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Uneven Burdens: Heterogeneity in Compliance Costs under the EU ETS

SHORT PAPER

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Abstract

This paper proposes a simple empirical framework to measure installation-level compliance costs under the EU Emissions Trading System (EU ETS). Using installation-level emissions data and institutional features of allowance allocation, we derive a tractable measure of compliance costs. Applying the method to Phase III of the EU ETS (2013–2020), we document that, on average, compliance costs amount to about €1.4 per ton of output, or equivalently about €5.4 per ton of CO_2. Beyond this average magnitude, we also find substantial heterogeneity in compliance costs across installations. A Shapley decomposition of the variance shows that most of the total variation arises from firm-level differences rather than sector or country effects. Linking installations to firm-level balance sheet data reveals that firm age is a key determinant of compliance costs, consistent with technological lock-in and capital-vintage effects, although the underlying relationship may be nonlinear and possibly non-monotonic. We further provide a back-of-the-envelope calculation of the gains from permit trading, showing that access to the permit market generates economically meaningful cost savings at the installation level, averaging about €74,400 per installation per year. These findings highlight the efficiency advantages of emissions trading systems.

Keywords: compliance costs; technological lock-in; EU ETS.

JEL codes: L50, L60, Q52, Q58

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1 Introduction

A central question in the economics of environmental regulation is how costly it is for firms to comply with climate policy (Gillingham and Stock, 2018; Colmer et al., 2025). In emissions trading systems such as the European Union Emissions Trading System (EU ETS), firms can comply either by reducing emissions internally or by purchasing emission allowances on the market. While allowance prices and emissions are observable, the underlying compliance costs faced by regulated firms are not. Yet these costs are crucial for quantifying both the efficiency and the distributional consequences of carbon pricing. In particular, the efficiency advantage of emissions trading rests on heterogeneity in abatement costs: if firms differ in their marginal costs of reducing emissions, trading allows reductions to be undertaken where they are cheapest. Despite the central role of this mechanism, empirical evidence on how compliance costs vary across firms and installations remains scarce. The policy relevance of compliance costs has become particularly salient in light of the current debate at the EU level on EU ETS reform (European Commission, 2026).

This paper proposes a simple empirical framework to measure installation-level compliance costs under the EU ETS. Building on a parsimonious model of abatement and allowance trading, we derive a tractable measure of compliance costs per ton of output that can be implemented using installation-level emissions data and institutional features of the EU ETS allocation rules. The approach combines information on emissions, allowance allocation, and sectoral benchmark intensities to recover the key components determining compliance costs, including abatement efficiency and output dynamics. Despite its simplicity, the method captures the main economic mechanisms underlying firms' compliance decisions and can be implemented using widely available administrative data.

We apply this framework to a large sample of installation-level data from Phase III of the EU ETS (2013–2020) for a set of energy-intensive sectors, obtained from the EU Operator Holding Accounts (EU OHA, 2024). On average, our measure implies compliance costs of about €1.4 per ton of output, or equivalently about €5.4 per ton of CO_2, across the installations in our sample. This magnitude sits comfortably within the range of annual average allowance prices observed during Phase III, roughly €4.45 to €24.84 per ton of CO_2 between 2013 and 2019. This provides a useful internal consistency check on our empirical strategy.

Our estimates also reveal substantial heterogeneity in compliance costs. While part of the variation reflects differences across sectors and countries, a large share arises across installations operating within the same sector, as shown by a Shapley decomposition of the variance.

To explore the sources of this heterogeneity, we link installation-level data to time-varying firm-level balance-sheet information from Orbis (Bureau van Dijk) and run a battery of regression models. Among the firm characteristics we examine, firm age emerges as the most important predictor of

compliance costs. Older firms tend to face significantly higher compliance costs, even within the same sector and country. Quantitatively, our estimates imply that firm age is positively and significantly associated with compliance costs, within a sector and controlling for country-year shocks. This pattern is consistent with technological lock-in: older firms are more likely to operate legacy capital and production technologies that are less compatible with low-carbon production processes, implying higher abatement costs. Additional analysis suggests that the relationship may be nonlinear and possibly non-monotonic, reflecting capital-vintage effects associated with the replacement cycle of productive assets.

This relationship also provides a useful validation of our measurement approach. The positive association between compliance costs and firm age is consistent with well-established insights on capital vintage and technological inertia in industrial production, lending further credibility to the proposed empirical strategy.

Our paper relates to three strands of the literature. First, it relates to the empirical literature evaluating the effects of the EU ETS on emissions and firm behavior (e.g., Calel and Dechezleprêtre (2016), Marin et al. (2018), Dechezleprêtre et al. (2023), Bortolan et al. (2026)). While this literature has generated important insights into the impacts of carbon pricing under the EU ETS, it has paid relatively little attention to the direct measurement of compliance costs at the installation level. Second, the paper contributes to the literature on heterogeneity in abatement costs and the efficiency of market-based environmental policy instruments. Commonly used indicators are based on aggregate pollution abatement costs and expenditures at the country, regional, or sectoral level (Co and List (2000); Keller and Levinson (2002)). Other studies have proposed sectoral approaches based on comparisons between emissions and allowances (e.g., Levinson (2001) and Borghesi et al. (2015)). However, these measures do not allow for a full exploration of cross-installation variation within countries and sectors and therefore have limited applicability when assessing firm-level effects of environmental regulation. Third, our findings connect to the literature on technological heterogeneity and lock-in in environmental regulation, highlighting how firm age and legacy capital shape firms' responses to carbon pricing. Conventional attempts to model and estimate abatement technologies at the installation level follow an engineering approach, which relies on subjective evaluations by engineering experts (Pizer and Kopp (2005)). Yet this approach can be problematic when applied on a broad scale, because it requires detailed information on the specific characteristics of individual plants, unless one makes strong assumptions about the degree of technological similarity across firms. More recent work uses indirect clustering procedures (Belloc and Valentini (2024)); however, these approaches do not link technological differences to potential heterogeneity in compliance costs.

Our paper makes four main contributions. First, we propose a simple and transparent method to recover installation-level compliance costs using administrative data and institutional features of the EU ETS. Second, we document substantial heterogeneity in compliance costs, showing that firm-level

differences dominate sectoral and country variation. Third, we identify firm age as a key driver of this heterogeneity, consistent with a technological lock-in mechanism linking capital vintage to the cost of complying with carbon pricing (Noailly and Smeets, 2015). Finally, we provide a back-of-the-envelope estimate of the gains from permit trading, showing that access to the permit market generates sizable compliance cost savings for many installations.

These findings have important policy implications. The large heterogeneity in compliance costs across installations reinforces the efficiency advantages of emissions trading systems relative to uniform regulatory standards. At the same time, the strong role of firm age suggests that technological lock-in may slow the adjustment of carbon-intensive sectors to carbon pricing. One possible interpretation is that the relatively low carbon prices prevailing during much of Phase III—when average annual allowance prices ranged between €4.45 and €7.69 from 2013 to 2017 before increasing to €15.88 in 2018 and €24.84 in 2019—may have provided limited incentives for technological upgrading, allowing firms to continue operating older production technologies.

The remainder of the paper proceeds as follows. Section 2 introduces the empirical framework and describes how we recover the key components required to measure installation-level compliance costs. Section 3 presents the empirical results, documenting the distribution of compliance costs, analyzing their determinants using firm-level data, and providing a back-of-the-envelope estimate of cost savings in the EU ETS. Section 4 concludes.

2 Empirical framework

2.1 A model of compliance costs

Let X_{its} and Y_{its} be, respectively, the emission and output levels of installation i operating in sector s in year t, and $x_{its} \equiv X_{its}/Y_{its}$ be the corresponding emission-to-output ratio (or emission intensity). Both X_{its} and Y_{its} are measured in tons. We express abatement in terms of reduction in the emission intensity and define it as $a_{its} = \bar{x}_{its} - x_{its}$, where $\bar{x}_{its}$ is the Business-As-Usual (BAU) emission intensity in the absence of abatement, with $x_{its} \leq \bar{x}_{its}$.

Total compliance costs for installation i operating in sector s in year t are defined as follows:

$$C_{its} = \beta_{its} Y_{its} a_{its}^{\theta} + P_t D_{its} \tag{1}$$

with the exponent $\theta > 1$ being common to all installations, and where $\beta_{its} > 0$ is an abatement cost parameter, P_t is the allowance price, and D_{its} is the demand for allowances. The first term on the right-hand side of (1) is the cost of abatement implying that the greater the output level, the greater the cost of reducing the emission-to-output ratio; the second term represents the costs of buying or the revenue of selling allowances. The net demand for allowances is:

$$D_{its} = Y_{its}(\bar{x}_{its} - a_{its}) - \hat{X}_{its} \tag{2}$$

with $\hat{X}_{its}$ being the number of allowances allocated to installation i in year t. If D_{its} is negative, the installation is selling allowances.

The optimal choice for each installation given Y_{its} is to reduce the emission intensity to the point where the marginal cost of abatement is equal to the marginal net benefit of trading allowances. Under this condition, compliance costs C_{its} in (1) are minimized and the optimal level $\mathbf{a}_{its}$ of abatement is:

$$\mathbf{a}_{its} = \left(\frac{P_t}{\theta\beta_{its}}\right)^{\frac{1}{\theta-1}} \tag{3}$$

which is increasing in the price of allowances and decreasing in the abatement cost parameter.

2.2 Recovering installation-level compliance costs

We want to measure empirically installation i's compliance costs per ton of output (i.e. the normalized compliance cost $c_{its} = \frac{C_{its}}{Y_{its}}$), where total installation i's compliance costs are defined as in (1). Given (2) and (3), and since P_t can be observed, to compute our empirical measure of installation i's compliance costs we need to recover Y_{its}, β_{its} and $\bar{x}_{its}$.

