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Access to finance and corporate emissions: A distributional perspective

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Abstract

We examine the relationship between capital structure and carbon intensity in manufacturing firms using a novel dataset that combines information from the EU Emission Trading System with firm-level financial accounts. Our findings indicate that higher financial leverage is associated with lower emission intensity at the firm level, primarily due to long-term debt, suggesting that improving access to such finance is generally conducive to corporate emissions reductions. However, this effect varies along the carbon intensity distribution. For firms with very high carbon intensity, increased leverage is linked to significant reductions in emissions, suggesting that better access to finance can facilitate the adoption of green technologies. Conversely, for firms that are already relatively carbon efficient, the effect disappears.

Keywords: low-carbon transition; climate change; debt finance; financial leverage; EU ETS
JEL: C58, G32, Q51, Q56, Q58

1. Introduction

The European Union (EU) has embarked on an ambitious path to make its economy carbon neutral by 2050, with an intermediate target of at least 55% reduction of net Greenhouse Gas (GHG) emissions by 2030, compared to 1990 levels. More recently, the ambition has been further strengthened by a recommendation to introduce a target of 90% net GHG reduction by 2040, which is in line with recent scientific advice and the EU's commitments under the Paris Agreement (European Commission, 2024). While clear progress is being made to reach these targets, recent evidence demonstrates that it has been predominantly driven by the power sector through a switch to renewable energy sources or less carbon-intensive fuels. Even though the manufacturing sector managed to reduce its carbon footprint, progress has been slower (EIB, 2024; Bijnens and Swartenbroekx, 2020). In fact, since 2019 manufacturing sector has been the single biggest contributor to the EU GHG emissions, surpassing

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power generation and households.[1]

The high carbon footprint of EU manufacturing firms is not only a source of concern for the green transition but also for EU competitiveness. For instance, the 2022 energy price shock affected primarily the producer prices of carbon-intensive sectors (EIB, 2024). It is not surprising therefore that the decarbonization of industry has received increased attention from policy makers (European Commission, 2023).[2] From a welfare perspective, it is the carbon intensity which matters as, in principle, lower emission levels should not come at a cost of reduced industrial output. Lowering the amount of GHG emissions per unit of output, is therefore an important aspect of the delivery of the European climate pledges in a socially fair way.

This study contributes to our understanding of the relationship between external finance and carbon intensity. We highlight that higher financial leverage is associated with lower carbon intensity and that long-term finance is particularly effective in reducing firm-level carbon intensity over time. In this context, we also show that firms, which can be considered as financially constrained, display 28 to 33% higher carbon intensity than other peers operating in the same sector.

Nonetheless, financial leverage is not a remedy for high carbon intensity. Despite the fact that extra debt can help firms to improve their carbon intensity over time, at excessive levels of debt, this improvement is slower compared to sector peers. This seems to be related to the fact that long-term debt is negatively correlated with carbon intensity primarily for highly carbon-intensive firms, implying that the marginal benefits of additional debt decrease as firms become more carbon-efficient. It seems therefore that while plain-vanilla long-term debt can facilitate the adoption of green technologies, its effectiveness diminishes for firms for which further decarbonization requires the development of new technologies.

Our study is built on the sample of manufacturing firms controlling at least one installation regulated under the EU Emission Trading System (ETS). The ETS regulation sets that, for a group of the biggest European emitters, each ton of emission needs to be covered by an equivalent emission certificate, as otherwise a firm would be fined. The total number of certificates is set by a regulator and decreases over time to align with the European climate objectives. Emission certificates are distributed among the regulated entities, either for free or through auctions, which are allowed to trade the certificates based on their emission and production needs.

There are three important advantages of using the ETS as an empirical playground. Firstly, the ETS covers an important share of European emissions. As of 2022, the ETS covered more than 14,500 installations in the energy and industrial sectors, as well as aviation and maritime transport. These sectors alone covered around 37% of the EU's GHG emissions in 2022. There are around 3,000 manufacturing installations which alone represent 59% of all the emissions attributed to the manufacturing sector in the EU27 in 2022. Secondly,

[1] In 2022 manufacturing sector contributed 22% of the EU GHG emissions, followed by power production with 20% and households with 19%.

[2] A comprehensive approach to boost net-zero industry was presented in the Green Deal Industrial Plan. It includes the Net-Zero Industry Act, which underpins industrial manufacturing of key technologies, and the European Critical Raw Materials Act, which secures a sustainable and competitive critical raw materials value chain in Europe.

even though it focuses on direct emissions only (Scope 1), the reported figures are audited therefore adding to the credibility and quality of the series. Last but not least, the ETS includes both listed and non-listed firms. This adds an extra layer of smaller entities to the analysis, which are often under the radar of climate reporting obligations and therefore unavailable in other databases. Overall, our data set consists of 2,682 manufacturing firms, for which we collect granular financial accounts between 2008 and 2020 from Orbis. We complement the data with the EIB Investment Survey to provide better understanding of financial constraints in the sample.

The data set offers unique insights into the heterogeneity of the decarbonization progress in the ETS manufacturing sector. We document that, except for refinery products, more than 25% of firms in each of the ETS manufacturing sectors increased their carbon intensity between 2013 and 2020. These firms are not only different in terms of emissions, but they also report lower investment and financial leverage. We take this observation as the main motivation for this study and we examine deeper the relationship between external finance and emission intensity, controlling for firm-level observed and unobserved heterogeneity.

Our empirical approach distinguishes between the effects of financial leverage on carbon intensity within a representative sector, and for a representative firm in the sample. More specifically, our panel regressions include different sets of fixed effects, such that the explanatory power of the coefficients comes from a variation of variables within a given sector-country-year data cut, or from a variation of variables within an average firm over time. Furthermore, controlling for sector fixed effects allows to filter out the unobserved effects which do not change over time but are different across sectors, such as technological availability or regulations.

Our results show that the low-carbon benefits of external finance are spread unevenly across firms. We search for a possible explanation in a quantile regression setup, whereby the effects are estimated for firms at different quantiles of carbon intensity distribution. To control for the unobserved country-sector-year and firm-level heterogeneity, we absorb the relevant fixed effects using the Mundlak (1978) method in a pooled quantile regression. We find that the long-term debt ratio is negatively correlated with carbon intensity but only at higher quartiles of the distribution. In other words, external finance can help in bringing down carbon intensity but only for very carbon intensive firms. As firms become more carbon efficient, the marginal benefits from an extra unit of debt decrease, up until the point when they become negligible for very carbon-efficient firms. This pattern holds for the distribution of carbon intensity within a representative sector but also for a representative firm over time.

The results are consistent with the innovative character of the green transition in the ETS, pointing to the benefits of long-term finance to the diffusion of green technology. For firms at higher percentiles of the carbon intensity distribution, the distance to the carbon-efficient firms is larger allowing for larger benefits from technology adoption (Rogers, 2003). Similarly, the higher the percentile of carbon intensity, the higher the chance of observing a firm producing similar products using more carbon-efficient technology. These conditions make the adoption of the technology more predictable, and therefore bankable, which improves the chances to meet the criteria of traditional debt financing contracts.

From the policy perspective, the results suggest that while external finance can help firms to prepare for the low-carbon future and to distribute green technologies within sector, debt-driven decarbonization is not enough to deliver on the broader climate ambitions. Adequate financial solutions need to support the entire technology development process from early innovation and technological breakthroughs, through the scale up, to technology diffusion. While long-term debt seems to help with green technology adoption, it is risk-sharing capital which helps to develop and scale up the technology. For instance, De Haas and Popov (2022) argue that deeper stock markets and the provision of equity capital facilitate green innovation in carbon-intensive sectors, resulting in lower carbon emissions per unit of output. This is consistent with Kellard et al. (2023), who find that green innovation is particularly strong among equity-based rather than bank-based economies. On top of deeper equity markets, subsidies can be another important instrument to alleviate the technological uncertainty and spur low-carbon innovation (Hasna et al., 2023).

The paper is structured as follows. Section 2 irons out the research question on the background of a few stylized facts from the ETS data. It also aligns the research direction with the growing body of literature on decarbonization and access to finance. Section 3 lays out our empirical strategy and Section 4 discusses the data. The results are presented in Section 5 and Section 6 concludes.

2. Motivation and snapshot of the literature

One of the cornerstones of the EU's green agenda has been the EU Emissions Trading System (ETS), as a key tool for reducing GHG emissions cost-effectively across the EU. The ETS has been in operation since 2005 and has gone through four phases of development, with changes in scope, emission cap, and allocation rules[3] Since the launch of the system, the regulated sectors have achieved significant emissions reductions, mainly driven by the electricity generation sector, which cut its GHG emissions by 30% between 2013 and 2020. This reduction could be attributed to the increased use of renewable energy sources and the switch to less carbon-intensive fossil fuels (EIB, 2024). However, the manufacturing sector has shown less progress in decarbonizing its activities, with a nearly 15% drop in total emissions between 2013 and 2020.

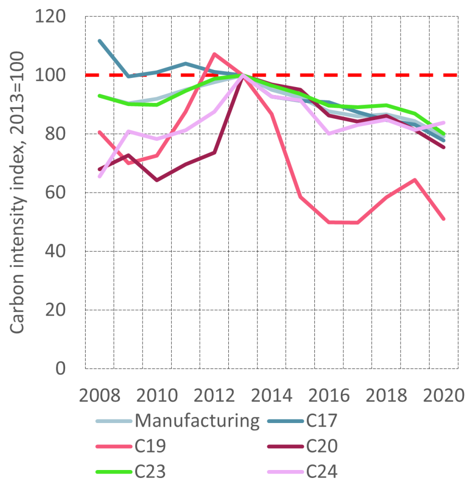
The drop in carbon footprint among manufacturing firms is reflected in an overall improvement of carbon intensity, suggesting that decarbonization occurs through improved means of production rather than decreased output. When looking at the median carbon intensity of manufacturing firms, defined as the sum of emissions from all company-owned ETS installations divided by the real value added created by the company, it improved between 2013 and 2020 by approximately 20% (Figure 1a). The improvement is visible for all ETS manufacturing subsectors, but it is the strongest among refineries (subsector code C19) and the weakest among metal producers (subsector code C24).

