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A positive trade-off: Emissions reduction and costs under Phase IV of the Emissions Trading System [★]

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Abstract

This paper investigates the impact of the EU Emissions Trading System (ETS) on the manufacturing sector, a significant contributor to greenhouse gas emissions within the EU. The ETS, a market-based policy tool, imposes a cap on emissions while enabling firms to trade emission allowances. Allocation of free allowances varies across sectors based on their carbon leakage status, indicative of the risk of losing competitiveness and relocating production to regions with less stringent climate policies. Leveraging a natural experiment design that exploits this variability, we employ a panel regression analysis at the sectorial level spanning 2012 to 2022 to examine how ETS prices influence sectors' carbon efficiency, direct emissions, production and prices, while controlling for other confounding factors. By contrasting the effects of ETS prices between sectors transitioning from carbon leakage status to facing higher allowance costs in Phase IV and those retaining their status across Phases III and IV, we also determine potential disparities in ETS price impacts. Additionally, we shed light on the mechanism of investment through which the EU ETS induces firms to reduce their emissions by employing a mediation analysis. Our analysis reveals that elevated ETS prices foster carbon efficiency and emission reduction, with marginal effects on production and prices. Notably, this effect is more pronounced for sectors transitioning from free to auctioned allowances. We identify investment as a key channel, which mediates the effect of ETS prices on the carbon efficiency of firms. Thus, our findings suggest that a reduction in free allowances combined with escalating ETS prices, mediated by increased investment, can bolster the environmental performance of the EU manufacturing sector without significantly compromising its competitive position.

Keywords: EU ETS, Phase IV, Joint impact analysis, Mediation analysis

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1. Introduction

The emission of greenhouse gases (GHG) as an unintended by-product of economic activity is often cited as one of the most prominent examples of market failure. The inadequate pricing of climate change costs by the market reflects a failure in economic decision-making to fully account for the costs of GHG emissions (Colmer et al., 2023). In response cap-and-trade emission trading systems, as a form of market-based regulation, have emerged as a key policy instrument for reducing GHG emissions (Clausing and Wolfram, 2023). By setting a price on emissions they intend to incentivise firms to invest in low-carbon solutions, refrain from energy intensive production and transition towards the use of renewable energy sources (Colmer et al., 2023).

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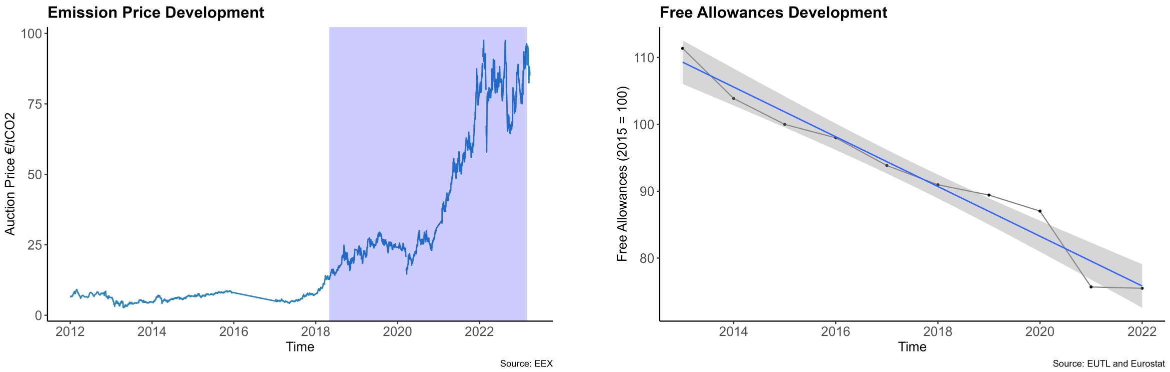
Unlike control-and-command regulation, market-based regulations allow regulated entities to be more flexible in their compliance strategies and pathways towards decarbonisation. This allows for a wide range of compliance strategies, each with distinct economic and environmental implications (Colmer et al., 2023). The imposition of carbon pricing mechanisms can thus engender adverse repercussions for regulated entities and the wider economy and environment. Concerns loom regarding the potential for cost pass-through to consumers, exacerbating inflationary pressures, or conversely, the inability of firms to pass on costs due to global competition, leading them to outsource their emission-intensive production to lower cost-abatement regions, thereby precipitating carbon leakage – a scenario aligning with the pollution haven hypothesis (Levinson and Taylor, 2008). Apart from potentially having negative economic implications by downscaling domestic production, the surge in emissions overseas might also offset the domestic emission reductions, undermining the purpose of the EU ETS (Marin et al., 2018). Hence, policymakers grapple with the intricate trade-offs between emission mitigation imperatives and the attendant economic ramifications.