We approximate $\bar{x}_{its}$ empirically, using installation-level emissions intensity observed prior to the policy period. Specifically, we use the median emission intensity observed over the years 2005–2008, consistent with the reference period used by the European Commission to compute installations' historical activity levels for free allocation purposes under Phase III, so that

$$\bar{x}_{is} = \frac{X^0_{is}}{Y^0_{is}} \tag{4}$$

where X^0_{is} and Y^0_{is} are the 2005-08 median level of emissions and output, respectively. While X^0_{is} is observed, Y^0_{is} can be recovered from the following allowance allocation rule of Phase III (2013-2020):

$$\hat{X}_{its} = \tilde{x}_s f_{ts} k_t Y^0_{is} \tag{5}$$

In (5), $\tilde{x}_s$ is the sectoral benchmark emission intensity, f_{ts} represents the carbon leakage exposure factor (CLEF) and k_t is the cross-sectoral correction factor (CSCF).[1] From (5), we can write Y^0_{is} as:

$$Y^0_{is} = \frac{\hat{X}_{its}}{\tilde{x}_s f_{ts} k_t} \tag{6}$$

[1]The CLEF determines the fraction of benchmark emissions that an installation receives for free. The Commission compiled a list of sectors deemed to be at significant risk of carbon leakage, which includes all six sectors analyzed in this paper. Installations in these sectors received all of their benchmark emissions for free (CLEF = 1). All other sectors received 80% of benchmark emissions for free in 2013, declining linearly to 30% in 2020. The total amount of free allowances calculated in this way may exceed the overall cap for non-electricity sectors. The CSCF ensures that this does not occur. In the years 2013-19, the CSCF was always below one, forcing the total amount of free allowances to equal the overall cap for industry.

where all the terms on the right-hand side are observed. Hence, Y_{is}^0 can be computed and therefore also $\bar{x}_{is}$ as in (4).

The output level Y_{its} is not directly observed, so we construct a proxy for it, denoted $\tilde{Y}_{its}$, using the baseline activity level Y_{is}^0 recovered from (6). Output may change over time relative to this baseline for several reasons, which we group into two broad categories. The first consists of common, within-sector variations, such as product demand shocks that do not alter emission-to-output ratios. These shocks are shared across installations within a sector-year and generate a time-varying component in emissions at the sectoral level. The second category includes all remaining sources of variation that affect emission intensity, such as economy-wide and idiosyncratic technological changes. These technological factors break the proportionality between emissions and output.

Ideally, one would isolate the variation in emission intensity and use the remaining component of emissions to proxy output, relying on a stable proportionality between emissions and production. However, this is not feasible empirically, as technological changes cannot be directly identified. We therefore adopt a more conservative strategy and exploit only the variation in emissions driven by product-sector shocks, assuming that common within-sector variations are mostly driven by product demand shocks that do not alter emission intensity.

In an estimation framework, we decompose the proportional change in emissions relative to the baseline level, defined as $\Delta_{its}^{X^0} = \frac{X_{its} - X_{is}^0}{X_{is}^0}$, as follows:

$$\Delta_{its}^{X^0} = \alpha_s + \underbrace{\text{Sector-year effects}_{st}}_{\substack{\text{Product-demand} \\ \text{shocks } (\delta_{ts})}} + \underbrace{\text{Time effects}_t + \text{Idiosyncratic effects}_{its}}_{\substack{\text{Technological} \\ \text{shocks}}} \tag{7}$$

Let δ_{ts} denote the estimated sector–year effects from (7). For each year t and sector s, δ_{ts} captures the proportional change in emissions relative to the baseline period induced by sector-wide shocks. Under the identifying assumption that product-sector (demand) shocks are primarily reflected in emissions through their impact on output, we use δ_{ts} to construct time-varying output as:

$$\tilde{Y}_{its} = Y_{is}^0(1 + \delta_{ts}) \tag{8}$$

Intuitively, we let sector-wide movements in emissions scale baseline output, treating within-sector common variation as a proxy for changes in production levels. Our estimated output $\tilde{Y}_{its}$ therefore serves as our proxy for installation i's actual output Y_{its}.[2]

[2]As an external validity check, we correlate year-on-year growth in $\tilde{Y}_{its}$ with growth in employees, a standard variable input closely tied to production volume and, being a physical quantity unaffected by price fluctuations, particularly well suited for comparison with our physical output measure. Using the Orbis-matched sample introduced in Section 3.4, the two growth rates are strongly and significantly correlated ($\rho = 0.65$, $p < 0.01$), supporting the validity of our time-varying output measure. The correlation is below 1, consistent with the well-documented fact that employment adjusts only partially to output changes due to hiring and firing costs (see, e.g., Schoefer (2025)).

Finally, the abatement cost parameter β_{its} can be calculated from (3) as

$$\tilde{\beta}_{its} = \frac{P_t}{\theta}\tilde{\mathbf{a}}_{its}^{1-\theta} = \frac{P_t}{\theta}\left(\bar{x}_{is} - \tilde{x}_{its}\right)^{1-\theta} \tag{9}$$

with $\bar{x}_{is}$ defined by (4) and where

$$\tilde{x}_{its} = \frac{X_{its}}{\tilde{Y}_{its}} \tag{10}$$

Now we have all the ingredients to compute, for any $\theta > 1$, the normalized compliance cost of any installation i. From (1), (2) and (9):

$$\tilde{c}_{its} \equiv \frac{C_{its}}{\tilde{Y}_{its}} = \frac{1}{\theta}P_t\tilde{\mathbf{a}}_{its} + P_t\left[\bar{x}_{is} - \tilde{\mathbf{a}}_{its} - \hat{x}_{its}\right] = P_t\left[\frac{1}{\theta}(\bar{x}_{is} - \tilde{x}_{its}) + \tilde{x}_{its} - \hat{x}_{its}\right] \tag{11}$$

where $\hat{x}_{its}$ is the allowance allocation per ton of output, i.e.:

$$\hat{x}_{its} = \frac{\hat{X}_{its}}{\tilde{Y}_{its}} \tag{12}$$

3 Compliance cost heterogeneity: empirical evidence

To study our compliance cost measure empirically in a tractable way, we set $\theta = 2$ in (1), which corresponds to the standard case of quadratic abatement costs. The quadratic specification represents the simplest nonlinear approximation to a generic convex cost function and ensures increasing marginal abatement costs while maintaining analytical tractability. Similar formulations are widely used in theoretical models of environmental regulation (see, e.g., Weitzman (1974)), where convex abatement costs play a central role in determining the welfare properties of alternative policy instruments. In Appendix A we show, using data introduced below, that the distribution of compliance costs is robust to the choice of θ: results computed with $\theta = 3$ and $\theta = 4$ are very similar. The empirical distribution of our compliance costs measure is therefore unlikely to be driven by a mis-specified value of θ. In subsection 3.5, we will discuss another advantage of setting $\theta = 2$: It produces a more conservative estimate of cost savings from emissions trading than higher values of θ.

3.1 Data, sample, and sectors

While in principle our method can be applied to the full universe of EU ETS installations, we focus on a subset of sectors for which product-specific benchmark emission intensities can be consistently matched to the sectoral classification of installation-level data in the EU Operator Holding Accounts (EU OHA). We restrict attention to Phase III (2013–2020) and exclude 2020 because the COVID-19 shock could distort output and emissions dynamics in ways that are not representative of the policy environment. We also limit the analysis to sectors with at least 100 installation-year observations and apply a sector-specific trimming procedure, dropping observations below the 5th and above the 95th percentiles of the key

model-generated variables (Y_{is}^0, $\bar{x}_{is}$ and δ_{ts}).[3] Allowance prices were calculated by taking the average of daily prices from ICE Endex EUA (2026) for the calendar year.

The final sample covers six energy-intensive sectors: Glass, Cement clinker, Other pulp, Lime and dolomite, Paper and cardboard, and Pig iron and steel. As already mentioned, in these sectors, installations received all of their benchmark emissions for free (i.e., the carbon leakage exposure factor, CLEF, is equal to 1). Figure 1 reports within-sector average emissions per installation. The figure highlights the strong differences in average scale across sectors: Cement clinker installations are, on average, much larger emitters than installations in the other sectors, while Other pulp and Paper and cardboard are at the lower end. This matters for interpretation because our core outcome is normalized (per ton of output): sector differences in scale do not mechanically translate into sector differences in compliance burden, and the dispersion in costs we document below is not simply a reflection of larger installations emitting more.

[insert Figure 1 about here]

3.2 Distribution of compliance costs

We compute normalized compliance costs $\tilde{c}_{its}$ using (11) with $\theta = 2$. Figure 2 plots kernel densities of $\tilde{c}_{its}$ by sector.

[insert Figure 2 about here]

Two patterns stand out. First, there is meaningful between-sector heterogeneity in the location and shape of the distributions. Some sectors display relatively concentrated densities at low compliance costs, while others exhibit distributions shifted to the right, suggesting systematically higher normalized burdens. This is consistent with the intuition that sectoral technological constraints, process emissions, and benchmark stringency differ across industries. Second—and more important—the figure shows substantial within-sector heterogeneity. Even within the same sector, costs span a wide range, with long right tails for several sectors. This within-sector dispersion is precisely the object that aggregate measures or sector-level proxies tend to conceal. From a policy perspective, these distributions imply that policies targeted at "the average firm" in a sector may miss much of the relevant variation in compliance burdens and abatement opportunities.

