text{-}1}$, *ln(Total assets)*$_{i,t\text{-}1}$, *Long term debt*$_{i,t\text{-}1}$, *ln(Age*$_{i,t\text{-}1}$*)* and *Sales gwth*$_{i,t\text{-}1}$. The standard errors are clustered at the firm level. ***, **, and * indicate significance at the 1%, 5%, and 10% levels.

Table B.4: Carbon pricing and firm level capital investment: Abatement investment sub-sample

	(1)	(2)	(3)	(4)
$\ln(C_{i,t})$	0.115***	0.083***	0.160***	0.163***
	(0.019)	(0.025)	(0.049)	(0.040)
Firm fixed effects	No	Yes	Yes	Yes
Year fixed effects	Yes	Yes	No	No
Industry x Year effects	No	No	Yes	Yes
Firm controls	No	No	No	Yes
Observations	2,046	1,845	995	815
Adjusted R^2	0.046	0.498	0.488	0.474

Table B.4 reports OLS estimates of Equation 1. *ln(Inv)*$_{i,t}$ is the dependent variable. *Inv* is the capital expenditure to sales ratio for firm i in year t. C is the cost of emitting CO_2 divided by sales for firm i in year t. The sample comprises Swedish manufacturing firms (NACE: 1000–3300) with capital expenditure, abatement investment and CO_2 emissions data during 2002–2019. Regressions in columns 2–4 include firm fixed effects. Regressions in columns 1–2 include year fixed effects and columns 3–4 include four digit industry-year fixed effects. Regression in column 4 includes the following firm control variables: *Cash flow*$_{i,t-1}$, *ln(Total assets)*$_{i,t-1}$, *Long term debt*$_{i,t-1}$, *ln(Age*$_{i,t-1}$*)* and *Sales gwth*$_{i,t-1}$. The standard errors are clustered at the firm level. ***, **, and * indicate significance at the 1%, 5%, and 10% levels.