However, the distribution of firm-level decarbonization progress within each subsector paints a more nuanced picture. With the exception of refineries, more than 25% of firms in each of the ETS subsectors increased the intensity of carbon between 2013 and 2020 (Figure 1b). Furthermore, there are a few firms which experienced a substantial deterioration in carbon intensity over the same period, as exemplified by average changes exceeding the median, or even the 3rd quartile, changes in carbon intensity over the period. These firms

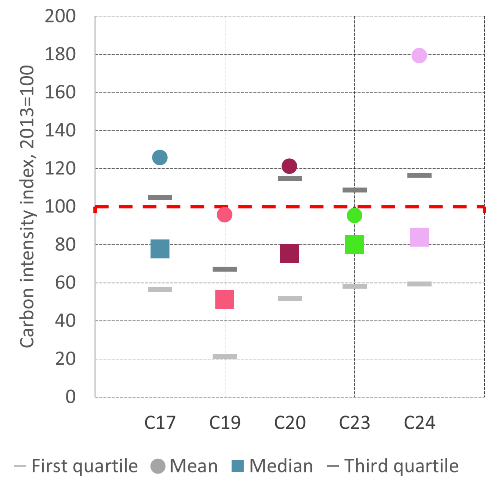
[3] For the detailed introduction to the ETS and its functioning see, for instance, Dechezleprêtre et al. (2023).

can constitute potential pockets of vulnerability as they will be particularly exposed to more ambitious climate objectives and further competitiveness pressures from higher carbon prices.

Figure 1: Carbon intensity of the EU manufacturing firms within each of the ETS subsectors.



(a) Evolution of carbon-intensity by subsector.



(b) Distribution of 2013-2020 decarbonization progress by subsector.

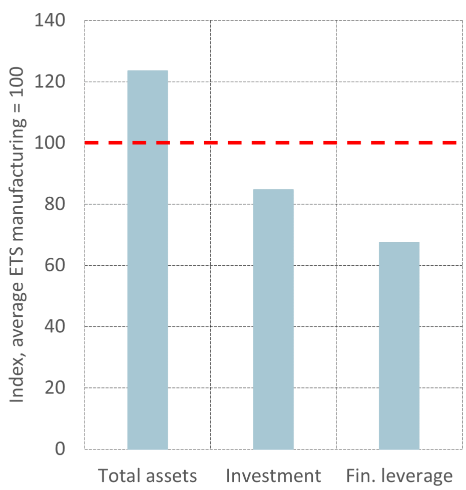
Notes: ETS subsectors are assigned to firms based on the installations which constitute the majority of firm-level emissions. C17 represents the pulp and paper sector, C19 is for refineries, C20 is for chemicals, C23 for non-metallic minerals and C24 is for basic metals. Dashed red line marks the baseline index level in 2013, i.e. the reported carbon intensity in 2013 = 100. Source: Own calculations based on EU ETS and Orbis databases.

The heterogeneity observed in Figure 1b is the source of inspiration for this study. It is possible that different firms begin their decarbonization adventure from different starting conditions, and therefore commit to different carbon strategies. For instance, Ruiz (2024) argues that decarbonization potential is sector-specific, since sectors encounter different levels of initial carbon and energy efficiency, investment potential and trade patterns. Nonetheless, the fact that carbon intensity stalls, or even deteriorates for some companies within the same sector, can be a signal of existing frictions which prevent those firms from fully rolling out their green investment plans.

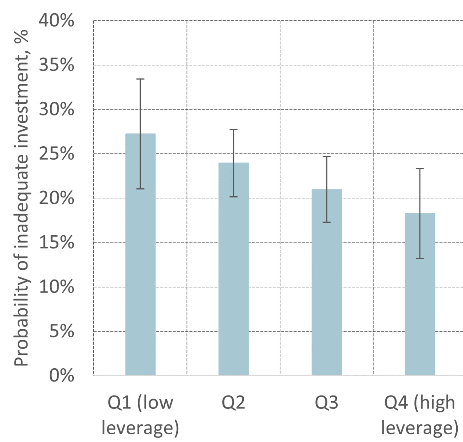
Sustained investment is essential to drive the transition towards a low-carbon economy and achieve long-term sustainability goals. However, we find that 25% of firms with the slowest improvement in carbon intensity between 2020 and 2013, invest nearly 20% less than an average firm in that period despite having some 20% larger asset stock (Fig. 2a). Among many possible reasons why firms limit their investment efforts, insufficient access to finance takes an important place in the recent debate (see for instance Barbera et al. (2022); Amamou et al. (2023)). Fig. 2a reveals that indeed, decarbonization laggards have 33% lower leverage ratio than an average ETS manufacturing firm.

Inferring causality structure within the nexus of investment, finance and green agenda remains a challenge, however. Higher investments have a chance to improve carbon intensity only if they contribute to low-carbon production. But the allocation of investment towards green and non-green assets is typically unobserved at the firm level. Furthermore, firms can use external finance to fund green and non-green activities, like capacity expansion under existing production technology, for instance. While many companies are shy of distinguishing between green and non-green asset in their financial reports, the recent EIB Investment Survey (EIBIS) evidence points to the direction that ETS firms with higher leverage report less frequently inadequate investment levels in green transition (Fig. 2b). There have been nearly 10pp less firms complaining about having invested too little into decarbonization among the most leveraged firms than among firms with the lowest leverage.

Figure 2: Characteristics of the firms lagging in decarbonization.



(a) Balance sheet statistics of decarbonization laggards against the average manufacturing firm.



(b) Reported inadequacy of green investment by financial leverage quartiles.

Notes: (a) Average values calculated for decarbonization laggards, defined as 25% of firms with the slowest improvement in carbon intensity between 2020 and 2013 in each of the ETS subsectors. Investment is defined as an annual change in tangible fixed assets. Financial leverage is defined as the sum of short-term loans and long-term debt scaled by the total assets. Dashed red line marks the average index value in the sample, i.e. the average reported value of the relevant variable = 100. (b) 95% confidence intervals are based on robust standard errors from a pooled logit regression. Question: Looking back at your decarbonisation investment over the last five years, was it too much, too little, or about the right amount to ensure the success of your decarbonisation strategy? Base: All firms who invested in decarbonization, excluding don't know and refused answers (overall 193 firms with 572 observations). Source: Own calculations based on EU ETS, Orbis and EIBIS 2023 ETS Module.

Since the green classification of investment assets is unobserved at the firm level, it is customary in the literature to focus either on higher level of variable aggregation, for which one can estimate green and non-green components from sectoral accounts, or estimate a reduced-form firm-level regression, where carbon-relevant variables are estimated on the general-purpose finance and investment. The broader evidence suggests that sectors and investment areas particularly relevant to low-carbon transition, appear to benefit more from releasing credit constraints. For instance, using global industry-level data, Haas et al. (2023) document that carbon-intensive industries reduce emissions faster in economies with deeper stock markets. They further argue that along weak green management practices, credit constraints are an important impediment which hold back corporate investment in green technologies.

Green benefits of external finance have also been confirmed for firm-level data, including the EU ETS. For instance, Carradori et al. (2023) argue that firms with higher leverage produce significantly lower emissions without constraining their economic activity. This relationship holds until the leverage becomes excessive. From this point on, extra unit of leverage impairs firm's ability to reduce emissions. Jonghe et al. (2020) report that firms exposed to regulatory ETS tightening increased their M&A activity in green companies after the ETS prices spiked in 2017. Since many of the M&A deals are are structured as leveraged buyouts, it exemplifies the role of external finance in the adoption of green technology.

This study is also related to the broad literature on the link between finance and innovation, since achieving net-zero emission targets depends on targeted R&D and innovation efforts in critical technologies. International Energy Agency (2020) estimates that almost 35% of the cumulative CO2 emissions reductions by 2070 will come from technologies that are currently at the prototype or demonstration phase, and which will not become available at scale without further innovation. In this respect, firms' innovation potential can be stimulated by alleviating financial constraints. For instance, Pavlova and Signore (2021) find the improving access to finance through EIF-supported venture capital funds contributed to more investment and patenting activity during the five years following the investment date in a firm. This is in line with Howell (2017), who argues that relief of financial constraints is associated with more patents, especially for firms in industries related to clean energy and clean production.

3. Empirical strategy

The central focus of this study is to verify to what extent access to finance affects firms' carbon-intensity performance. The underlying hypothesis suggests that lack of external finance can lead to lower investment in the areas necessary for decarbonization. With sufficiently detailed data, one could decompose this hypothesis into two transmission channels which could be tested separately, i.e. i) access to external finance enables green investment and ii) green investment reduces the company's carbon intensity. Due to the fact firms' asset allocation decisions between green and non-green assets are unobserved at the firm level, our strategy is to test the hypothesis jointly in a reduced-form equation, controlling for the level of general-purpose investment and several unobserved fixed effects. Our main proxy measure for access to external finance is the level financial leverage, defined as a sum of short- and long-term debt relative to total assets.