While our preferred measure expresses compliance costs per ton of output, it is worth pausing on how this figure relates to the more conventional per-ton-of-CO_2 metric typically used in the literature. Appendix C shows the straightforward relation between the two measures: since compliance cost per

[3]These restrictions mean that our results should be interpreted with some caution: the analysis covers a limited set of energy-intensive sectors selected on data availability grounds, and observations are missing even within those sectors due to the trimming procedure and matching requirements. As such, our findings may not be fully representative of the broader population of EU ETS installations. Descriptive statistics are in Table A.1 in Appendix B.

ton of output is $\tilde{c}_{its} \equiv C_{its}/\tilde{Y}_{its}$ and emission intensity is $x_{its} = X_{its}/\tilde{Y}_{its}$, the per-ton-of-$CO_2$ compliance cost $\tilde{c}^{CO2}_{its}$ is obtained by rescaling our preferred measure by the installation's emission intensity: $\tilde{c}^{CO2}_{its} = \tilde{c}_{its}/x_{its}$. In Appendix C, Figure 5 confirms that the two measures are highly and consistently correlated within each sector, and Table A.2 reports summary statistics for both.[4] On average, compliance costs amount to about €1.4 per ton of output and about €5.4 per ton of CO_2 in our sample—a figure that sits comfortably within the range of allowance prices observed during Phase III (roughly €4.5–25 per ton of CO_2 between 2013 and 2019). This provides an additional internal consistency check on our empirical strategy: since our measure is built on the assumption that firms equate marginal abatement cost with the allowance price, the fact that it recovers compliance costs of a comparable order of magnitude (and generally below) the observed allowance price is consistent with our theoretical framework.

The patterns in Table A.2 already hint at where most of the variation in compliance costs is likely to come from. Sector means differ considerably—from about €0.20 per ton of output in Other pulp to over €2.5 in Lime and dolomite, a more than tenfold spread—confirming that sectoral technological and process characteristics matter. Yet within-sector dispersion is comparably large: the coefficient of variation (the ratio of the standard deviation to the mean) is close to or above 1 in almost every sector for the per-ton-of-output measure, and exceeds 1 in four of the six sectors for the per-ton-of-CO_2 measure, ranging from 0.73 in Cement clinker to 1.43 in Other pulp. This indicates that within-sector variation is generally of the same order of magnitude as the sector mean itself, thereby suggesting that cross-sector differences, while real, account for only part of the overall heterogeneity documented in Figure 2, and that substantial dispersion persists even among installations operating in the same sector and facing the same benchmark emission intensity. Next, we formalize this intuition through a variance decomposition that quantifies the relative contribution of sector, country, and firm-level factors to the total variation in compliance costs.

3.3 Sources of heterogeneity

To quantify the relative importance of broad versus granular drivers of compliance costs, we perform a Shapley-value decomposition of the variance of $\tilde{c}_{its}$ across three sets of fixed effects: country, sector, and firm (Shorrocks, 2013). For each factor, the Shapley share averages its marginal contribution to the R^2 of the model across all possible orderings in which the three fixed-effect sets could be introduced. This procedure has an important advantage over a simple sequential decomposition: because country, sector, and firm effects are not orthogonal to one another, the order in which they are added to the model matters, and a marginal contribution computed from a single ordering would not be directly comparable

[4] We view the per-ton-of-output measure as our preferred metric for the regression analysis that follows, since it is the more natural scale on which to interpret firm-level determinants of compliance costs such as firm age (Section 3.4); the per-ton-of-CO_2 version is offered in Appendix C as a complementary, more conventional benchmark.

across factors. The Shapley approach removes this ordering dependence and, by construction, yields shares that sum exactly to the joint R^2 of the three factors combined, with any remaining variance attributed to a residual, unexplained component. The results are reported in Table 1.

[insert Table 1 about here]

Country effects account for a small share of total variance (2.21%), while sector effects explain a considerably larger share (14.17%). Firm effects are the single largest identified source of heterogeneity, accounting for 35.07% of total variance, i.e. more than twice the combined contribution of country and sector (16.38%). All three shares are estimated precisely, with bootstrapped confidence intervals (based on 500 replications clustered at the installation level) that do not overlap. The residual component captures idiosyncratic installation-year variation not attributable to any of the three factors, such as firm-year-specific abatement decisions that are not well captured by a time-invariant firm effect.

This finding is informative for both measurement and policy. From a measurement standpoint, it confirms that recovery of compliance costs at the level of production units is valuable: broad, sector- or country-level indicators would substantially understate the extent of firm-level heterogeneity in compliance burdens, even after accounting for the sizable residual component. From a policy standpoint, the dominance of firm effects over country and sector effects underscores why carbon pricing and tradable permits can outperform "one-size-fits-all" regulatory approaches: when compliance costs differ substantially across installations within the same country and sector, uniform standards risk forcing high-cost abatement at some plants while leaving low-cost abatement opportunities unexploited at others. The fact that firm-level heterogeneity dominates geographic and sectoral heterogeneity by a wide margin further suggests that policies aimed at reducing compliance-cost dispersion should target firm-level characteristics directly, rather than relying on sector- or country-specific regulatory adjustments.

3.4 What explains firm differences?

To explore the sources of heterogeneity in greater detail, we link EU OHA installations to firm-level balance sheet data from Orbis and construct time-varying measures of firm size (employees share within sector), firm age (years since incorporation), liquidity, tangible capital intensity, and productivity (value added per employee).

We then estimate the following panel specification:

$$\tilde{c}_{its} = \alpha + \mathbf{b}\mathbf{X}_{its} + [\text{Country} \times \text{Year}]\ \text{FE}_{ct} + \eta_{its}, \tag{13}$$

where $\mathbf{X}_{its}$ is a vector of time-varying company-level variables and $\mathbf{b}$ is its corresponding vector of parameters, α is the constant term and η_{its} the residuals. In the regression model, we also control

for country-year effects, in order to capture country-specific shocks common to installations in a given year. We run (13) with different estimators, to check the robustness of the estimates: Panel FE, Log-Linear OLS (LL-OLS), Poisson Pseudo–Maximum Likelihood (PPML), Gamma GLM with log link. In the Log-Linear OLS regression, the dependent variable is $\ln(\tilde{c}_{its})$. Obviously, the Panel FE model controls for installation fixed effects absorbing time-invariant plant characteristics (including persistent technological differences and unobservable sector-specific factors). Table 2 reports the results.

[insert Table 2 about here]

The most robust pattern is the role of firm age. Across specifications, the age coefficient is always positive and statistically significant. In the Panel FE model (our preferred specification, since it is the most conventional way to absorb unobserved, time-invariant installation heterogeneity) the coefficient on age is around 2.06.[5] Because this specification includes installation fixed effects, the age coefficient is identified purely from within-installation variation over time, net of any common country-year shocks; it therefore captures how compliance costs evolve as a given firm ages, rather than reflecting differences across firms or sectors with different age profiles and production technologies. This is an economically and statistically meaningful effect, particularly given the wide dispersion of compliance costs documented in Figure 2.

While this estimate summarizes the average relationship, Appendix D suggests that the association between firm age and compliance costs may not be fully linear. Compliance costs increase steeply during the first two decades of a firm's life, peak around 20–30 years of age, and then gradually decline. This pattern is consistent with a lock-in mechanism operating through capital vintage (Noailly and Smeets, 2015). McKinsey & Company (2009) reports that major industrial plants and production infrastructures typically have an operational lifespan of roughly 20–30 years. Under this interpretation, young firms may benefit from relatively recent and more energy-efficient equipment, while firms around 20–30 years old may still operate the capital installed at entry, which has become relatively obsolete but has not yet been fully replaced. The subsequent decline in compliance costs for older firms may reflect major capital replacement, modernization, or restructuring episodes, which weaken the link between firm age and the vintage of production technologies.

By contrast, the coefficients on size and the additional balance-sheet controls are comparatively imprecise and less stable across specifications. If anything, firms with higher financial liquidity tend to have lower compliance costs, arguably because they are more capable of investing in new and less polluting technologies. This is consistent with previous literature on the firm-level determinants of environmental efficiency (e.g., Belloc et al. (2025)). Taken together, these results suggest that the

[5]Identification of this coefficient relies on our installation-year panel being unbalanced within country-year cells, since installations enter, exit, or are trimmed at different points in time.

main observable correlate of compliance-cost heterogeneity in our setting is not productivity or short-run financial conditions per se, but rather characteristics related to capital vintage and technological obsolescence.

3.5 Cost saving from emissions trading

Our empirical framework allows us to compute a simple measure of the gains from permit trading under the EU ETS. Intuitively, the idea is to compare the compliance costs that an installation would incur in a counterfactual scenario without access to the permit market with the costs observed when trading is allowed. In the no-trade benchmark, each installation must meet its emissions constraint solely through internal abatement. We set the allowed emissions per installation equal to the amount of free allowances in the EU ETS.[6] By contrast, under the trading regime firms can combine internal abatement with permit purchases or sales, depending on their relative abatement costs.

Let $\hat{a}_{its} = \bar{x}_{is} - \hat{x}_{its}$ be the abatement level required for installation i in sector s at time t in the counterfactual no-trade scenario, with $\hat{x}_{its}$ given by (12). From (1) and (11), the cost saving from emission trading can be written as:

$$\text{Cost saving}_{its} = \underbrace{\beta_{its}\tilde{Y}_{its}\hat{a}_{its}^{\theta}}_{\substack{\text{Compliance}\\ \text{costs}\\ \text{w/out trade}}} - \underbrace{\left[\beta_{its}\tilde{Y}_{its}\tilde{\mathbf{a}}_{its}^{\theta} + P_t D_{its}\right]}_{\substack{\text{Compliance}\\ \text{costs}\\ \text{w/ trade}}} = \tilde{Y}_{its}\left(\frac{P_t}{\theta}\tilde{\mathbf{a}}_{its}^{1-\theta}\hat{a}_{its}^{\theta} - P_t\left[\frac{1}{\theta}\tilde{\mathbf{a}}_{its} + \hat{a}_{its} - \tilde{\mathbf{a}}_{its}\right]\right) \quad (14)$$

where $\tilde{Y}_{its}$ is given by (8). In Appendix F we show that the cost savings estimate (14) is increasing in θ. This gives us another reason for setting $\theta = 2$ rather than higher values of θ in our estimates: Setting $\theta = 2$ produces a more conservative estimate of cost savings from emissions trading.