To enhance the efficacy of carbon pricing policies and streamline the impact of cap-and-trade systems, policymakers have implemented various measures. These include the allocation of free allowances or rebates to emission-intensive and trade-exposed sectors (Fischer and Fox, 2012), the adoption of carbon border adjustments and tariffs on imports and exports based on their carbon content (Cosbey et al., 2019), and the harmonisation or linkage of carbon pricing systems across jurisdictions (Edenhofer et al., 2019). The design and implementation of these options involve various challenges and trade-offs, such as legal feasibility, political acceptability, environmental integrity, economic efficiency, and distributional equity. Therefore, policymakers need to carefully assess the expected impacts and implications of different options for their national context and objectives.

Among market-based regulations, the European Union Emission Trading System (EU ETS) stands as one of the foremost and largest, encompassing over 40% of the EU's total greenhouse gas emissions [1] across more than 14,500 installations spanning 31 countries.[2] Originating in 2005, the EU ETS has undergone iterative revisions, poised to navigate an evolving landscape of environmental imperatives and industrial dynamics. However, the future trajectory for sectors regulated by the EU ETS portends a more stringent climate regulatory regime, marked by two significant disruptions, a pronounced surge in allowance prices and a substantial reduction in free allowance allocation.



(a) EU ETS price development

(b) Free allowance allocation

Figure 1: Changes in policy stringency

Figure 1 shows these trends. Allowance prices soared by over 400% from 2018 to 2022, driven by reforms aimed at rectifying the initial oversupply of allowances in the market. Movements in other variables over the same period, such as gas prices, extreme weather conditions, and macroeconomic shocks, which are identified as key drivers of ETS prices, have underpinned this surge in ETS prices (Bai and Okullo, 2023; Chung et al., 2018). Despite anticipation, the price escalation surpassed forecasts, with the 2023 average doubling the projected peak of 40€/ton CO2 (De Clara and

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[1] Besides carbon dioxide, the EU ETS also covers nitrous oxide and perfluorocarbons.

[2] China recently introduced its ETS system, now the largest carbon market by emissions.

Mayr, 2018a). Concurrently, the allotment of free allowances witnessed a substantial decline in 2021, coinciding with the commencement of Phase IV of the EU ETS. This decline stemmed primarily from the reclassification of fewer sectors as susceptible to carbon leakage, since policymakers attribute a diminished risk of competitiveness erosion or production relocation to jurisdictions with less stringent environmental standards.

In this paper, we investigate whether these reforms have been sufficient to achieve meaningful improvements in carbon efficiency at the four-digit NACE sector level and how they have influenced sectors in terms of their environmental behaviour and economic activities. For this purpose, we employ a panel regression analysis at sector level spanning from 2012-2022 and follow Richter and Schiersch (2017) in developing a carbon efficiency – the inverse of of emission intensity – estimation model derived from the production function framework.

To provide a more holistic and comprehensive examination we extend our research by looking at two further specifications. First, in light of the latest revision of EU ETS we undertake an empirical analysis of the environmental and economic ramifications ensuing from transitioning manufacturing sectors from receiving free emission allowances to procuring them within the EU ETS framework in combination with the evolution of ETS prices. We use a natural experiment based on the classification of carbon leakage sectors, which determines the level of free allowance allocation, and compare the impact of the ETS prices on various outcomes of manufacturing sectors that lost their carbon leakage status in Phase IV of the EU ETS (the treatment group) with those that kept their status in both Phases III and IV (the control group). Second, we refine our estimation model to shed light on the channels through which the EU ETS induces sectors to reduce their emissions. To this end, we employ a mediation analysis to specifically investigate the mediating role of firms' investment in the EU ETS impact on improving sectors' carbon efficiency, thereby adding to the current modernisation vs. downsizing debate (Dlugosch and Kozluk, 2017).