We use the following baseline specification

$$ln\left(\frac{CO2_{icst}}{VA_{icst}}\right) = \beta_0 + \beta_1 FL_{icst-1} + \beta_2 ETS_{icst-1} + \beta_3 X_{icst-1} + \nu_{cst} + \mu_i + \varepsilon_{icst}, \qquad (1)$$

where $CO2/VA$ is the measure of carbon intensity, expressed as the annual sum of verified CO_2 emissions, as reported in the ETS, divided by firms' real value added. FL describes financial leverage calculated as the sum of loans and long-term debt relative to total assets. We further include two sets of control variables. Those related to the functioning of the

ETS are captured by vector ETS and include the number of installations and the amount of free allocations received. Financial characteristics are captured by vector X and include the level of tangible fixed assets, returns on assets, taxes paid, cash ratio, total assets (in log) and firm's age. Fixed effects are absorbed at the country-sector-time level by ν and at the firm-level by μ. Finally, subscripts i, c, s and t capture firm, country, sector and time dimensions, respectively.

To shed more light on possible mechanics of how access to finance spurs decarbonization, we further break down the total effect of financial leverage into the short and long components, by estimating the following augmented model

$$ln\left(\frac{CO2_{icst}}{VA_{icst}}\right) = \beta_0 + \beta_1 ShortFL_{icst-1} + \beta_2 LongFL_{icst-1} + \beta_3 ETS_{icst-1} + \beta_4 X_{icst-1} + \nu_{cst} + \mu_i + \varepsilon_{icst}, \tag{2}$$

where $ShortFL$ and $LongFL$ stand for financial leverage of maturity shorter and longer than 12 months, respectively.

We also study the possible nonlinearities between financial leverage and carbon intensity, by including the squared $ShortFL$ and $LongFL$ terms to Eq. (2), in the spirit of Carradori et al. (2023). The quadratic model equation becomes

$$\begin{aligned} ln\left(\frac{CO2_{icst}}{VA_{icst}}\right) &= \beta_0 + \beta_1 ShortFL_{icst-1} + \beta_2 ShortFL^2_{icst-1} \\ &+ \beta_3 LongFL_{icst-1} + \beta_4 LongFL^2_{icst-1} + \beta_5 ETS_{icst-1} + \beta_6 X_{icst-1} + \nu_{cst} + \mu_i + \varepsilon_{icst}. \end{aligned} \tag{3}$$

Financial leverage is an equilibrium outcome indicating the intersection of supply and demand conditions for each firm. Firms that operate with little leverage may do so because they find it optimal, not because they are credit constrained. To better explore the relevance of access to finance problems, we borrow the methodology from Ferrando and Wolski (2018), who estimate the probability of a firm being finance constrained using the information derived from the EIB Investment Survey (EIBIS).

The survey considers companies as financially constrained when they are dissatisfied with the amount of finance obtained (received less), or they sought external finance but did not receive it (rejected) and they did not seek external finance because they thought borrowing costs would be too high (too expensive) or they thought they would be turned down (discouraged). The probability of being constrained for firms in EIBIS is regressed in a pooled logit regression on a set of lagged indicators of their financial situation (cash flow ratio, financial leverage and cash ratio), total assets as well as on sector and country dummies. The estimated coefficients are then fit to our sample of ETS firms. The resulting score is used to rank the firms according to their probability of being credit constrained or not. For each year, financially constrained firms are finally identified as those with a value of the score greater than a country threshold, which is directly derived from the survey. Financially constrained firms are tagged by a dummy $\hat{FC}$, which we substitute in Eq. (1)

as[4]

$$ln\left(\frac{CO2_{icst}}{VA_{icst}}\right) = \beta_0 + \beta_1\hat{FC}_{icst-1} + \beta_2 ETS_{icst-1} + \beta_3 X_{icst-1} + \nu_{cst} + \mu_i + \varepsilon_{icst}. \quad (4)$$

On top of the model specifications outlined above, for better tractability of the results, we experiment with the levels of the fixed effects. At the first level (aggregate), we substitute ν_{cst} with either the country-year and sector-year fixed effects ($\nu_{ct} + \nu_{st}$), or with the very granular country-sector-year fixed effects (ν_{cst}).

In a class of fixed effects models, adding a fixed effect eliminates any variation in higher level units in coefficient estimation, or in other words it absorbs the variation between units at a higher level. In our case, country-year fixed effects absorb unobserved country-specific variation common across firms in a given year such that the estimated coefficients will be unbiased by the possible difference in firms' performance between the countries (as a result of differences in tax regimes, for example). Sector-year fixed effects capture unobservable factors on the sector level in given year such that they correct for possible bias from between sectors (as a result of differences in technological availability, for example). Country-sector-year fixed effects absorb very granular unobserved shocks which are common to all firms in a given sector in a given country, and in a given year. Absorbing aggregate levels of fixed effects allows us to check if the coefficient estimates are affected by the level variation between sectors in different countries, like for instance a specific policy targeting refineries in one of the member states.

At the second level (individual), we switch on and off the firm-level fixed effect μ_i in each of the regressions. Keeping the other elements constant, including μ_i in the regressions effectively demeans the variables by each firm. As a result, the coefficients of interest reflect the average relation between model variables per firm over time. If we skip μ_i, the coefficients reflect the average relation between firms up to the level of included first level fixed effect, as determined by ν_{cst}.

4. Data

4.1. EU Emissions Trading System

Our starting point are the relevant EU Emissions Trading System (ETS) files from the official website of Union's Registry (see Appendix for exact references). The data sets were extracted in March 2023 and comprise information about emissions of EU's installations and aircraft operators, and corresponding operator accounts of the installations as of 2021. Altogether, the data set spans over 12,971 stationary installations and 1,427 aircraft operators for the years 2008-2022, i.e. covering the Phases II-IV of the EU ETS. Each installation is uniquely identified by a pair of register code and installation ID. Register code determines the country where the installation is located, while installation ID is typically a numerical (not necessarily consecutive) label for each record in a given registry.

The file contains two key emission variables for each installation, related to participation in different phases of the ETS. These include the annual verified CO2 emissions and annual

[4] Since the cash ratio and total assets are the explanatory variables of the $\hat{FC}$ indicator, we exclude them from the vector of control variables X in Eq. (4).

allocation of emission allowances, i.e. how much an installation can emit for free. The variables are reported as either a positive value suggesting actual emissions and/or allocations, -1 indicating that no allocation has been made and/or no emissions have been verified or 'Excluded' meaning that an installation is out of scope of the ETS for the specific year. Zeros mean that 0 units have been allocated and/or the amount of verified emission reported is zero.

While the historical data goes back to 2008, data from Phase III (i.e. 2013 onward) uses the extended scope of sectoral classification (sectoral codes 20-47 instead of 1-9 before). To match the activity sectors of installations in Phase II to the new classification, we use the correspondence table provided by the European Energy Agency as of 2019 (see the Appendix for the exact link).

To identify the firms behind the operator accounts in the ETS, we rely on the correspondence table provided by the Joint Research Centre (JRC) or the European Commission (EC). To clean the file from possible duplicates or false-positive links, we use the following procedure. Firstly, we drop all the records with missing account identifiers (EUTL_REGID) or with missing firm identifiers (ORBIS_BVD_ID). Secondly, we drop all the records which assign multiple firm identifiers to the same account holder. We then drop duplicate records to allow for many-to-one matching with the emission file, i.e. one company may have multiple accounts in the EU ETS.

In the last step we collapse the installation level information by firm. We keep track of the number of installations owned by a firm over time and the sum of all the verified emissions and emission allowances attributed to them. We also assign an ETS subsector to each firm, based on which 2-digit sector was responsible for the majority of emissions of a firm over the years. (It should be noted that sectoral classification of ETS installations can differ from the NACE sectoral classification of the owner company.) Since our focus is on the manufacturing sector, we keep only the firms for which the ETS emissions are reported in subsectors C17 (pulp and paper), C19 (refineries), C20 (chemicals), C23 (non-metallic minerals), C24 (basic metals) and C26 (electronics).

4.2. Orbis and EIB Investment Survey

We use the Orbis database provided by Bureau van Dijk (BvD). The database contains firm-level financial statements and ownership data, gathered and standardized to the so-called 'global format', being comparable across jurisdictions. Our database updates come semi-annually in vintages, where each vintage is cleaned up from companies which haven't reported any information for 10 years or more. Therefore, to correct for the survivorship bias, we aggregate the data for all the vintages to obtain a sample covering 13 years, from 2008 until 2020. This also effectively shortens the last year of the sample to 2020.

To maximize the coverage, we match financial accounts to the ETS file in two steps. Firstly, we match the unconsolidated accounts based on the reported ORBIS_BVD_ID number. In the second step, we match the consolidated accounts for a fraction of companies which do not have unconsolidated records but have consolidated ones. (Keeping in mind potential impact on the results in the subsequent analysis, we confirm the main results on the set of unconsolidated accounts only.)

In the data-cleaning procedure, we exclude observations with odd or inconsistent values in the spirit of Barbiero et al. (2020). We set to missing firm-year observations in which total assets, fixed assets, intangible fixed assets, sales, long-term debt, loans, creditors, debtors, other current liabilities, or total shareholder funds and liabilities have negative values. We then check for the reporting consistency and drop the firm-year financial statements which violate the basic balance-sheet equivalences by more than 10%. Specifically, we impose that (i) total assets match total liabilities, (ii) total assets match the sum of fixed assets and current assets, and (iii) current liabilities match the sum of loans, trade credit and other current liabilities. We also deflate variables using the country-specific GDP price indices. All data are winsorized at 1% level.