For $\theta = 2$, (14) simplifies to:

$$\text{Cost saving}_{its}(\theta = 2) = \tilde{Y}_{its}P_t\left(\frac{\hat{a}_{its}}{2\tilde{\mathbf{a}}_{its}} + \frac{1}{2}\tilde{\mathbf{a}}_{its} - \hat{a}_{its}\right) = \frac{\tilde{Y}_{its}P_t}{2\tilde{\mathbf{a}}_{its}}(\hat{a}_{its} - \tilde{\mathbf{a}}_{its})^2 = \frac{\tilde{Y}_{its}P_t}{2(\bar{x}_{is} - \tilde{x}_{its})}(\tilde{x}_{its} - \hat{x}_{its})^2 \quad (15)$$

This expression provides a simple measure of the cost saving associated with access to the permit market.

[insert Figure 3 about here]

Figure 3 reports the distribution of this cost-saving measure across installations and sectors. Two features emerge clearly. First, the estimated gains from trade are economically meaningful. On average, the annual cost saving per installation is about €74,400, while installations in the top 1 percent of the distribution save approximately €807,000 per year. These magnitudes are sizable, especially considering

[6] This is a reasonable assumption because, as explained in Section 2.2, all installations in our sample received free allowances covering their benchmark emissions (they had a CLEF of 1), subject to a pro-rata reduction to force the total amount of free allowances to equal the total industry cap (the CSCF was less than 1).

that they arise from a relatively simple comparison between compliance with and without permit trading. They therefore suggest that the flexibility embedded in the EU ETS generates non-trivial efficiency gains at the installation level.

Second, the distribution of gains from trade is highly skewed. Most installations experience modest savings, while a relatively small number of plants account for very large gains. This pattern is consistent with the heterogeneity documented in the previous subsections. If installations differ substantially in their marginal compliance costs, the opportunity to trade permits should benefit especially those plants for which the gap between internal abatement costs and market-based compliance options is largest. In this sense, the evidence provides a simple quantitative illustration of the mechanism through which emissions trading improves efficiency relative to a no-trade allocation system.

The sectoral distributions also indicate that the gains from trade are not uniform across industries. This reflects differences in technological constraints, production processes, and the scope for substituting between internal abatement and permit trading. At the same time, even within sectors the dispersion of cost savings remains substantial, further confirming that installation-level heterogeneity is a key feature of the compliance burden under the EU ETS.

These calculations should be interpreted as a back-of-the-envelope exercise rather than a full structural welfare analysis. Nevertheless, they provide a useful order-of-magnitude estimate of the efficiency gains generated by permit trading. In a context where compliance costs are highly uneven across installations, as documented in the previous sections, allowing firms to trade permits can substantially reduce the overall cost of achieving a given emissions target.[7]

4 Conclusions

This paper proposes a simple empirical framework to recover installation-level compliance costs under the EU Emissions Trading System (EU ETS). Applying the method to installation-level data from Phase III (2013–2020), we document that compliance costs are highly uneven across regulated installations. A Shapley decomposition of the variance shows that most of this variation arises from cross-firm differences rather than sector or country effects. Linking installations to firm-level balance sheet data further reveals that firm age is a key determinant of compliance costs, consistent with a technological lock-in mechanism whereby older production capital is less compatible with low-carbon technologies. A simple back-of-the-envelope calculation further suggests that access to permit trading generates economically meaningful compliance cost savings for many installations.

The simplicity of the proposed framework makes it suitable for large-scale empirical applications, but

[7] Figures 7 and 8 in Appendix E show the distributions of installation-year-level cost savings, as a percentage of compliance costs in the counterfactual no-trade scenario, by sector and by country respectively.

it also entails limitations. In particular, the approach relies on reduced-form assumptions about output dynamics and abatement technologies. Moreover, the empirical implementation relies on institutional features of the EU ETS allowance allocation rules to recover key variables—such as baseline output and emissions intensities—rather than on directly observed plant-level production data. While this strategy allows the method to be implemented using widely available administrative data, it also reflects underlying data availability constraints. Future research could extend this framework using richer plant-level information on production technologies or by applying the method to other emissions trading systems to better understand how the uneven burden of carbon pricing evolves over time. More broadly, our results highlight that when compliance costs are uneven across firms and installations, market-based instruments such as emissions trading are particularly well suited to achieving emissions reductions at minimum cost (Fowlie et al., 2016).

References

[1] Belloc, F., Bimonte, S. and Martino, R. (2025) Is TFP Clean or Dirty? The Nexus between Environmental and Economic Efficiency. *Energy Economics*, 152: 108990.

[2] Belloc, F. and Valentini, E. (2024) Dissecting Environmental Efficiency: The Role of Technology Adoption and Usage. *Journal of Economic Behavior and Organization*, 228: 106776.

[3] Borghesi, S., Cainelli, G. and Mazzanti, M. (2015) Linking Emission Trading to Environmental Innovation: Evidence from the Italian Manufacturing Industry. *Research Policy*, 44(3): 669-683.

[4] Bortolan, L., Prosperi, L., Taschini, L. and Zanin, L. (2026) Mind the Emission Gap: Firm-Level Policy Stringency Matters for Emission Reductions in the EU ETS. Unpublished manuscript, University of Edinburgh Business School.

[5] Calel, R. and Dechezleprêtre, A. (2016) Environmental Policy and Directed Technological Change: Evidence from the European Carbon Market. *Review of Economics and Statistics*, 98(1): 173-191.

[6] Co, C. and List, J. (2000) The Effects of Environmental Regulations on Foreign Direct Investment. *Journal of Environmental Economics and Management*, 40(1): 1-20.

[7] Colmer, J., Martin, R., Muûls, M. and Wagner, U.J. (2025) Does Pricing Carbon Mitigate Climate Change? Firm-Level Evidence from the European Union Emissions Trading System. *The Review of Economic Studies*, 32(3): 1625–1660.

[8] Dechezleprêtre, A., Nachtigall, D. and Venmans, F. (2023) The Joint Impact of the European Union Emissions Trading System on Carbon Emissions and Economic Performance. *Journal of Environmental Economics and Management*, 118: 102758.

[9] EU Operating Holding Accounts (2024) Available at: http://ec.europa.eu/environment/ets/oha.do.

[10] European Commission (2026) Proposal for Amending Directive 2003/87/EC and Decision (EU) 2015/1814 as Regards Driving Competitiveness and Cost-effective Decarbonisation. COM(2026) 616. Available at: https://climate.ec.europa.eu/document/download/c0b4ca8e-0e12-4b4e-9976-98c0b4224410_en.

[11] Fowlie, M., Reguant, M. and Ryan, S. (2016) Market-Based Emissions Regulation and Industry Dynamics. *Journal of Political Economy*, 124: 249-302.

[12] Gillingham, K. and Stock, J. (2018) The Cost of Reducing Greenhouse Gas Emissions. *Journal of Economic Perspectives*, 32: 53-72.

[13] ICE Endex EUA (2026) Carbon Emissions Futures Historical Data aggregated by Investing.com. Available at: https://www.investing.com/commodities/carbon-emissions-historical-data.

[14] Keller, W. and Levinson, A. (2002) Pollution Abatement Costs and Foreign Direct Investment Inflows to US States. *Review of Economics and Statistics*, 84(4): 691-703.

[15] Levinson, A. (2001) An Industry-Adjusted Index of State Environmental Compliance Costs. In Carraro, C. and Metcalf, G.E. (Eds) *Behavioral and Distributional Effects of Environmental Policy*, pp. 131-158. Chicago: University of Chicago Press.

[16] Marin, G., Marino, M. and Pellegrin, C. (2018) The Impact of the European Emission Trading Scheme on Multiple Measures of Economic Performance. *Environmental and Resource Economics*, 71: 551-582.

[17] McKinsey & Company (2009) *Pathways to a Low-Carbon Economy: Version 2 of the Global Greenhouse Gas Abatement Cost Curve*. New York, NY: McKinsey & Company.

[18] Noailly, J. and Smeets, R. (2015) Directing Technical Change from Fossil-Fuel to Renewable Energy Innovation: An Application Using Firm-Level Patent Data. *Journal of Environmental Economics and Management*, 72: 15-37.

[19] Pizer, W.A. and Kopp, R. (2005) Calculating the Costs of Environmental Regulation. In Maler, K.G. and Vincent, J.R. (Eds) *Handbook of Environmental Economics*, pp. 1307-1351. Amsterdam: Elsevier.

[20] Schoefer, B. (2025) Decomposition Procedures for Distributional Eurosclerosis at 40: Labor Market Institutions, Dynamism, and European Competitiveness. NBER Working Paper 33975.

[21] Shorrocks, A. (2013) Decomposition Procedures for Distributional Analysis: A Unified Framework Based on the Shapley Value. *Journal of Economic Inequality*, 11(1): 99-126.

[22] Weitzman, M. (1974) Prices vs. Quantities. *Review of Economic Studies*, 41(4): 477-491.

Table 1: Shapley decomposition of the variance of normalized compliance costs.