Our findings show that sectors improve their carbon efficiency by 0.04% and decrease their direct emissions by 0.05% in response to a 1% increase of the ETS price, while it has only marginal economic repercussions for regulated sectors. This is concurrent with the observation that sectors transitioning from free to auctioned allowances are more inclined to improve their carbon efficiency and decrease their direct emissions, with production and producer prices only being mildly affected. These trends suggest that while the direct costs of heightened ETS prices remain relatively constrained, the advantages, particularly in carbon efficiency and emissions reduction, are notably substantial. This might imply that firms refrain from shifting carbon intensive production abroad and importing carbon-intensive goods from less regulated political realms when faced with stricter EU ETS regulations. The results of the mediation analysis indicate that higher ETS prices motivate firms to invest in green technologies as a primary mechanism to address the rising carbon costs and reduce their emissions.

Our paper contributes to several stances in literature. First, we add to literature examining the effect of environmental regulation on industry sector behaviour (Bartram et al., 2022; Ben-David et al., 2021; He et al., 2020; Löschel et al., 2019; Pietzcker et al., 2020). While those papers have looked either at the economic or environmental repercussions separately, we look at both sector level effects simultaneously to shed light on the intricate environmental and economic trade-offs of the EU ETS. Second, our study provides new evidence on the effectiveness of the latest EU ETS revision in enhancing carbon efficiency in sectors affected by changes in carbon leakage status, by examining the impact of ETS prices. Third, by looking at the role of investment through which the ET ETS induces firms to reduce their carbon emissions we enrich the current debate between the modernisation and downscaling effect in context of environmental regulation (Dlugosch and Kozluk, 2017).

The remainder of this paper is structured as follows. Section 2 discusses the relevant literature, while Section 3 provides an overview of the EU ETS, with particular emphasis on the allocation of free allowances across different phases. Section 4 presents the dataset, alongside descriptive insights and the parallel trend assumption. In Section 5, the empirical strategy is delineated. Section 6 presents the obtained results, along with pertinent robustness checks and encapsulates the findings. Finally, Section 7 concludes the study.

2. Literature Review

Soon after its inauguration, studies have investigated the effectiveness of the EU ETS in reducing carbon emissions and emission intensity at the firm level, while also addressing concerns about its impact on the economic performance of regulated firms (Dechezleprêtre and Kruse, 2018). According to Martin et al. (2016), studies evaluating EU ETS' impact on emission reduction have either based their estimations on aggregate emissions or on emission data at firm or plant level. Depending on different data sources Phase I of EU ETS is estimated to have reduced emissions on average between 2.5% and 5% (Anderson and Di Maria, 2011; Ellerman and Buchner, 2008; Ellerman et al., 2010). Egenhofer and Alessi (2011) further expand those studies onto the first two years of Phase II, to which they attribute a reduction of 3.35% in emission intensity.

Studies relying on firm and sector level data have typically combined propensity score matching with a difference-in-difference analysis to compare regulated and most similar unregulated firms before and after the implementation of the EU ETS. They take advantage of the specific design of the EU ETS, where the size of installations determines whether a firm is regulated. The difference at installation and firm level thus enables researchers to compare firms with similar characteristics, but which fall under different regulatory regimes within the EU ETS as they operate different sized installations (Dechezleprêtre and Kruse, 2018). Most of such studies focus on a single country such as Germany or Norway. Petrick and Wagner (2014) build a comprehensive panel dataset using data from the German production census and found that Phase II of EU ETS induced regulated German firms to reduce their emissions by around 25% compared to their non-regulated peers. Similarly, Klemetsen et al. (2020) study the impact of the EU ETS on the environmental performance of Norwegian firms using plant level data from 2001 to 2013. They find weak evidence that regulated firms decreased their emissions by approximately 30% in comparison to unregulated firms during Phase II. However, they find no evidence that any other Phase of the EU ETS had any significant impact on emission intensity.