At this stage we have 2,682 firms spread across 5 ETS subsectors: 586 in C17 (pulp and paper), 96 in C19 (refineries), 229 in C20 (chemicals), 1,354 in C23 (non-metallic minerals) and 417 in C24 (basic metals).[5] Based on the business profile of firms as reported in Orbis, the vast majority of firms are located in NACE Section C (Manufacturing). We find however 10% of firms belonging to other business sections, like for example 94 are assigned to Section G (Wholesale and Retail Trade), and 45 are assigned to Section B (Mining and quarrying). Our sectoral classification is based on the ETS assignment, however, to keep the investigation comparable to other studies, we confirm the results using the NACE 4-digit classification.

The time span of the sample covers fully the 2nd and the 3rd phases of the ETS. We provide a breakdown of the basic summary statistics for the full sample of firms, including their ETS-related statistics and financial accounts. Mindful of a possible structural break in the middle of the sample, in the empirical investigation we carry out a robustness check on the 3rd phase (2013-2020) only.

Last but not least, we complement the financial data by a measure of financial constraints derived from the EIB Investment Survey (EIBIS). EIBIS is an EU-wide survey that gathers qualitative and quantitative information on investment activities by both SMEs and larger corporates, their financing requirements and the difficulties they face. Using a stratified sampling methodology, EIBIS is representative across all 27 Member States of the EU and applies to four firm size classes (micro, small, medium and large) and four sector groupings (manufacturing, services, construction and infrastructure) within countries. It is set up in such a way that survey data can be linked to firms' reported balance sheet and profit and loss accounts. The survey has been administered every year since 2016, hence it covers only the most recent years of the ETS sample.

EIBIS recognizes firms as being financially constrained if they had applied for a loan and got less, their application was rejected, or they didn't apply for a loan due to too high cost or risk of being turned down. This indicator is regressed on a set of the reported balance sheet items and fixed effects. The estimated coefficients are then used to construct an index of financial constraints, as a linear combination of the observed balance sheet figures in the ETS sample. The index is then mapped to a dummy variable based on country-specific characteristics, following Ferrando and Wolski (2018).

Several interesting patterns emerge from the bird-eye overview of the firms in the sample. Descriptive statistics in Table 1 show the dispersion of carbon intensity among the ETS is substantial. Firstly, the top 1% of the most carbon-efficient firms produce on balance some

[5] Only one firm in subsector C26 (electronics) survives our data merging and cleaning procedures, which we drop for consistency reasons.

Table 1: ETS-related summary statistics.

	Obs.	Mean	St. dev.	p1	p99
Carbon intensity (log)	17,438	-1.38	1.59	-8.02	2.97
Verified emissions (mton)	28,332	0.21	0.64	0.00	5.04
Free allocations (mton)	29,711	0.19	0.53	0.00	3.44
Number of inst.	34,879	1.21	1.34	0	10

Notes: Carbon intensity is calculated as verified emissions scaled by real value added. Source: Authors' calculations based on Orbis and EU ETS.

Table 2: Financial summary statistics.

	Obs.	Mean	St. dev.	p1	p99
Total assets (log)	26,853	17.67	1.99	10.82	23.13
Number of empl.	24,437	468.07	1,043.97	1	13,164
Firm's age	28,617	28.05	16.27	0	50
Fin. leverage	24,906	0.20	0.23	0.00	1.18
Long-term debt/TA	25,252	0.13	0.19	0.00	0.98
Short-term debt/TA	26,039	0.07	0.13	0.00	0.85
Tangible investment	25,408	0.07	0.49	-0.76	4.66
ROA	24,949	0.02	0.10	-0.43	0.35
Taxation/CF	22,187	0.11	0.36	-1.42	1.95
Cash/TA	25,485	0.06	0.11	0.00	0.72
Fin. constraints dummy	19,857	0.07	0.26	0	1

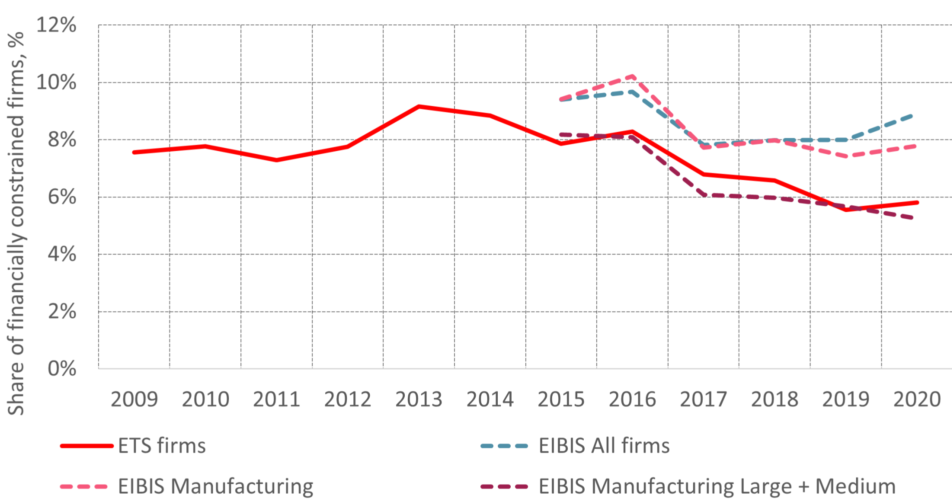
Notes: Financial leverage is defined as a sum of loans and long-term debt over total assets. TA = Total Assets, CF = Cash Flow, ROA = Returns On Assets calculated on the net income. Source: Authors' calculations based on Orbis and EIBIS.

60,000 times less carbon per unit of value added, even within the same ETS sectors. Secondly, we see that, on average, companies had to pay for what they emitted with the amount of average emissions exceeding the amount of free allocations. This pattern varies over time, as the amount of free allocations has been gradually decreasing. Last but not least, companies in the sample own on average 1.2 installations regulated under the ETS. This aggregate is taken over firms who own as much as 10 installations and firms who successfully managed to bring their emissions down under the ETS radar.

Table 2 provides further information on the balance sheet structure of ETS manufacturing firms. An average firm's balance sheet was approximately EUR 50m, with roughly 500 people employed. For a few firms in the sample, the amount of outstanding financial liabilities exceeded the value of the underlying assets in some years throughout the sample, as exemplified by the maximum financial leverage bigger than 1. Similarly, while on balance firms in the sample are modestly profitable, some of them struggle with losses exceeding 40% of ROA. We decide to keep those firms in the sample to reflect all the the aspects of the business environment in the results.

On average, 7% of firms in the ETS sample can be considered as financially constrained, based on the linear prediction score from EIBIS. This share seems a bit below the average share reported in the subsequent EIBIS waves since 2016. EIBIS data is based on representative samples of smaller and larger firms, from which smaller entities typically suffer relatively more from the lack of external finance (EIB, 2024). Since ETS firms are typically larger, it is not surprising that they display lower level of financial constraints. In fact, the share of firms tagged as financially constrained in the ETS closely tracks the evolution of financial constraints among medium and large firms in the manufacturing sector reported in EIBIS (Fig. 3).

Figure 3: Financial constraints in the EU ETS and EIB Investment Survey.



Notes: Unweighted averages. Survey administered in year t corresponds to the financial year $t-1$. Source: Authors' calculations based on EU ETS, Orbis and EIBIS.

5. Results

We begin by estimating the relation between financial leverage and carbon intensity, as proposed in the model in Eq. (1). To better understand which factors contribute to the magnitude and statistical significance of the coefficient of interest (in this case β_1), we include two levels of fixed effects. The first level is determined by a combination of the sector, country and year of each observation. For example, if we include sector-year fixed effects only, the estimated effect would be driven by variation of firms' characteristics within each sector in the same year but possibly across countries. If we include sector-year and country-year fixed effects, coefficients will be estimated on variation of firms within each sector in the same year, variation of firms within each country in the same year, and variation between the two included fixed effects. To control for that last between effect, we include country-sector-year fixed effects, such that the coefficients would be estimated on the variation of firms in the same sector in the same country and in the same year.

The second level of fixed effects is determined by a company to which the observation belongs. Firm-level fixed effects control for unobserved characteristics of firms which are constant over time. When they are turned on, the coefficients are effectively estimated on the difference between the variables and their means, such that the explanatory power of the model comes from the within-firm variability over time. When they are turned off, the coefficients are estimated on the variability across firms up to the higher level fixed effects included in the model.

The results are presented in Table 3. We start with the least saturated model, i.e. controlling for country-year and sector-year dummies (Column 1) to which then add firm-level fixed effects (Column 2). We then saturate the model with more granular country-sector-year fixed effects (Column 3) to which we add firm-level fixed effects (Column 4). The last column represents the most saturated specification, in which the estimated relation absorbs shocks happening to all firms in the same country, in the same sector and in the same year (like for example one-off tax relief to a specific industry), as well as the firm-level unobserved differences, which are constant over time.

It can be readily observed that higher leverage is typically associated with lower carbon intensity. This relation seems to be particularly strong, both in terms of magnitude and statistical significance, when looking at the variation of firms across firms within a representative country or representative sector (Columns (1) and (3)). When we look at the relation per firm over time, i.e. controlling for firm-level fixed effects in Columns (2) and (4), the magnitude of the coefficients drops by 7-8%, and statistical significance weakens but remains significant at 10% level. The relation seems to be only marginally affected by the differences in the variation between the same sectors across countries, when comparing Column (1) to (3), and Column (2) to (4).

The remaining coefficients, if significant, give interesting insights about the relation between balance sheet variables and carbon intensity. Typically, more profitable companies, bigger entities, and cash-rich firms display lower carbon intensity. At the same time, carbon intensity seems to be higher for firms with more installations regulated under the ETS, and for firms which receive more free allowances as their incentives to decarbonize drop (Bijnens and Swartenbroekx, 2020). Interestingly, higher taxation seems to be associated with higher carbon intensity but this effect is visible only when looking at the distribution of firms within

Table 3: Financial leverage and carbon intensity.