	[1] Country	[2] Sector	[3] Firm	[4] Residual	[5] Total
Shapley share (%)	2.212	14.171	35.066	48.551	100.00
Bootstrap SE	(0.488)	(1.380)	(1.405)	(1.825)	—
95% CI (bias-corrected)	[1.186, 2.785]	[11.919, 17.629]	[33.089, 36.854]	[46.512, 52.398]	—

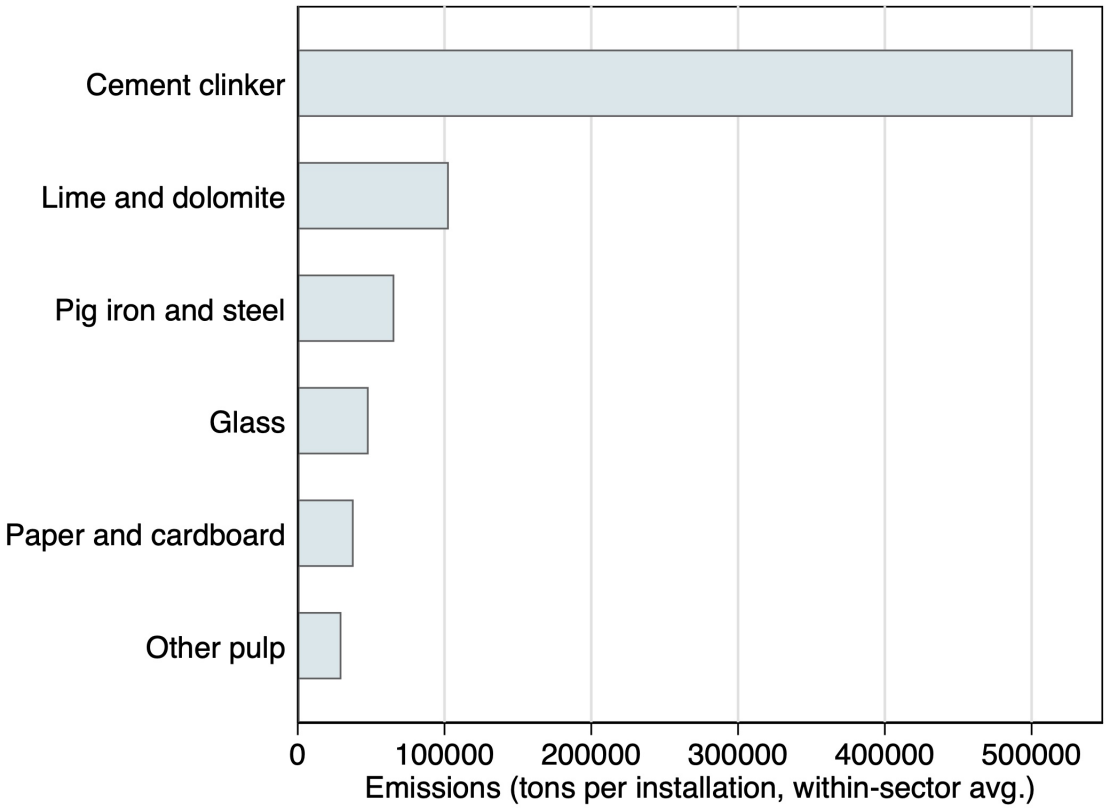
Note. Shapley shares are obtained by averaging the marginal contribution to R^2 of each fixed-effect set (country, sector, firm) across all possible orderings of inclusion, and are expressed as a percentage of the total variance of $\tilde{c}_{its}$. By construction, the four columns (country, sector, firm, residual) sum to 100%. Standard errors and bias-corrected 95% confidence intervals are based on 500 bootstrap replications (898 clusters at the installation level).

Table 2: Firm characteristics and compliance costs.

	[1] Panel-FE	[2] LL-OLS	[3] PPML	[4] GLM
Age	2.063***	0.005***	0.003***	0.004***
	(0.256)	(0.000)	(0.000)	(0.000)
Size	5.203	-2.063	0.185	1.189
	(6.383)	(1.984)	(1.162)	(1.283)
Capital intensity	-0.000	0.000	0.001*	0.000
	(0.000)	(0.000)	(0.000)	(0.000)
Productivity	0.001*	-0.000	-0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)
Liquidity	0.001	-0.029***	-0.024***	-0.021***
	(0.006)	(0.009)	(0.008)	(0.004)
Constant	-95.429***	-1.540***	-0.939***	-1.050***
	(12.185)	(0.162)	(0.155)	(0.205)
Country-year FEs	Y	Y	Y	Y
# obs.	1,966	1,960	1,960	1,960

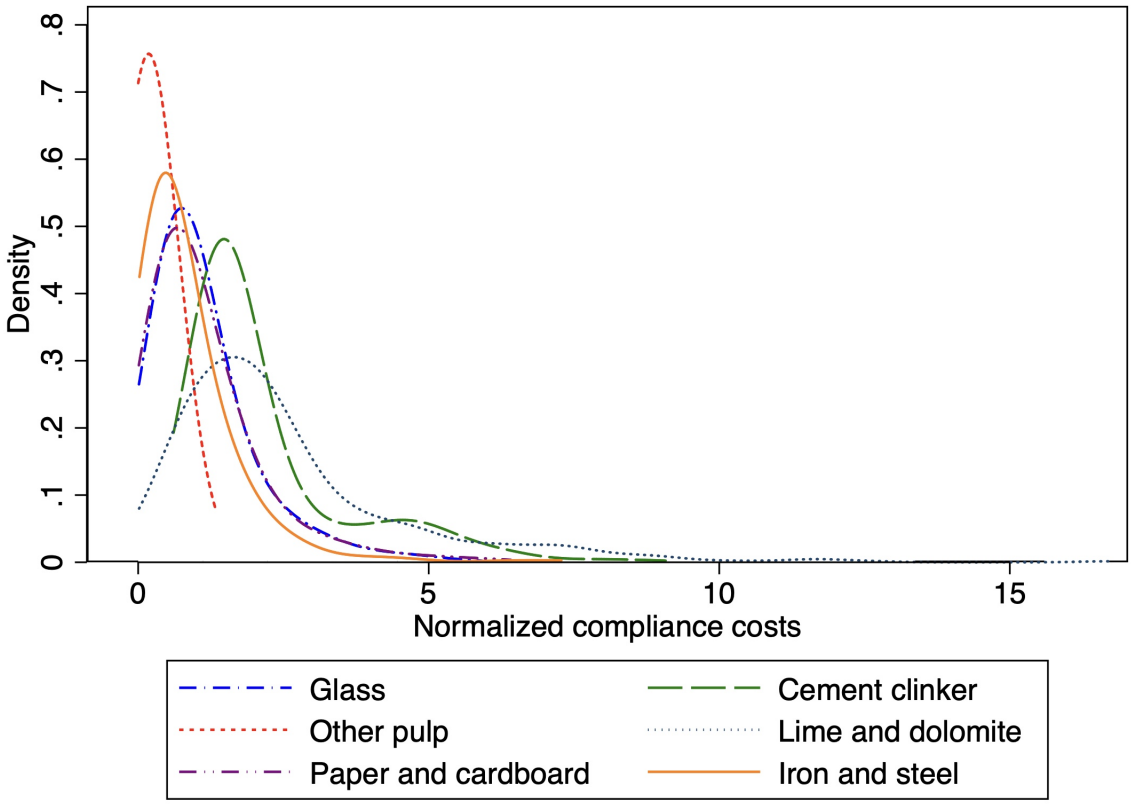
Note. Installation-level data from the EU Operator Holding Accounts (EU OHA) and Orbis (Bureau van Dijk). The sample is restricted to installations active during Phase III (2013–2020). A sector-specific trimming procedure removes observations below the 5th and above the 95th percentiles of key variables. The dependent variable is $\tilde{c}_{its}$ in columns [1] and [3]-[4], the natural logs of $\tilde{c}_{its}$ in column [2]. Estimators: Panel FE in column [1], Log-Linear OLS (LL-OLS) in column [2], Poisson Pseudo–Maximum Likelihood (PPML) in column [3], Gamma GLM with log link column [4]. Standard errors (heteroskedasticity robust) are in parentheses. Statistical significance: * significant at 10%, ** significant at 5%, *** significant at 1%.

Figure 1: Within-sector average emissions per installation.



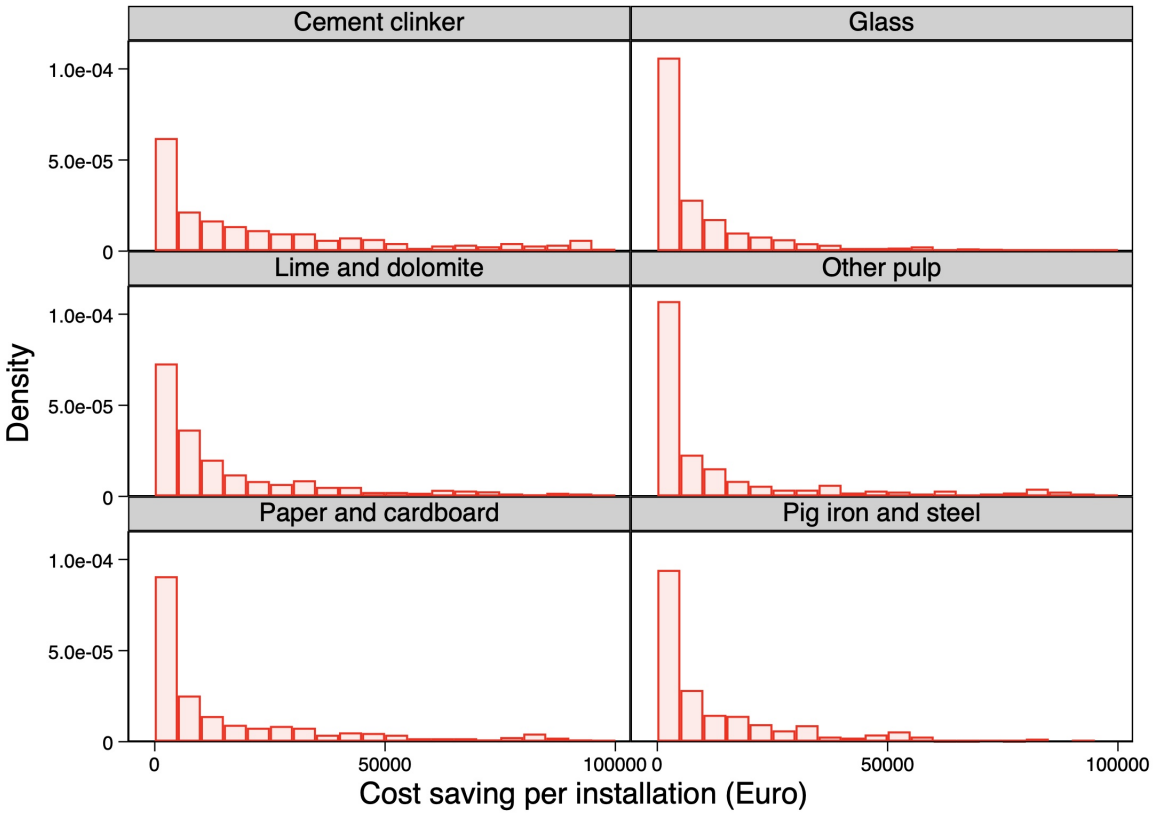
Note. Installation-level data from the EU Operator Holding Accounts (EU OHA). The sample is restricted to installations active during Phase III (2013–2020). A sector-specific trimming procedure removes observations below the 5th and above the 95th percentiles of key variables.