In terms of economic consequences, concerns have been widely raised about regulated firms losing their competitiveness against less environmentally regulated international competitors due to the additional cost burden imposed by the EU ETS (Dechezleprêtre and Kruse, 2018; Dechezleprêtre and Sato, 2017). In response, a sizable body of literature centred around the debate between the pollution haven hypothesis and the Porter hypothesis has emerged (Dechezleprêtre and Kruse, 2018). According to the pollution haven hypothesis, compliance costs incurred through environmental regulations will eventually lead firms to move their carbon-intensive to low-abatement regions (Levinson and Taylor, 2008). In contrast, the Porter hypothesis claims that more stringent environmental regulation can have net-positive productivity effects for regulated firms, by fostering innovation in new technologies and implementing cost-cutting improvements, which in turn may raise their productivity and give them a technological leap over their competitors (Porter and Linde, 1995).

In light of the Porter hypothesis, Calel and Dechezleprêtre (2016) examine whether the EU ETS has induced directed technological innovation and change at the firm level within the first five years since its implementation. Using a matched difference-in-difference identification strategy, their results show that the EU ETS increased patenting in low-carbon technology by non-regulated firms by 10% compared to unregulated firms without crowding out the patenting of other technologies. Extrapolating those results to the whole economy Calel and Dechezleprêtre (2016) only observe a mere rise of 1% in the innovation of low carbon technology. Rather, they suggest that most emission reductions in the EU ETS have been caused by operational changes such as fuel switching rather than technological change, implying that the EU ETS has not provided the economic incentives necessary to achieve technological change on scale (Calel and Dechezleprêtre, 2016).

Several studies examine the impact of the EU ETS on a number of different metrics such as employment, value added or return of equity to assess the effect of the ETS on firms' economic performance. Marin et al. (2018) construct an European-wide panel dataset for the manufacturing sector from 2005-2009 by matching emissions data on installation-level with nine economic performance metrics at firm level. Other than expected, their results do not confirm any negative impact of the EU ETS on firms' economic performance. Instead, they imply that firms were able to pass-through their higher costs to their customers and could simultaneously increase their labour productivity (Marin et al., 2018). Other studies have instead examined the economic effects of the EU ETS within a single country and focused on only one or a few selected economic performance indicators as outcome variables. Anger and Oberndorfer (2008) investigate the impact of the EU ETS on employment and revenue, whereas other scholars, such as Löschel et al. (2019) and Lutz (2016) for German manufacturing firms and D'Arcangelo et al. (2022) for the Italian manufacturing sector, explore the relationship between the EU ETS and firms' productivity. The first two studies find no significant negative effect on firms' productivity; in fact, they even report an increase (Löschel et al., 2019; Lutz, 2016). In contrast, D'Arcangelo et al. (2022) observe a small but negative effect on productivity that varies across industries. They explain these results with the fact that firms are not economically tempted enough to undergo substantial process change and instead just rely on switching fuels in their production (D'Arcangelo et al., 2022).

Whilst there is a rich list of literature on the separate environmental and economic ramifications of environmental regulation and more specifically the EU ETS, there is only a limited amount of joint causal impact analyses of environmental regulations (Dechezleprêtre and Kruse, 2018). At the national level, joint impact analyses were conducted by Jaraitė and Maria (2016) in the Lithuanian context and by Colmer et al. (2023) within the French manufacturing sector. Both do not find evidence that the EU ETS had a significant negative impact on the economic performance of firms. In terms of environmental impact, Colmer et al. (2023) findings show that the EU ETS led to a reduction in carbon emissions by 14-16% across French manufacturing firms. In contrast, Jaraitė and Maria (2016) research results indicate that the first trading phase of EU ETS did not cause a reduction in carbon emissions and only led to a slight decrease in emission intensity. At the EU level, there have only been two joint impact analyses to date: Abrell et al. (2011), who scrutinise the influence of the transition from Phase I to Phase II on firms' environmental and economic performance, and Dechezleprêtre et al. (2023), who conduct a similar analysis for the first two trading phases between 2005 and 2012. Abrell et al. (2011) identify an emission reduction of 3.6% in Phase II compared to Phase I which the authors attribute to increased stringency of the EU ETS, whilst Dechezleprêtre et al. (2023) results reveal a 10% decrease in carbon emissions. Both studies come to similar conclusions regarding the economic consequences, as neither finds any evidence that the EU ETS has had any significant negative effect on the economic performance metrics of firms (Abrell et al., 2011; Dechezleprêtre et al., 2023).