	(1) log(CO2/VA)	(2) log(CO2/VA)	(3) log(CO2/VA)	(4) log(CO2/VA)
Fin. leverage	-0.166**	-0.152**	-0.160**	-0.149*
	(0.066)	(0.076)	(0.066)	(0.077)
Tangible investment	0.007	-0.026	0.009	-0.020
	(0.026)	(0.017)	(0.025)	(0.018)
RoA	-0.773***	-0.728***	-0.824***	-0.762***
	(0.154)	(0.118)	(0.152)	(0.118)
Taxes payable / EBITDA	0.173***	-0.004	0.170***	-0.005
	(0.034)	(0.021)	(0.035)	(0.021)
Cash ratio	-0.222*	-0.165	-0.194	-0.209*
	(0.134)	(0.141)	(0.133)	(0.121)
Total assets (log)	-0.330***	-0.155***	-0.325***	-0.182***
	(0.011)	(0.055)	(0.011)	(0.055)
Firm age	0.001	-0.004	0.001	-0.004
	(0.001)	(0.005)	(0.001)	(0.005)
N. of installations	0.052***	0.172***	0.055***	0.187***
	(0.008)	(0.026)	(0.008)	(0.027)
Free em. allowance	1.205***	0.677***	1.202***	0.589***
	(0.026)	(0.084)	(0.025)	(0.080)
Constant	4.235***	1.159	4.142***	1.658*
	(0.186)	(1.003)	(0.187)	(0.999)
Firm-level FE	No	Yes	No	Yes
Country x Year FE	Yes	Yes	No	No
Sector x Year FE	Yes	Yes	No	No
Country x Sector x Year FE	No	No	Yes	Yes
Observations	12,382	12,257	12,291	12,166
R-squared	0.355	0.882	0.404	0.889
Adjusted R-squared	0.342	0.862	0.367	0.864

*Notes: Column (1): baseline model with country-year and sector-year fixed effects. Column (2): Model (1) with firm-level fixed effects. Column (3): baseline model with country-sector-year fixed effects. Column (4): Model (3) with firm-level fixed effects. All independent variables are lagged by one period. Robust standard errors are reported in parentheses. *, **, and *** imply significance at the 10%, 5%, and 1% significance level respectively. Source: Authors' calculations based on EU ETS and Orbis.*

sector (Columns (1) and (3)). When we look at the average carbon performance of firms over time the effect disappears (Columns (2) and (4)). It signals that a change in tax policy disproportionally affects carbon performance of some firms in a sector but overall it does not slow down the decarbonization progress over time.

We further look into the long- and short-term components of financial leverage, as proposed in Eq. (2). The results are presented in Table 4.

Table 4: Maturity structure of financial leverage and carbon intensity.

	(1) log(CO2/VA)	(2) log(CO2/VA)	(3) log(CO2/VA)	(4) log(CO2/VA)
Long-term debt ratio	-0.073	-0.201**	-0.093	-0.214***
	(0.081)	(0.080)	(0.082)	(0.083)
Short-term debt ratio	-0.361***	0.014	-0.299***	0.060
	(0.113)	(0.119)	(0.108)	(0.121)
Tangible investment	0.007	-0.026	0.009	-0.020
	(0.026)	(0.017)	(0.025)	(0.018)
RoA	-0.778***	-0.715***	-0.827***	-0.747***
	(0.154)	(0.118)	(0.152)	(0.117)
Taxes payable / EBITDA	0.173***	-0.004	0.170***	-0.005
	(0.034)	(0.021)	(0.035)	(0.021)
Cash ratio	-0.235*	-0.158	-0.204	-0.200
	(0.135)	(0.142)	(0.134)	(0.122)
Total assets (log)	-0.331***	-0.156***	-0.326***	-0.183***
	(0.011)	(0.055)	(0.011)	(0.055)
Firm age	0.001	-0.004	0.001	-0.004
	(0.001)	(0.005)	(0.001)	(0.005)
N. of installations	0.052***	0.171***	0.055***	0.185***
	(0.008)	(0.026)	(0.008)	(0.027)
Free em. allowance	1.203***	0.683***	1.201***	0.597***
	(0.026)	(0.085)	(0.025)	(0.080)
Constant	4.264***	1.163	4.162***	1.664*
	(0.187)	(1.004)	(0.188)	(1.000)
Firm-level FE	No	Yes	No	Yes
Country x Year FE	Yes	Yes	No	No
Sector x Year FE	Yes	Yes	No	No
Country x Sector x Year FE	No	No	Yes	Yes
Observations	12,382	12,257	12,291	12,166
R-squared	0.355	0.882	0.404	0.889
Adjusted R-squared	0.342	0.862	0.367	0.864

*Notes: Column (1): baseline model with country-year and sector-year fixed effects. Column (2): Model (1) with firm-level fixed effects. Column (3): baseline model with country-sector-year fixed effects. Column (4): Model (3) with firm-level fixed effects. All independent variables are lagged by one period. Robust standard errors are reported in parentheses. *, **, and *** imply significance at the 10%, 5%, and 1% significance level respectively. Source: Authors' calculations based on EU ETS and Orbis.*

The estimates reveal an interesting difference in how the maturity structure of leverage is related to decarbonization progress. When we look at the aggregate sector level, either when controlling for the country-year and sector-year fixed effects in Column (1) or for the country-sector-year fixed effects in Column (3), it is rather the short-term financial leverage which is a significant predictor of less carbon-intensive firms. In those within-sector specifications financial leverage of maturity longer than 12 months is not statistically significant. When we look at the dynamics of firms over time, i.e. we control for firm-level fixed effects in Columns (2) and (4), the long-term leverage becomes significant and short-term debt not.

While we cannot directly observe the purpose of firms' financing, we can match its maturity to the maturity of the underlying assets. Short-term financing is typically used to increase inventory orders, payrolls and daily supplies. It provides flexibility and oftentimes is much cheaper due to lower maturity premium. Businesses need long-term financing for acquiring new equipment, R&D, cash flow enhancement and company expansion. To finance multi-annual investment plans or acquisitions, firms lock in multiyear financing for which they agree to pay the maturity premium.

The results in Table 4 suggest that if we look at the distribution of firms within a representative sector, the ones which are less carbon intensive have also more short-term debt, on average. We view this relation rather through a prism of reverse causality, as firms who are already carbon efficient may not need to further reduce the emissions compared to their carbon-intensive peers, hence they use their financing opportunistically with more flexibility and better pricing. On the other hand, the path through which firms decide to reduce their carbon intensity typically requires substantial investment effort, which is rather financed in a long-term perspective.

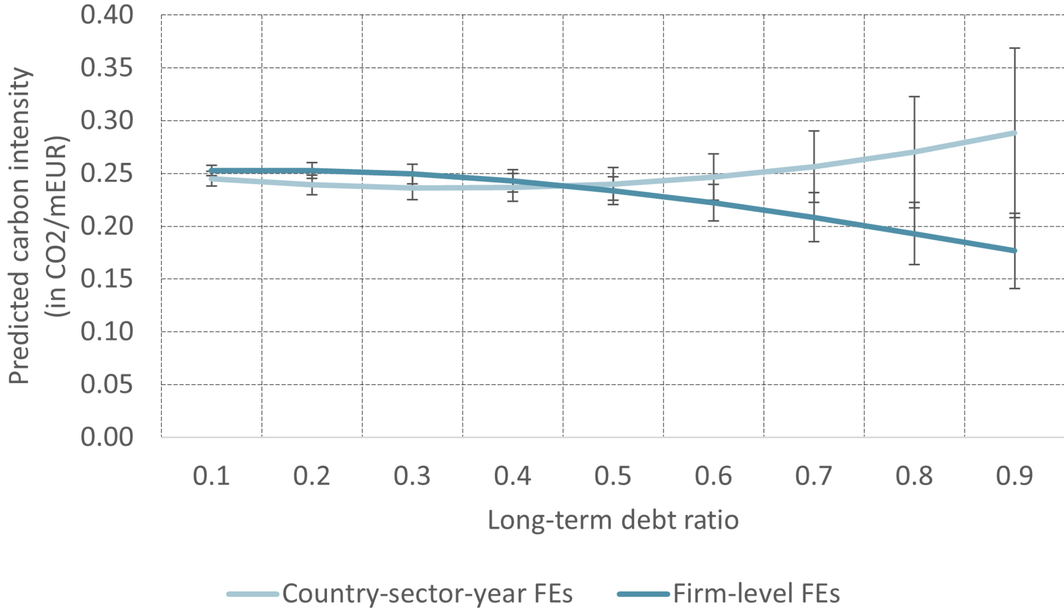
We view these findings as a first indication of a possible mechanics through which external leverage can support decarbonization. Following EIB (2024), shifting production technology to less carbon-intensive methods requires long-term vision and strategy. The evidence from the ETS suggests that this can be achieved with longer term financing options.

In the next step, we look deeper into the possible nonlinear relationship between the variables. In particular, we estimate the quadratic effects function of the short- and long-term debt on carbon intensity, as proposed in Eq. (3). The detailed results are depicted in Table B.1 in the Appendix but for the ease of interpretation we present them graphically in Figure 4, where we plot the predicted carbon intensity levels for an average firm, based on specifications from Columns (3) and (4) from Table B.1, i.e. including the country-sector-year fixed effects without and with the firm-level fixed effects, respectively.