Figure 2: Normalized compliance costs, sector-by-sector.



Note. Installation-level data from the EU Operator Holding Accounts (EU OHA). The sample is restricted to installations active during Phase III (2013–2020). A sector-specific trimming procedure removes observations below the 5th and above the 95th percentiles of key variables. Kernel distributions of compliance costs $\tilde{c}_{its}$ obtained as in (11) with $\theta = 2$, by sector (all years).

Figure 3: Compliance cost saving in the EU ETS.



Note. Installation-level data from the EU Operator Holding Accounts (EU OHA). The sample is restricted to installations active during Phase III (2013–2020). Compliance cost saving obtained as difference between compliance costs without trade of permits and compliance costs with trade, as in (15).

Online Appendix

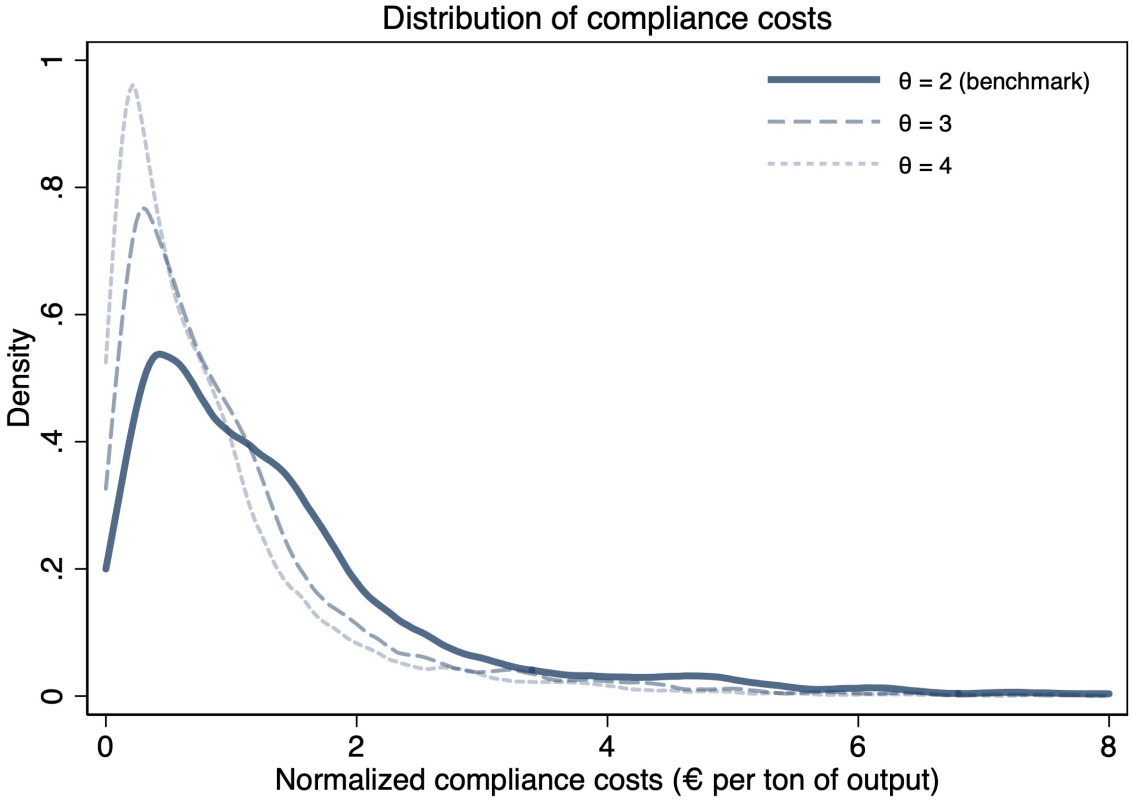
A Sensitivity of compliance costs to θ

Recall the normalized compliance cost of installation i, defined by equation (11):

$$\tilde{c}_{its} \equiv \frac{C_{its}}{\tilde{Y}_{its}} = P_t \left[\frac{1}{\theta}(\bar{x}_{is} - \tilde{x}_{its}) + \tilde{x}_{its} - \hat{x}_{its} \right]$$

In the empirical analysis in the paper we set $\theta = 2$, because this is the simplest non-linear approximation to a generic convex cost function, ensuring increasing marginal abatement costs while maintaining analytical tractability. Here we test whether different values of θ change our normalized compliance costs measure significantly. In particular, we compare empirical values of (11) with $\theta = 2, 3, 4$. Figure 4 shows that the distribution of our normalized compliance cost measure remains largely unchanged when θ varies between 2 and 4. This indicates that our results are robust to alternative values of θ.

Figure 4: Normalized compliance costs under different values of θ.



Note. Installation-level data from the EU Operator Holding Accounts (EU OHA). The sample is restricted to installations active during Phase III (2013–2020). Sectors with fewer than 100 installation-year observations are excluded. A sector-specific trimming procedure removes observations below the 5th and above the 95th percentiles of key variables. Distributions of compliance costs $\tilde{c}_{its}$ obtained as in (11), with $\theta = 2, 3, 4$ (all sectors, all years).

B Descriptive statistics

Our analysis focuses on Phase III of the EU ETS (2013–2020) and on sectors where product benchmarks can be consistently matched to installation-level data from the EU Operator Holding Accounts. We restrict the sample to sectors with at least 100 installation-year observations and trim the top and bottom 5% of key model variables. The final dataset includes six energy-intensive sectors: Glass, Cement clinker, Other pulp, Lime and dolomite, Paper and cardboard, and Pig iron and steel. Table A.1 reports descriptive statistics of the key baseline variables used in our empirical framework.

Table A.1: Descriptive statistics.

Variable	Description	# Obs.	Mean	Std. Dev	Min	Max
$\hat{X}_{its}$	Allowances, CO_2-equivalent tons	4,122	124123.4	230013.1	2737	5732056
X_{its}	Emissions, CO_2-equivalent tons	4,100	129204	228597.2	12	5073764
Y^0_{is}	Product output, 2005-08 median, tons	4,122	291911.7	654552.3	3571.01	2.42e+07
D_{its}	Demand of permits, CO_2-equivalent tons	4,100	4639.408	58892.31	-776443	1492621

Note. Installation-level data from the EU Operator Holding Accounts (EU OHA). The sample is restricted to installations active during Phase III (2013–2020). Sectors with fewer than 100 installation-year observations are excluded. A sector-specific trimming procedure removes observations below the 5th and above the 95th percentiles of key variables.

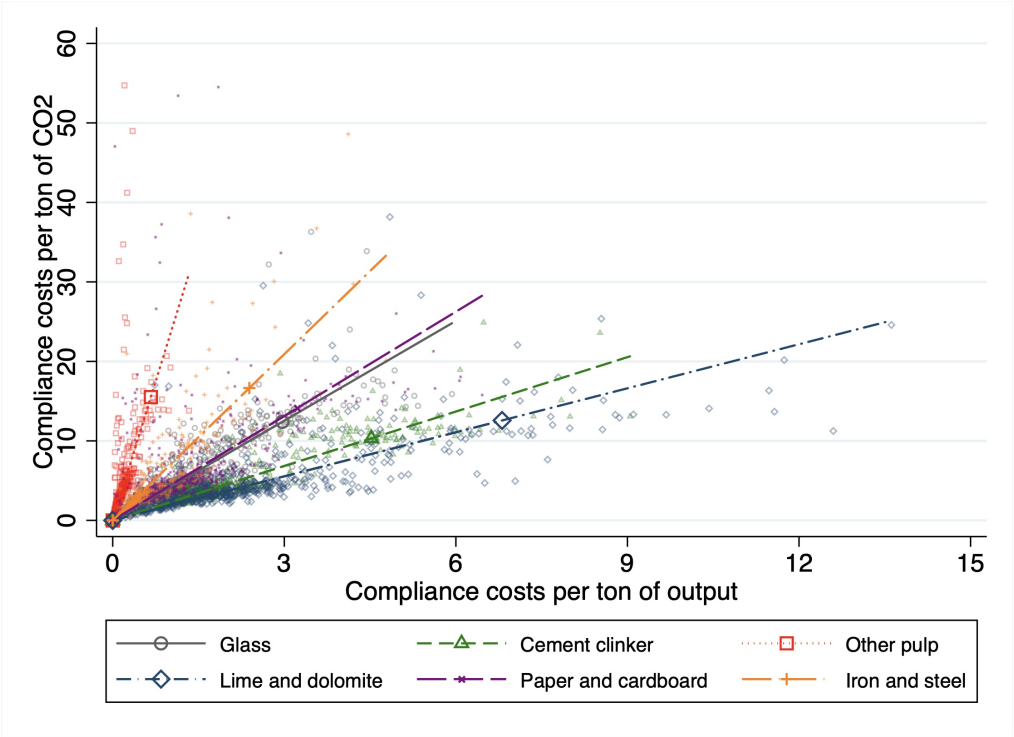
C Converting compliance costs into a per-ton-of-CO_2 measure

While our preferred measure expresses compliance costs per ton of output—a metric that, to our knowledge, is rarely available in this literature precisely because installation-level physical output data are seldom observed—the same framework can be trivially rescaled into a more conventional per-ton-of-CO_2 measure, given emissions data are directly observed. Since $\tilde{c}_{its} \equiv C_{its}/\tilde{Y}_{its}$, and emission intensity is defined as $x_{its} = X_{its}/\tilde{Y}_{its}$ in (11), it follows immediately that

$$\tilde{c}^{CO2}_{its} \equiv \frac{C_{its}}{X_{its}} = \frac{\tilde{c}_{its}}{x_{its}} \tag{16}$$

i.e., the per-ton-of-CO_2 compliance cost is simply the per-ton-of-output measure rescaled by the (observed) emission intensity of the installation. Figure 5 plots the installation-level relationship between $\tilde{c}^{CO2}_{its}$ and $\tilde{c}_{its}$ distinguishing by sector. As expected, the two measures are highly and consistently correlated within each sector, confirming that our output-based measure can be readily converted into a CO_2-based one whenever the latter is preferred, without altering the substantive properties of the underlying cost measure.