Building upon these findings, our study extends the analysis to encompass the effects of the EU ETS from 2012 onwards, thereby providing a longitudinal perspective on its outcomes. We thereby aim to fill the gap in the literature identified by Dechezleprêtre and Kruse (2018) in bringing to the forefront a joint impact study based on the most recent data available, encapsulating the most recent transition of the EU ETS from Phase III to Phase IV. In a similar vein to studies such as Ulmer (2022) and Colmer et al. (2023), who have utilised quantitative criteria for assessing carbon leakage sectors during Phase III and Phase II, respectively, to evaluate diverse economic ramifications, our research represents a novel contribution. To the best of our knowledge, we are the first to investigate the effects of the allocation rule change between Phase III and Phase IV, thereby enriching the understanding of carbon leakage dynamics. At the same time, we contribute to the discussion about the neutrality of the allocation mechanism within the EU ETS, which has attracted the attention of numerous authors who have elucidated the theoretical and practical considerations underpinning this mechanism (De Vivo and Marin, 2018; Hahn and Stavins, 2011; Zaklan, 2023, 2016)

A further ongoing discourse in the literature surrounds the different channels or mechanisms through which the EU ETS induces firms to reduce their emission intensity. There is good amount of literature, which have implicitly looked at possible channels of the EU ETS such Lise et al. (2010), who scrutinise the impact of the EU ETS on energy prices and how it has further impacted consumers prices and firms profitability. In turn, Venmans (2016) utilises survey data conducted among managers to study the impact of the allocation mechanism of allowances under the EU ETS and its induced price uncertainty on abatement investment decisions made by firms. In their study Colmer et al. (2023) analyse explicitly several mechanisms through which the EU ETS influences the economic and environmental performance of regulated entities, which they broadly classify as the leakage, the abatement investment channel and the productivity channel. For this purpose, they use a difference-in-difference analysis with the different mechanisms as outcome variables and the different phases of the EU ETS as treatments. We draw on their idea by specifically investigating the role of the investment channel in inducing firms to improve their carbon efficiency, however uniquely through the lenses of mediation analysis with net investment. By doing so, our study contributes to the ongoing discourse on the modernisation and downsizing effect within the EU manufacturing sector in response to changes in ETS pricing and carbon leakage status (Dlugosch and Kozluk, 2017). These findings underscore the intricate interplay between environmental policies, economic behaviours, and technological advancements, thus enriching our understanding of the implications of climate change mitigation policies.

3. Background the EU ETS and the allocation of free allowances

The EU ETS has been executed across four distinct phases, with Phase IV commencing in 2021. Over these phases, the EU ETS has undergone continuous refinements and enhancements, empowering policymakers to address prevailing concerns. Phase I (2005-2007) introduced firms to the EU ETS framework, regulating CO2 emissions from power generators and energy-intensive manufacturing. Allowances were primarily allocated for free, with Member States determining the cap. Due to limited data and other factors, an oversupply of allowances occurred, resulting in a decline in prices.

In Phase II (2008-2012), the EU ETS expanded its scope by covering more countries and a wider range of greenhouse gases and sectors. It was characterised by a persistent oversupply of allowances, partially stemming from the aftermath of the 2008 Global Financial Crisis, which resulted in subdued emissions, prompting critics to raise questions about the efficacy of the EU ETS (Grubb et al., 2022).

Phase III (2013-2020) introduced a centralised framework with the implementation of a single Union Registry, which standardised performance benchmarks and regulations for the allocation of free allowances to manufacturing sector installations. Additionally, a consolidated list of sectors vulnerable to carbon leakage, characterised by high trade and carbon intensity, was established, resulting in a greater proportion of free allowances allocated to these sectors[3]. Measures to mitigate the oversupply of allowances were enacted, with auctioning becoming the predominant method of allocation. As illustrated in Figure 1, prices remained subdued for the majority of Phase III but exhibited a marked increase post-2018.