Firstly, in all specifications with quadratic terms, short-term debt is statistically insignificant. This is in line with our previous suggestion that the relation between the short-term debt and carbon intensity observed in Table 4 is rather a statistical artifact.

Secondly, we observe that the quadratic function changes its shape depending on the firm-level fixed effects. When we look at the distribution of firms within a representative sector, excessive debt levels seem to be correlated with higher carbon intensity, implying a possible debt overhang problem (Barbiero et al., 2020). The coefficient on the quadratic term changes the sign when we include firm-level fixed effects, suggesting that for a representative firm taking up more financial leverage is, on average, associated with lower carbon intensity in the next year. It seems therefore that while indeed external finance helps firms to gradually reduce their carbon intensity over time, other firms, which have less long-term debt, observe

Figure 4: Predicted carbon intensity for different levels of long-term debt ratio.



faster decarbonization paths.

For lower debt ratios, say up to 0.4, the effect of external finance on carbon intensity is largely flat. For higher debt ratios, it seems that decarbonization benefits from higher financial leverage for a representative firm are largely offset by debt overhang problem at a sector level. Let's say a firm has long-term debt to asset ratio at 0.4, in which case carbon intensity scores 0.24 CO2/mEUR both when firm-level fixed effects are switched off and on. If a firm takes up extra debt and increases the debt ratio by, let's say, 20pp to 0.6, looking at the firm's history its carbon intensity is expected to drop to 0.22 CO2/mEUR but on the background of other firms in the sector, one would expect an increase to 0.25 CO2/mEUR. Overall, the net effect becomes still negative but much smaller in magnitude.

5.1. Financial constraints

The main regressions are estimated under the proxy assumption that lower financial leverage indicates problems with access to external finance. It is possible, however, that firms decide to operate with low leverage on purpose, such that low leverage is an equilibrium outcome rather than symptomatic of financial frictions. To correct for this possible misinterpretation in the main results, we propose to replace the financial leverage variable by a measure of EIBIS-derived financial constraints, as suggested in Eq. (4). The results are presented in Table 5.

Table 5: Financial constraints and carbon intensity.

	(1) log(CO2/VA)	(2) log(CO2/VA)	(3) log(CO2/VA)	(4) log(CO2/VA)
Fin. constraints dummy	0.332***	0.02	0.278***	0.026
	(0.054)	(0.05)	(0.054)	(0.05)
Tangible investment	0.027	-0.017	0.026	-0.019
	(0.028)	(0.02)	(0.027)	(0.02)
RoA	-1.110***	-0.710***	-1.121***	-0.733***
	(0.161)	(0.118)	(0.159)	(0.12)
Taxes payable / EBITDA	0.218***	-0.004	0.219***	-0.001
	(0.037)	(0.022)	(0.038)	(0.022)
Firm age	-0.001	0.002	-0.001	0.001
	(0.001)	(0.006)	(0.001)	(0.006)
Free em. allowance	0.890***	0.633***	0.899***	0.582***
	(0.024)	(0.093)	(0.022)	(0.089)
Constant	-1.600***	-1.597***	-1.599***	-1.562***
	(0.029)	(0.172)	(0.029)	(0.18)
Firm-level FE	No	Yes	No	Yes
Country x Year FE	Yes	Yes	No	No
Sector x Year FE	Yes	Yes	No	No
Country x Sector x Year FE	No	No	Yes	Yes
Observations	11,379	11,266	11,294	11,180
R-squared	0.293	0.89	0.348	0.896
Adjusted R-squared	0.279	0.87	0.308	0.873

*Notes: Financial constraints dummy is derived from EIBIS, following Ferrando and Wolski (2018). Column (1): baseline model with country-year and sector-year fixed effects. Column (2): Model (1) with firm-level fixed effects. Column (3): baseline model with country-sector-year fixed effects. Column (4): Model (3) with firm-level fixed effects. All independent variables are lagged by one period. Robust standard errors are reported in parentheses. *, **, and *** imply significance at the 10%, 5%, and 1% significance level, respectively. Source: Authors' calculations based on EU ETS, Orbis and EIBIS.*

The initial prediction from Table 3, that firms with rationed access to external finance have higher carbon intensity, seems to be confirmed for a group of firms classified as financially constrained. More specifically, looking at the distribution of firms within a sector (Columns (1) and (3)), credit-constrained entities seem to have 28-33% higher carbon intensity than not constrained, but otherwise similar, peers. Coefficients on control variables seem to remain stable and they preserve their statistical power.

While the sign of the coefficient on the financial constraints dummy remains positive, it becomes not statistically significant in regressions with firm-level fixed effects (Columns (2) and (3)). This can be attributed to little variation in the financial constraints dummy per firm over time. Actually, less than 15% of firms change the classification over time, which given the sample properties seems too little to provide sufficient evidence that alleviating financial constraints for a given firm in period t is associated with lower carbon intensity in period $t+1$. Nonetheless, the sector-wide results point to substantial decarbonization gains from lowering access to finance frictions among ETS manufacturing firms.

5.2. Robustness

We took a few assumption in data preparation procedures, which could potentially impact the sample composition and therefore affect the main regression results. Therefore, to ensure stability of the findings, we carry out four robustness checks. The results for each of them are presented in Table 6, where for transparency we show the main coefficients of interest from the linear model from Eq. (2) and quadratic model from Eq. (3). [6]

Firstly, in Panel A we change the sectoral classification of firms to the one defined by the primary sector of activity in Orbis, rather than the one implied by the sectors of ETS installations. The Orbis classification uses 4-digit NACE Rev. 2 codes, bringing more granular identification of the sector fixed effects. This comes at a cost of fewer observations since a few companies seem to be missing their Orbis sectors, however.

The estimates confirm that long-term external finance is associated with lower carbon intensity, on average. In fact, the absolute magnitude of the coefficient is nearly two times bigger than in the baseline regression. Excessive debt decreases these effects, however, as exemplified by the results from the quadratic specification in Columns (3) and (4) in Panel A. Interestingly, the sector-wide quadratic effects become stronger and more statistically significant but firm-level quadratic effects disappear.

This sheds more light on the main results as it seems that the positive effects of financial leverage on a representative firm decarbonization are driven by external shocks to carbon efficiency of firms in few different 4-digit business sectors keeping installations in the same ETS sector. If we control for these shocks, the quadratic effects disappear.

Secondly, the evolution of the ETS framework could also potentially affect the findings. For instance, in Phase II of the ETS (2008-2012) total amount of allowances was lowered by 6.5% compared to 2005. In the third phase (2013-2020) the cap on allowances become even stricter, with 1.74% reduction annually and more sectors and gases were covered, including aviation, petrochemicals and aluminum (see Dechezleprêtre et al. (2023)). To keep consistency of regulatory environment in the regression, we estimate the models on the sample of firms between 2013 and 2020. The results are presented in Panel B of Table 6.

While the linear specifications in Columns (1) and (2) offer similar conclusions to the ones presented in Table 4, the quadratic specification in the model with firm-level fixed effects again loses the statistical significance. Quadratic effects continue to be visible in a representative sector specification in Column (3), however. This again casts a shadow the possible benefits of external finance to bring down carbon intensity, as the relationship appears to be present in the Phase II of the ETS and it weakens afterwards.

Thirdly, to maximize the coverage of the financial data in the sample, we bring together firms with unconsolidated accounts with a few firms with consolidated accounts. While these can be considered as firm-level fixed effects which are absorbed in the models with firm-level dummies, for the specifications with higher levels of fixed effects, it can bring additional

[6] The detailed results for all the variables are available upon request.

noise to the estimates. Therefore, we estimate the models on a subsample of firms with unconsolidated accounts only. The results are presented in Panel C.

It is can be readily observed that excluding the few firms with consolidated accounts from the regression does not change the main findings. Statistical significance and the coefficient of the results remain virtually unchanged from the baseline regressions.

Last but not least, we alter also the carbon intensity variable. At the level of the firm, one may want to scale emissions by the level of assets because these are the assets that generate the emissions. As a robustness check therefore, we re-estimate the model regressions for an asset-based carbon intensity, expressed as the sum of firm-related verified emissions divided by the real value of firm's total fixed assets.[7] The results, which fully support the main findings, can be found in Panel D.

The general conclusion from the robustness checks puts in question the nonlinear relationship between long-term debt and carbon intensity. The benefits of long-term debt on firm-level decarbonization seem to be attributed to the developments in a few business sectors with installations in the same ETS sector, to the dynamics observed in Phase II of the ETS, and/or to the definition of carbon intensity. Controlling for these factors, as suggested in the robustness checks, we see that long-term debt is no longer associated with firms' reduction in carbon intensity over time. Nonetheless, the problems associated with excessive debt levels within sectors seem to be still relevant in every robustness check. In the next subsection, we offer a possible explanation why this may be the case.

5.3. Quantile effects

We shed more light on the relationship between financial leverage and decarbonization by estimating the baseline regression for different quantiles of the outcome variable using a quantile regression. To keep the model comparable to the fixed effects specifications presented in Section 3, we control for unobserved firm-level heterogeneity using the Mundlak device (Mundlak, 1978), whereby the fixed effects are absorbed by fixed-effects means of relevant variables in a pooled regression specification. In other words, each RHS variable from Eq. (1) enters the pooled quantile regression two times, i.e. untransformed and as a mean of the relevant fixed effects. More formally, we estimate the following quantile function

$$Q_q\left(ln\left(\frac{CO2_{icst}}{VA_{icst}}\right) \mid V_{icst-1}, FE\right) = \gamma_0^q + \gamma_1^q V_{icst-1} + \gamma_2^q \bar{V}^{FE} + \varepsilon_{icst}, \tag{5}$$

where Q_q is the q-percentile of the conditional distribution of $CO2/VA$ given the control variables V and the vector of fixed effects FE. In our case, we switch FE between the country-sector-year fixed effects (such that $FE = cst$) and the firm-level fixed effects ($FE = i$) to reflect the linear model specification.[8] For each variable V, the means of relevant fixed

[7] In principle, one can also scale total emissions by the level of total assets. This, however, could result in the colinearity problems with other control variables. Furthermore, because of the balance sheet equivalence, an increase in debt level is matched by a corresponding increase in total assets. Since current assets probably contribute little to the net-zero transition, we focus on the fixed assets instead to calculate asset-based carbon intensity.