Figure 5: Compliance costs per ton of CO_2 vs per ton of output.



Note. Installation-level data from the EU Operator Holding Accounts (EU OHA). The sample is restricted to installations active during Phase III (2013–2020). Sectors with fewer than 100 installation-year observations are excluded. A sector-specific trimming procedure removes observations below the 5th and above the 95th percentiles of key variables. The Figure plots normalized compliance costs per ton of output versus compliance costs per ton of CO_2. Dots represent installations. Linear regression lines are sector-specific OLS fits of compliance costs per ton of CO_2 on compliance costs per ton of output.

Table A.2 reports summary statistics for both versions of the measure, by sector. On average, compliance costs amount to about €1.4 per ton of output and about €5.4 per ton of CO2 across the full sample. The per-ton-of-CO_2 figures are economically plausible: they sit comfortably within the range of allowance prices observed during Phase III (roughly €4.5–25 per ton of CO_2 between 2013 and 2019), which is reassuring given that the allowance price represents an upper bound on the average cost of compliance. As with the per-ton-of-output measure, there is meaningful variation across sectors — Pig iron and steel, for instance, has a comparatively low mean cost per ton of output (€0.78) but a mean cost per ton of CO_2 (€5.64) similar to more output-cost-intensive sectors such as Cement clinker and Lime and dolomite, reflecting differences in emission intensity across sectors. There is also substantial within-sector dispersion for both measures: the coefficient of variation (Std. Dev./Mean) is close to or above 1 in nearly every sector, indicating that within-sector variation is generally of the same order of magnitude as the sector mean itself. This is particularly pronounced for the per-ton-of-CO_2 measure, where the coefficient of variation exceeds 1 in four of the six sectors, ranging from 0.73 in Cement clinker to 1.43 in Other pulp, consistent with the heterogeneity documented in Section 3.2.

Table A.2: Compliance costs per ton of output and per ton of CO_2 (by sector, €).

Sector	Compliance costs per ton of output			Compliance costs per ton of CO_2		
	Mean	Std. Dev.	CV	Mean	Std. Dev.	CV
Cement clinker	2.147	1.418	0.660	5.080	3.693	0.727
Lime and dolomite	2.571	2.112	0.822	5.415	6.447	1.191
Pig iron and steel	0.779	0.766	0.983	5.635	6.973	1.237
Glass	1.097	0.874	0.797	4.881	4.064	0.833
Paper and cardboard	1.095	0.977	0.892	6.153	7.226	1.174
Other pulp	0.202	0.184	0.911	6.045	8.618	1.426
Sample average	1.374	1.421	1.034	5.449	6.041	1.109

Note. Installation-level data from the EU Operator Holding Accounts (EU OHA) and Orbis (Bureau van Dijk). The sample is restricted to installations active during Phase III (2013–2020). Sectors with fewer than 100 installation-year observations are excluded. A sector-specific trimming procedure removes observations below the 5th and above the 95th percentiles of key variables. CV denotes the coefficient of variation (Std. Dev./Mean).

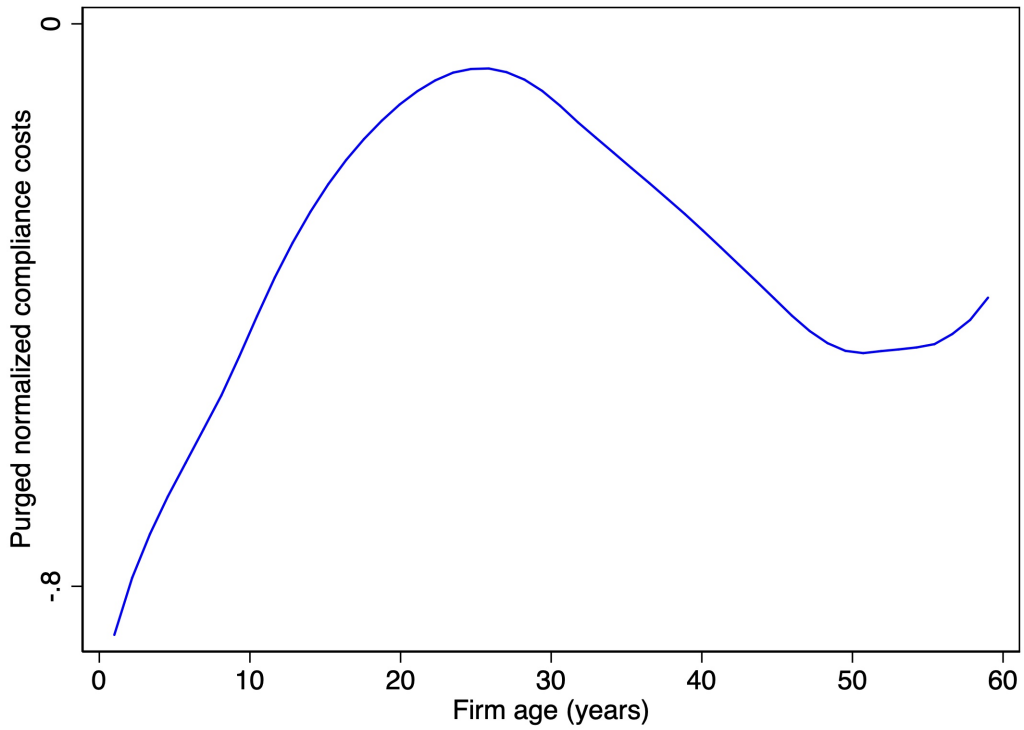
D Compliance costs and firm age

The regression results reported in Table 2 show a positive correlation between firm age and compliance costs. Here, we further investigate this relationship to assess whether the estimated effect of age on our compliance cost measure is constant across the age distribution.

We proceed as follows. First, we estimate equation (13) excluding firm age from the vector $\mathbf{X}_{its}$ of time-varying controls and save the residuals. Let us denote these residuals by ψ_{its}. They measure the deviation of an installation's normalized compliance cost from the value predicted by its other characteristics and by country-year shocks. Only the variation of ψ_{its} across firm age, not its level, is therefore informative. Second, we compute the average of ψ_{its} for each firm age in our sample and plot these age-specific averages against age.

The resulting pattern is shown in Figure 6. We find that the relationship between purged normalized compliance costs and firm age is positive overall, consistent with the linear coefficient estimated from equation (13). However, compliance costs increase more markedly for younger firms—below approximately 20 years of age—while, if anything, they slightly decline for older firms.

Figure 6: Purged normalized compliance costs and firm age.



Note. Installation-level data from the EU Operator Holding Accounts (EU OHA). The sample is restricted to installations active during Phase III (2013–2020). Sectors with fewer than 100 installation-year observations are excluded. A sector-specific trimming procedure removes observations below the 5th and above the 95th percentiles of key variables. The Figure plots normalized compliance costs purged of time-varying firm characteristics and fixed effects, averaged within each year of firm age (all sectors, all years). The sample is restricted to firms below 60 years of age for readability.

One possible interpretation of this hump-shaped relationship is related to the life cycle of industrial capital. Existing evidence suggests that major industrial plants and production infrastructures typically have an operational lifespan of roughly 20–30 years before substantial replacement or upgrading becomes economically necessary (McKinsey & Company, 2009). Under this interpretation, younger firms may benefit from having entered the market with relatively recent production technologies and equipment, which are likely to be more energy efficient and better adapted to a carbon-pricing environment. To the extent that the introduction of the EU ETS and the growing importance of climate policy influenced investment decisions, newer firms may also have adopted technologies specifically designed to operate under stricter environmental constraints.[8]

The peak in compliance costs observed for firms around 20–30 years of age may therefore reflect a phase in which firms are still operating the capital installed at entry, but that capital has become progressively less efficient relative to newer technologies. In this sense, firms in this age range may face the greatest degree of technological lock-in. Beyond approximately 30 years of age, compliance costs begin to decline, which may indicate that firms progressively undertake major capital replacement, modernization, or restructuring activities. Such processes may include technological upgrading as well as organizational changes. As firms become older, they are also more likely to be observed at different stages of their investment cycle, which would naturally weaken the relationship between firm age and compliance costs. While speculative, this interpretation is consistent with the notion that the age profile of compliance costs partly reflects the life cycle of industrial capital and the timing of technological renewal.

[8]Younger firms may also include entities resulting from mergers and acquisitions, as firm age is measured from the date of incorporation. A large literature finds that ownership changes are followed by productivity improvements at the plant level (e.g., McGuckin and Nguyen (1995)), which may operate partly through the reorganization of production and the upgrading of capital.