Phase IV of the EU ETS introduced a series of measures to achieve more significant emission reductions.[4] Among these measures was a notable reduction in the proportion of free allowances, as illustrated in Figure 1. This reduction resulted from two key policy changes. First, there was a decrease in the number of sectors deemed vulnerable to carbon leakage. Second, the allocation of free allowances for the remaining sectors was subjected to a gradual linear phase-out, ultimately reaching zero by 2030.

As the classification of sectors vulnerable to carbon leakage is central to our second-step identification analysis, we shed closer light onto the introduced centralised system through the Union Registry in Phase III.[5] Whilst the allocation of free allowances primarily depends on its production sector, installations engaged in multiple sectors are subdivided into distinct sub-installations, each linked to a specific product category. Thus, the formula for the allocation of free allowances (A_{ist}) for an installation i in sector s during time t is as follows:

$$A_{ist} = b_s \cdot ac_i \cdot r_{it} \cdot cl_{st}$$

where b_s denotes the benchmark for sector s, signifying the count of allowances required by the most efficient 10% of installations to generate a single product unit.[6] The historical activity level ac_i mirrors the median activity level of an installation within the reference period (2005-2008 or 2009-2010). The reduction or correction factor r_{it} operates to ensure that the allowance count remains within the confines of total emission caps. Two distinct types of factors emerge: the linear correction factor is applicable to electricity generators, while the cross-sectoral correction factor is imposed on all other installations.[7]

The carbon leakage exposure factor cl_{st} , crucial for our analysis, facilitates the allocation of 100% of allowances at benchmark levels to sectors presumed to be vulnerable to carbon leakage. In contrast, sectors lacking this designation are compelled to purchase an escalating proportion of allowances from the market.

4. Data

The analysis uses a comprehensive panel dataset derived from various sources, aggregated into annual observations at the country-sector level. The dataset adopts the four-digit NACE classification

Direct Emissions: The European Union Transaction Log (EUTL) provides comprehensive information about all installations subject to regulation under the EU ETS. This paper utilises a refined dataset curated by Jan Abrell based on the EUTL.[8] This dataset is pivotal as it already incorporates the NACE sector classification, which is essential for constructing the final dataset. It encompasses various details, such as verified emissions, received free allowances,

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[3] This allocation approach aimed to ensure their international competitiveness.

[4] For a comprehensive overview of Phase IV amendments, consult De Clara and Mayr (2018b).

[5] Article 10a of Directive 2009/29/EC, amending Directive 2003/87/EC, specifies these rules.

[6] The reference period encompasses 2007-2008.

[7] Emissions from the electricity sector undergo a linear reduction, around 1.74% annually from 2013 onward. Notably, the linear reduction factor exceeds the cross-sectoral correction factor by approximately 0.5-0.6 percentage points.

[8] For complete documentation, see https://www.euets.info/.

NACE classification, and country registry, offering yearly observations for regulated installations from 2005 to 2022. Note that the data on emissions only entail the emissions that are regulated under the EU ETS system. Given that all other data sets we use in our analysis entail information on the whole sector, we provide additional evidence that regulated emissions are a valid approximation of the emissions of the whole sector in Section A.2 in the Appendix.

Throughout our analysis, we adhere to common data cleaning procedures. Initially, we retain information for installations categorised at either the four- or two-digit level. Notably, the four-digit level installations constitute a subset of the two-digit installations. Consequently, the two-digit dataset generally encompasses more comprehensive information than the four-digit counterpart. Furthermore, our sample is confined to the manufacturing sector. Our key outcome variable to estimate the environmental impact of the EU ETS, carbon efficiency[9] (defined as the inverse of emission intensity), is calculated by dividing the value of turnover by direct emissions.[10]

Allowance Prices: The allowance prices are retrieved as auction prices from Bloomberg. This data is reported daily and has been aggregated to provide yearly observations. The final dataset encompasses the average auction price spanning from 2012 to 2022.