[8] We don't include two levels of group means, i.e. $FE = cst$ and $FE = i$, in one equation due to algorithm convergence problems.

Table 6: Robustness checks.

Panel A: Sectoral fixed effects defined at 4-digit NACE level

	(1) log(CO2/VA)	(2) log(CO2/VA)	(3) log(CO2/VA)	(4) log(CO2/VA)
Long-term debt ratio	-0.119	-0.356***	-0.618***	-0.096
	(0.088)	(0.104)	(0.194)	(0.191)
(Long-term debt ratio)^2			0.786***	-0.445
			(0.293)	(0.311)
Observations	9,915	9,803	9,915	9,803
R-squared	0.621	0.906	0.622	0.906
Adjusted R-squared	0.534	0.867	0.535	0.867

Panel B: 2013-2020 sample period only

	(1) log(CO2/VA)	(2) log(CO2/VA)	(3) log(CO2/VA)	(4) log(CO2/VA)
Long-term debt ratio	-0.141	-0.196**	-0.481**	0.106
	(0.094)	(0.087)	(0.219)	(0.178)
(Long-term debt ratio)^2			0.579*	-0.513
			(0.338)	(0.316)
Observations	8,836	8,721	8,836	8,721
R-squared	0.413	0.926	0.413	0.926
Adjusted R-squared	0.378	0.906	0.378	0.906

Panel C: Unconsolidated accounts only

	(1) log(CO2/VA)	(2) log(CO2/VA)	(3) log(CO2/VA)	(4) log(CO2/VA)
Long-term debt ratio	-0.092	-0.213***	-0.378**	0.147
	(0.082)	(0.083)	(0.186)	(0.162)
(Long-term debt ratio)^2			0.488*	-0.623**
			(0.288)	(0.27)
Observations	12,256	12,135	12,256	12,135
R-squared	0.404	0.888	0.404	0.888
Adjusted R-squared	0.367	0.864	0.367	0.864

Panel D: Carbon intensity in terms of total Fixed Assets (FA)

	(1) log(CO2/FA)	(2) log(CO2/FA)	(3) log(CO2/FA)	(4) log(CO2/FA)
Long-term debt ratio	-1.031***	-0.382***	-1.782***	-0.437***
	(0.083)	(0.074)	(0.184)	(0.135)
(Long-term debt ratio)^2			0.428*	0.128
			(0.242)	(0.182)
Observations	11,918	11,796	11,918	11,796
R-squared	0.457	0.926	0.457	0.926
Adjusted R-squared	0.409	0.907	0.409	0.907

*Notes: Column (1): linear model specification from Eq. (2) with country-sector-year fixed effects. Column (2): linear model specification from Eq. (2) with country-sector-year fixed effects and firm-level fixed effects. Column (3): quadratic model specification from Eq. (3) with country-sector-year fixed effects. Column (4): quadratic model specification from Eq. (3) with country-sector-year fixed effects and firm-level fixed effects. Coefficients on control variables are skipped for transparency. Robust standard errors are reported in parentheses. *, **, and *** imply significance at the 10%, 5%, and 1% significance level respectively. Source: Authors' calculations based on EU ETS and Orbis.*

effects are given by

$$\bar{V}^{FE=cst} = \bar{V}_{\cdot cst} = N_{cst}^{-1} \sum_{i=1}^{N_{cst}} V_{icst},$$
$$\bar{V}^{FE=i} = \bar{V}_{i\cdot} = T_i^{-1} \sum_{t=1}^{T_i} V_{icst}, \tag{6}$$

where N_{cst} is the number of firms in country-sector-year group, and T_i is the number of time periods in the sample for which firm i reports.

Mundlak (1978) notes that the fixed effects estimator and a pooled ordinary least squares regression which controls for group differences by including fixed-effects averages of the covariates are identical. In the context of quantile regression, assuming that ε_{icst} is independent of V_{icst-1}, we can estimate γ_1^q and and γ_2^q using pooled quantile regression based on Eq. (5).

There are two modifications we introduce to the baseline model. Firstly, to get a meaningful representation of the quantiles of the variables per firm over time, we use a balanced sample of firms, such that $T = 12$.. Secondly, to provide more accurate confidence intervals, we use standard errors clustered at the relevant fixed effect level (Imbens and Wooldridge, 2008).

We estimate the effect for quartiles $q = 0.25$, $q = 0.5$ (or the median) and $q = 0.75$. The results are presented in Fig. 5, but the detailed results are given in Table B.2 in the Appendix.

Figure 5: Effects of long-term debt ratio on different quartiles of carbon intensity.

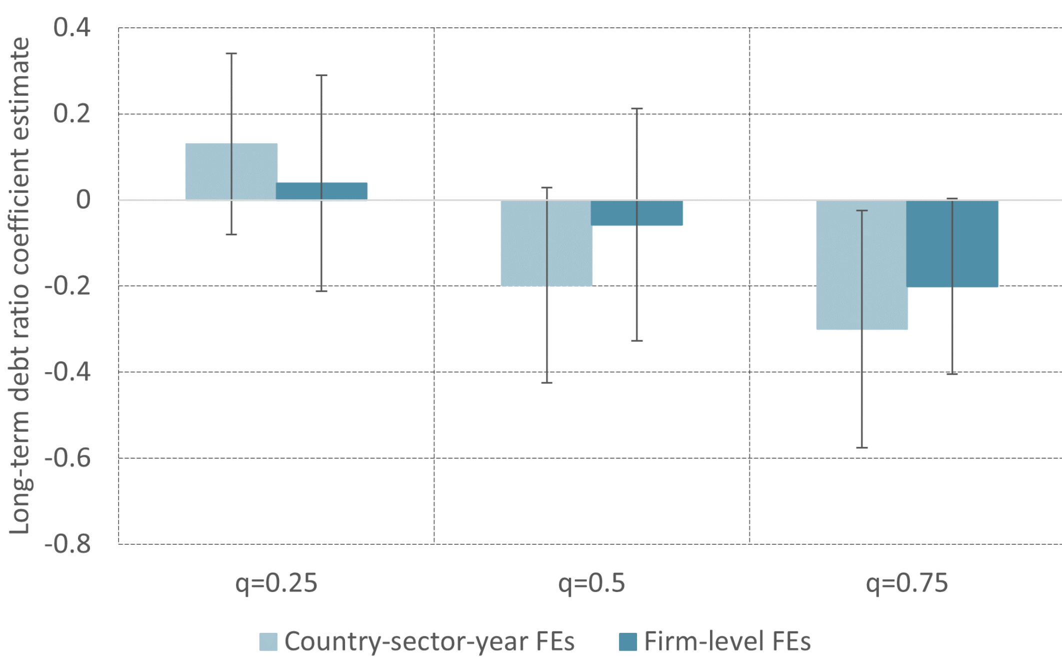


Fig. 5 shows that the decarbonization benefits from higher financial leverage are rather visible among more carbon-intensive firms. In particular, the effects appear to be strongly negative for the third quartile $q = 0.75$. The more carbon efficient a firm becomes, both firm-specific and within-sector effects weaken.

One possible explanation to this pattern can be found in the difference between firms to what extent new or existing technologies can help in their net-zero transitions. Innovation and technology adoption, while closely related, differ significantly in their economic implications and the ways they can be financed. Innovation refers to the creation of new products, processes, or ideas, often driven by research and development (R&D) activities. It is the initial phase where novel solutions are conceived and developed, typically involving high uncertainty and investment. On the other hand, technology adoption is the process by which these innovations are accepted and utilized by the market. This phase involves diffusion, where the new technology spreads across different sectors and regions, often influenced by factors such as relative advantage, complexity, compatibility, trialability and observability (Rogers, 2003). Economically, innovation can lead to competitive advantages and market leadership for firms, while widespread technology adoption can drive productivity growth and enhance efficiency.

For firms at higher percentiles of carbon intensity, the distance to the carbon-efficient firms is larger such that the larger the potential benefits from technology adoption (relative advantage condition, after Rogers (2003)). Similarly, the higher the percentile of carbon intensity, the higher the chance of observing a firm producing similar products using more carbon efficient technology (observability condition) and exploring the technology (trialability condition). In the context of green innovation, an important derivative factor to implement a given technology is the confidence of its deployment (Guo et al., 2020), which is also larger for more carbon-intensive firms in a given sector.

Put together, it seems that long-term debt can help ETS firms to reduce their carbon intensity if it finances technology adoption. Firms which are already carbon efficient probably need new technology to reduce their carbon footprint further, for which long-term debt may not be the right financing strategy. To offset information asymmetry, debt providers typically require tangible collateral and/or monitoring of the borrower before they agree on a credit contract (Beck and Demirguc-Kunt, 2006). Proven technologies offer the predictability and stability of cash flows that external investors are looking for, such that technology adoption has a higher chance to be financed by debt instruments. Kellard et al. (2023) confirm on a macro-level that application of green technologies in organizational practices is an attribute of bank-based financial systems, due to the high roll-out costs, longer investment timelines and more stable revenue flows from green investment, for instance.