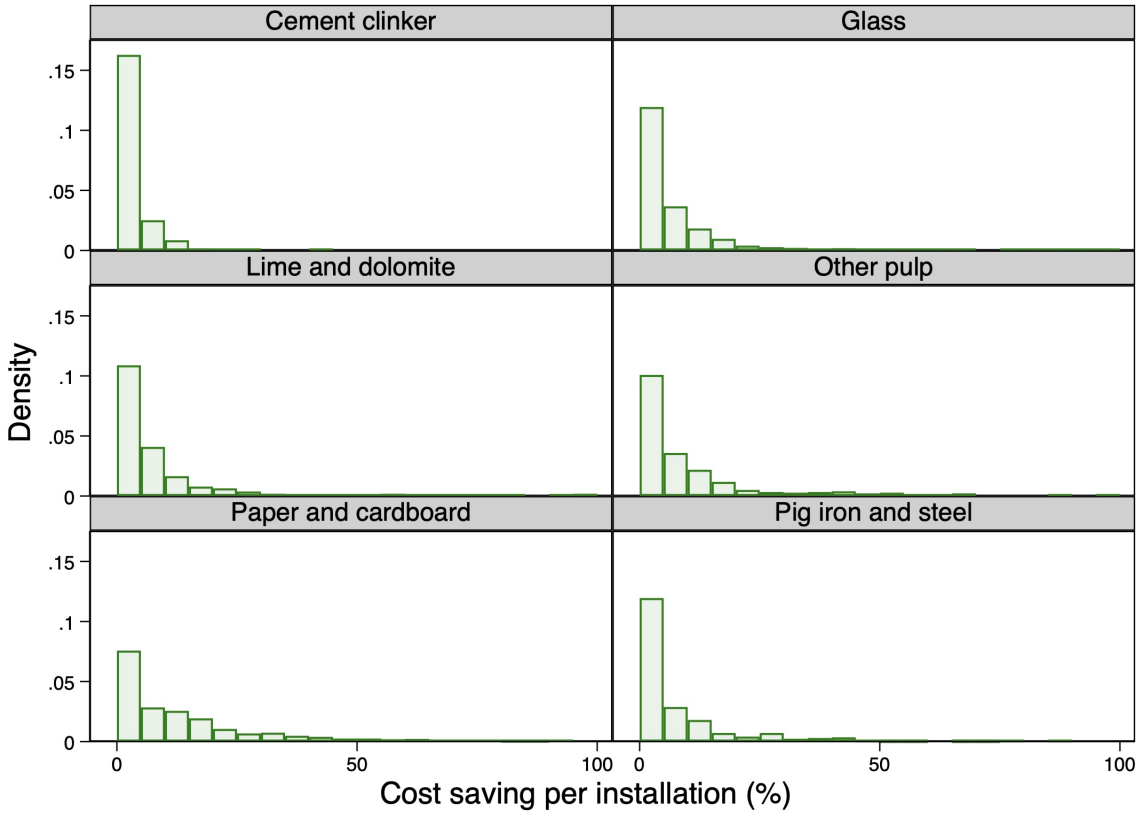
E Relative cost savings

Let us recall the notation of the paper and measure cost savings for installation i in year t and sector s with $\theta = 2$ as in equation (15):

$$\text{Cost saving}_{its}(\theta = 2) = \frac{\tilde{Y}_{its} P_t}{2(\bar{x}_{is} - \tilde{x}_{its})} (\tilde{x}_{its} - \hat{x}_{its})^2 \tag{17}$$

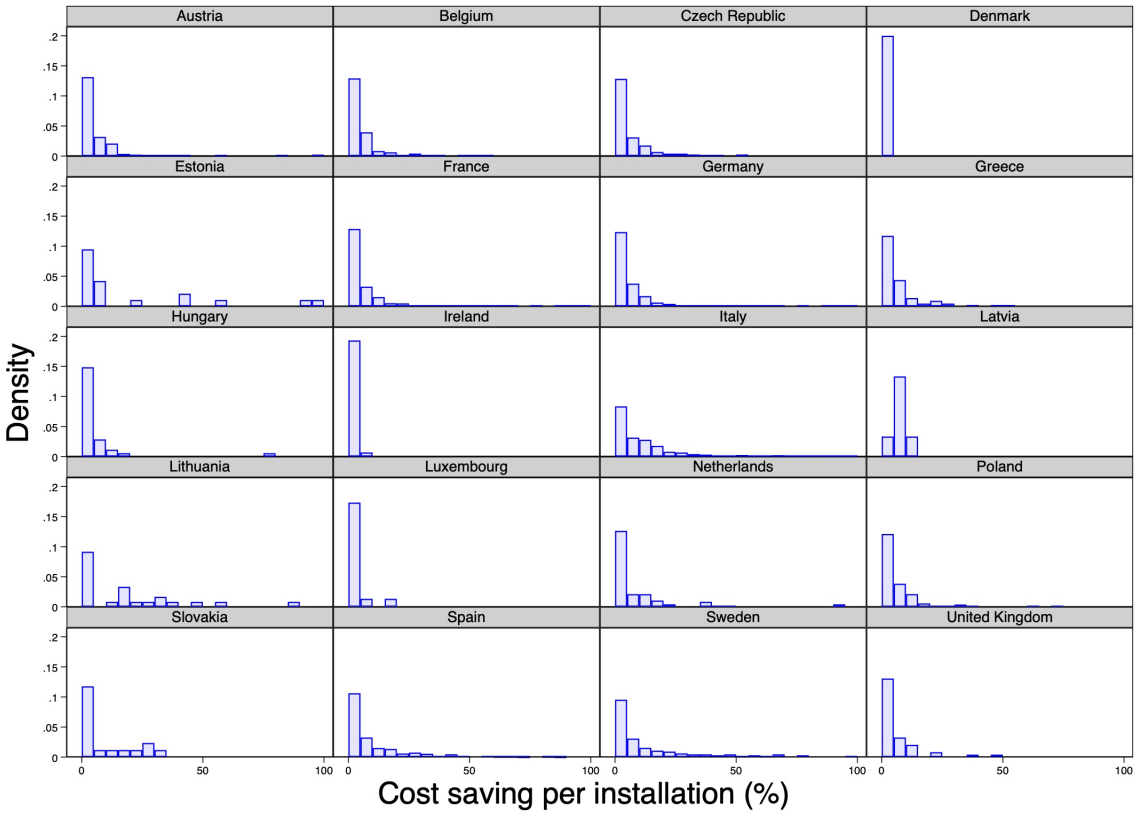
with $\hat{x}_{its} = \frac{\hat{X}_{its}}{\tilde{Y}_{its}}$. In Figures 7 and 8, we report the distributions of installation-year-level cost savings, as a percentage of compliance costs in the counterfactual no-trade scenario, by sector and by country respectively. These distributions are economically plausible. Across sectors and countries, the bulk of the mass lies below 50% of no-trade compliance costs. The consistency of this shape across both sectors and countries reinforces that the gains from trade documented in the paper are not an artifact of a few extreme observations, but reflect a broadly plausible distribution of relative cost savings across the sample. Averaging across all six sectors and the whole 2013–19 period, the mean relative cost saving is 10.11% of no-trade compliance costs (see Section 3.1 for caveats on sample coverage and representativeness).

Figure 7: Compliance cost saving in the EU ETS (by sector, in relative terms).



Note. Installation-level data from the EU Operator Holding Accounts (EU OHA). The sample is restricted to installations active during Phase III (2013–2020). Compliance cost saving (in %) is obtained as difference between compliance costs without trade of permits and compliance costs with trade, as in (17), and then expressed as a percentage of compliance costs in the counterfactual no-trade scenario.

Figure 8: Compliance cost saving in the EU ETS (by country, in relative terms).



Note. Installation-level data from the EU Operator Holding Accounts (EU OHA). The sample is restricted to installations active during Phase III (2013–2020). Compliance cost saving (in %) is obtained as difference between compliance costs without trade of permits and compliance costs with trade, as in (17), and then expressed as a % of compliance costs in the counterfactual no-trade scenario.

F Cost savings are increasing in θ

In this Appendix, we will show that cost savings are increasing in the parameter θ in equation (1).

We can rewrite cost savings equation (14) as:

$$\text{Cost saving}_{its} = \tilde{Y}_{its} P_t \left(\frac{1}{\theta} \tilde{\mathbf{a}}_{its}^{1-\theta} \hat{a}_{its}^{\theta} - \frac{1}{\theta} \tilde{\mathbf{a}}_{its} - \hat{a}_{its} + \tilde{\mathbf{a}}_{its} \right) = \tilde{Y}_{its} P_t \tilde{\mathbf{a}}_{its} \phi \tag{18}$$

with

$$\phi \equiv \frac{1}{\theta} z^{\theta} - z - \frac{1}{\theta} + 1, \quad z \equiv \frac{\hat{a}_{its}}{\tilde{\mathbf{a}}_{its}} > 0 \tag{19}$$

We will now see that ϕ is increasing in θ for $z \neq 1$ (when $z = 1$, cost savings and ϕ are trivially zero for any value of θ). Differentiating ϕ in (19) with respect to θ yields:

$$\frac{\partial \phi}{\partial \theta} = \frac{\eta}{\theta^2} \geq 0 \tag{20}$$

with strict inequality for $z \neq 1$ and

$$\eta \equiv \theta z^{\theta} \ln z - z^{\theta} + 1$$

The inequality in (20) follows from:

$$\frac{\partial \eta}{\partial z} = \theta^2 z^{\theta - 1} \ln z$$

Thus η is decreasing (increasing) in z for $z <$ (>)1. Since $\eta = 0$ for $z = 1$, this means $\eta > 0$ for $z \neq 1$.

References (Online Appendix)

[1] McGuckin, R. H. and Nguyen, S. V. (1995) On Productivity and Plant Ownership Change: New Evidence from the Longitudinal Research Database. *RAND Journal of Economics*, 26(2): 257–276.

[2] McKinsey & Company (2009) *Pathways to a Low-Carbon Economy: Version 2 of the Global Greenhouse Gas Abatement Cost Curve*. New York, NY: McKinsey & Company.