Carbon Leakage Classification: The determination of a sector's carbon leakage status is pivotal for our second-step analysis. Sectors classified as exposed to carbon leakage are denoted as *carbon leakage sectors*. Carbon leakage sectors are characterised by a substantial risk that elevated EU ETS prices cannot be fully transferred to consumers and that the risk of production decline within Europe, relative to non-regulated installations, is substantive. These sectors are entitled to receive *free allowances*, ensuring a 100% allocation of allowances up to the benchmark level. We sourced a sector's carbon leakage status from the European Commission's carbon leakage list. This includes trade and emission intensity metrics, alongside the carbon leakage factor—essential components for the quantitative rule used to establish a sector's carbon leakage status. [11]

Economic Performance Data: Our economic performance data comprises details on production and producer prices. All of these metrics are retrieved from Eurostat and are reported at the four-digit NACE level, spanning from 2012 to 2022. Both producer prices and production are indexed to 100 in 2015, thus not reflecting the sector's size, and are based on the product of prices and volumes.

Controls: Several control variables, directly sourced from Eurostat, have been incorporated. These include electricity prices as a proxy for energy intensity and the cost of alternative energy sources, employees per enterprise as a measure of labor input, and net investment as a measure of capital input. Additionally, we utilise direct emissions, retrieved from the curated dataset from Jan Abrell, as further control for energy input. All of these controls are reported at the four-digit NACE level and at a yearly frequency.

5. Empirical Strategy

In our analysis, we aim to explore the effect of ETS pricing on the economic and environmental performance of regulated sectors, as well as the impact channel of investment as part of a mediation analysis. We are particularly focused on understanding how these effects vary between sectors that are subject to ETS charges and those that receive allowances for free. Estimating the effect of ETS pricing is challenging due to potential issues such as omitted variable bias (OVB) and reverse causality, where the direction of impact between variables might be misconstrued. Additionally, we acknowledge that certain outcome variables in our study may present more significant challenges than others due to these estimation issues.

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[9] For complete explanation why we use carbon efficiency instead of emission intensity, please refer to Section 5.

[10] Direct emissions correspond to the verified emissions generated directly by the sector, such as emissions resulting from fuel combustion during the production process.

[11] A detailed outline about the carbon leakage classification status can be found in Section A.3 of the Appendix.

OVB occurs when variables that affect both ETS prices and the outcome variables we are studying are left out of the analysis. We follow a two-fold approach to address the issue of OVB. First, we employ country and sector fixed effects to control for time-invariant unobservable effects across industries and countries, such as varying levels of market competition or different regulatory environments, which might affect the outcome variables. Instead of employing separate country and sector fixed effects, we use identifier fixed effects, which group the country and sector dimensions. This results in a more restrictive estimation strategy, thereby further corroborating the robustness of our results. Second, we follow the approach of Richter and Schiersch (2017) in deriving our estimation model within the context of the production function framework to resolve the issue of simultaneity and endogeneity, caused by OVB. In the development of our baseline estimation model, we start with a classic Cobb-Douglas production function with turnover as dependent variable, that requires labour, capital as well as energy as additional input variable, so the production function becomes:

$$Y_{cst} = L_{cst}^{\beta_l} K_{cst}^{\beta_k} E_{cst}^{\beta_e} e^{\epsilon_{cst}} \tag{1}$$

where Y_{cst} is turnover, L_{cst} denotes labour input, K_{cst} capital input and E_{cst} energy input for country c in sector s in year t. ϵ_{cst} is the unobservable error term.[12] Taking logs and subtracting the energy input on both sides of the equation, transforms the production function in an energy production function:

$$y_{cst} - e_{cst} = \beta_l l_{cst} + \beta_k k_{cst} + (\beta_e - 1)e_{cst} + \epsilon_{cst} \tag{2}$$

where small letter cases denote the logarithmic input values.