6. Conclusions

This paper looks into the finance-decarbonization nexus on the example of the EU Emission Trading System (ETS). Our primary focus is on the role that access to external finance plays in supporting investment into low-carbon production. We are motivated by the fact that ETS firms, which improved carbon intensity the least between 2013 and 2020, had distinctly lower investment and financial leverage ratios, suggesting possible access to finance constraints.

We estimate multiple firm-level panel regressions, combining the reported ETS data with financial information reported in Orbis and EIB Investment Survey (EIBIS). We indeed find that financial leverage is correlated with lower carbon intensity levels but the relation is driven by debt instruments with maturity longer than 12 months. We also find evidence that firms which can be considered as financially constrained, according to the EIBIS classification, report between 28 to 33% higher carbon intensity than other firms in the sector.

Our investigation further reveals that the effects of financial leverage change depending on the reference point. We use a combination of country-sector-year and firm-level fixed effects to better understand if debt is correlated with lower carbon intensity within a representative sector, or rather reduces carbon intensity over time for a representative firm. It turns out that firms which took up extra long-term debt observe an improvement in carbon intensity in a subsequent period but their position within a sector deteriorates. This suggests that other firms, which have lower leverage, must have experienced larger improvement in their carbon intensity.

We further look into possible transmission channels through which financial leverage affects carbon intensity. To this end, we estimate a quantile panel regression, controlling for the relevant fixed effects using the Mundlak approach. We find that improvement in carbon intensity from an extra unit of financial leverage typically happens for firms which are very carbon intensive. There is no evidence that carbon efficient firms can further reduce their carbon footprint by taking up more debt. We explain this pattern by the difference in technologies necessary to improve firms' carbon performance, i.e. if those are rather technologies which require further innovation effort or whether the technology is ready to be adopted.

Financing innovation and technology adoption requires a range of financial products tailored to different stages of development and risk profiles. Venture capital is crucial for early-stage startups, providing the necessary funds to develop and commercialize new technologies. Angel investors also play a significant role at this stage, offering both capital and mentorship. For more mature companies, private equity and corporate bonds can be effective in raising large sums for scaling operations and expanding market reach. Government grants and subsidies are essential in reducing the financial burden of R&D, especially in high-risk areas. Additionally, crowdfunding platforms have emerged as a popular means for smaller projects to gain initial funding from a broad base of supporters. Bank loans and lines of credit are traditional but still vital, particularly for established firms looking to adopt new technologies.

While our study points out that traditional long-term finance can be an effective way to finance technology diffusion among the ETS firms, the results also suggest that financial leverage have its limits in supporting decarbonization. For very carbon inefficient firms, external debt can help to implement the necessary improvements in production processes. As firms take up more debt and improve their carbon intensity, the effectiveness of additional leverage decreases. We also find that firms which are less debt dependent observe faster improvement in carbon technology within sector.

The results suggest that while external finance helps firms to prepare for the low-carbon future and to distribute green technologies within sector, from the aggregate perspective debt-driven decarbonization is not enough to deliver on the EU climate targets. Adequate financial solutions need to support the entire technology development process from early innovation and technological breakthroughs, through the scale up, to the technology diffusion. While the long-term debt seems to help with the green technology adoption, it is rather risk-sharing capital which helps to develop and scale up the new technology.

Adequate financing is an indispensable element of any successful green transition strategy. While we provide early insights into how external leverage can support the greening of the manufacturing sector, other sectors deserve further scrutiny. A natural continuation of this study is to explore the finance-decarbonization nexus among power producers and households. Furthermore, the approach can be further extended by event studies or natural experiments, to better determine the direction of causality between finance and the adoption of low-carbon technologies.

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Appendix A. Sources of the EU Emissions Trading System (ETS) data

- Union Registry
  https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/union-registry_en
- ETS-ORBIS correspondence table
  https://data.jrc.ec.europa.eu/collection/id-0115
- Sectoral classification of Phase II installations
  https://www.eea.europa.eu/data-and-maps/data/european-union-emissions-trading-schem
  eu-ets-background-note/translation-of-activity-codes

Appendix B. Detailed results

Table B.1: Debt overhang, maturity structure and carbon intensity.

	(1) log(CO2/VA)	(2) log(CO2/VA)	(3) log(CO2/VA)	(4) log(CO2/VA)
Long-term debt ratio	-0.464**	0.191	-0.372**	0.141
	(0.185)	(0.156)	(0.186)	(0.161)
(Long-term debt ratio)^2	0.671**	-0.680***	0.476*	-0.615**
	(0.284)	(0.261)	(0.288)	(0.270)
Short-term debt ratio	-0.130	0.110	-0.108	0.147
	(0.270)	(0.225)	(0.252)	(0.233)
(Short-term debt ratio)^2	-0.462	-0.215	-0.394	-0.199
	(0.637)	(0.504)	(0.555)	(0.516)
Tangible investment	0.009	-0.028	0.011	-0.022
	(0.026)	(0.017)	(0.025)	(0.017)
RoA	-0.760***	-0.733***	-0.816***	-0.763***
	(0.155)	(0.118)	(0.152)	(0.117)
Taxes payable / EBITDA	0.170***	-0.003	0.168***	-0.004
	(0.034)	(0.021)	(0.035)	(0.021)
Cash ratio	-0.236*	-0.148	-0.203	-0.191
	(0.135)	(0.141)	(0.135)	(0.122)
Total assets (log)	-0.330***	-0.161***	-0.325***	-0.188***
	(0.011)	(0.055)	(0.011)	(0.055)
Firm age	0.001	-0.004	0.001	-0.004
	(0.001)	(0.005)	(0.001)	(0.005)
N. of installations	0.052***	0.173***	0.055***	0.186***
	(0.008)	(0.026)	(0.008)	(0.027)
Free em. allowance	1.202***	0.682***	1.200***	0.596***
	(0.026)	(0.085)	(0.025)	(0.080)
Constant	4.256***	1.228	4.153***	1.721*
	(0.187)	(1.003)	(0.188)	(1.000)
Firm-level FE	No	Yes	No	Yes
Country x Year FE	Yes	Yes	No	No
Sector x Year FE	Yes	Yes	No	No
Country x Sector x Year FE	No	No	Yes	Yes
Observations	12,382	12,257	12,291	12,166
R-squared	0.356	0.882	0.404	0.889
Adjusted R-squared	0.342	0.862	0.367	0.864

*Notes: Column (1): baseline model with country-year and sector-year fixed effects. Column (2): Model (1) with firm-level fixed effects. Column (3): baseline model with country-sector-year fixed effects. Column (4): Model (3) with firm-level fixed effects. All independent variables are lagged by one period. Robust standard errors are reported in parentheses. *, **, and *** imply significance at the 10%, 5%, and 1% significance level respectively. Source: Authors' calculations based on EU ETS and Orbis.*

Table B.2: Financial leverage and carbon intensity per quartile.

	q=0.25 log(CO2/VA)	q=0.5 log(CO2/VA)	q=0.75 log(CO2/VA)	q=0.25 log(CO2/VA)	q=0.5 log(CO2/VA)	q=0.75 log(CO2/VA)
Long-term debt ratio	0.130	-0.198	-0.300*	0.038	-0.057	-0.201
	(0.128)	(0.138)	(0.168)	(0.152)	(0.164)	(0.124)
Short-term debt ratio	0.881***	0.114	-0.246	0.220	0.191	0.408
	(0.173)	(0.155)	(0.212)	(0.259)	(0.241)	(0.266)
Tangible investment	-0.060	0.011	-0.038	0.003	0.026	0.021
	(0.047)	(0.050)	(0.038)	(0.032)	(0.035)	(0.038)
RoA	0.271	-0.365	-0.702***	-0.949***	-0.914**	-0.966***
	(0.302)	(0.314)	(0.215)	(0.223)	(0.362)	(0.302)
Taxes payable / EBITDA	0.032	0.060	0.105	-0.059	-0.089**	0.055
	(0.075)	(0.061)	(0.069)	(0.073)	(0.039)	(0.057)
Cash ratio	0.461*	0.186	0.099	0.429	0.166	0.243
	(0.255)	(0.257)	(0.309)	(0.332)	(0.305)	(0.342)
Total assets (log)	-0.306***	-0.266***	-0.300***	-0.367***	-0.128*	-0.134
	(0.013)	(0.022)	(0.027)	(0.121)	(0.075)	(0.086)
Firm age	0.000	0.002*	0.003**	0.004	-0.001	-0.005
	(0.002)	(0.001)	(0.002)	(0.007)	(0.006)	(0.008)
N. of installations	0.091***	0.037***	-0.013	0.187	0.075**	0.123
	(0.012)	(0.010)	(0.010)	(0.121)	(0.038)	(0.085)
Free em. allowance	0.970***	1.038***	1.413***	1.433***	1.238***	1.243***
	(0.041)	(0.057)	(0.090)	(0.405)	(0.239)	(0.361)
Constant	6.977***	7.313***	10.085***	4.065***	4.077***	6.673***
	(0.538)	(0.619)	(0.595)	(0.781)	(0.927)	(1.060)
Firm-level group averages	No	No	No	Yes	Yes	Yes
Country x Sector x Year group averages	Yes	Yes	Yes	No	No	No
Observations	5,312	5,312	5,312	5,312	5,312	5,312
R-squared	0.322	0.327	0.303	0.274	0.280	0.275

*Notes: Quartile results for q=0.25, q=0.5 (median) and q=0.75. All independent variables are lagged by one period. Standard errors are clustered at the group average level and reported in parentheses. *, **, and *** imply significance at the 10%, 5%, and 1% significance level respectively. Source: Authors' calculations based on EU ETS and Orbis.*

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