In line with Richter and Schiersch (2017), we exploit the special link that exists between energy consumption and and CO2 emissions, in which different forms of energy inputs can be linearly transformed into CO2 emissions, as proven by various papers (Forslid et al., 2018; Jaraitė and Maria, 2016; Petrick and Wagner, 2014). This enables us to replace the logarithmic energy input variable e_{cst} with the logarithmic form of direct emissions $co2_{cst}$ as direct input in the production function:

$$y_{cst} - co2_{cst} = \beta_l l_{cst} + \beta_k k_{cst} + (\beta_{co2} - 1)co2_{cst} + \epsilon_{cst} \tag{3}$$

This leaves us with a carbon efficiency function in logarithmic form, which is the inverse of an emission intensity function. As a further measure to avoid the issue of endogeneity and reverse causality (Bellemare et al., 2017) and under our assumption that regulated sectors adjust their economic and environmental behaviour to a rise in allowance prices in the preceding period, we lag our treatment variable and the covariates by one year. Adding our treatment to equation 3 results in the following baseline estimation model:

$$y_{cst} - co2_{cst} = \beta_l l_{cst-1} + \beta_k k_{cst-1} + (\beta_{co2} - 1)co2_{cst-1} + \beta_{p^e} P_{t-1}^{e} + \epsilon_{cst} \tag{4}$$

which we also use to analyse the effects of ETS allowance prices on economic outcomes as well as direct emissions as further robustness check. This renders equation 4 to the following specification:

$$ln(Y_{cst}) = \beta_{p^e} ln(P_{t-1}^{e}) + \delta ln(\mathbf{X_{cst-1}}) + \beta_{ep} ln(EP_{ct-1}) + \alpha_{cs} + \epsilon_{cst} \tag{5}$$

where $ln(Y_{cst})$ covers the natural logarithm of the key indicators of economic performance and environmental impact, including producer prices, production, direct emissions, and carbon efficiency. $ln(P_{t-1}^{e})$ denotes the natural logarithm of our treatment ETS prices, while $ln(\mathbf{X_{cst-1}})$ represents a vector that includes the aforementioned country-sector level control variables, such as direct emissions, employees per enterprise, and investment, all in logarithmic form and lagged by one period. As a further control, we add the country level variable $ln(EP_{ct})$ to account for the costs of energy sources and the substitution effect between electricity and fuel-based energy. α_{cs} denote country-sector fixed effects[13], capturing the unobserved heterogeneity specific to individual countries and sectors. To control for possibly

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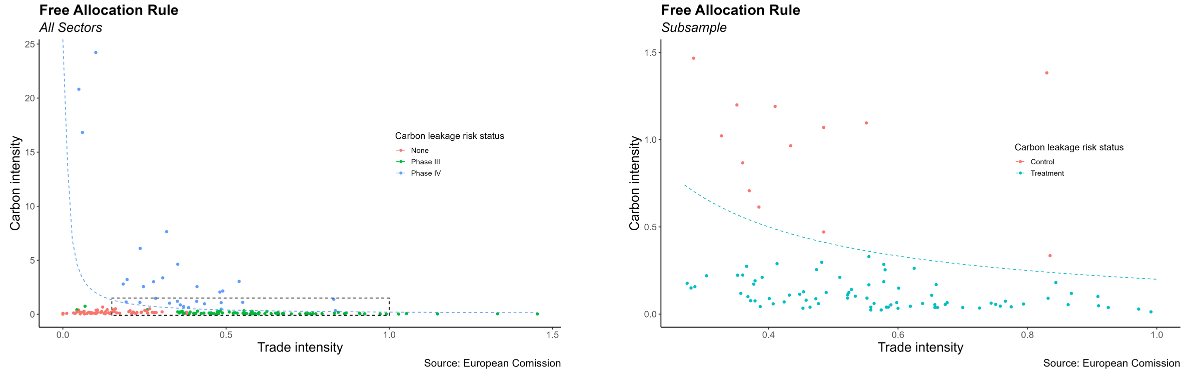
[12] Notably, we do not consider a separated unobservable total factor productivity term $\tilde{\omega}_{cst}$ in our study, which could later be derived with for example the Olley-Pakes method (Olley and Pakes, 1992), as this would extend the scope of this study.

[13] We conducted the Hausman specification test for all three estimation models, which was significant across all estimation strategies, implying that the fixed effects model is preferred to the random effects model (Hausman, 1978). Please refer to the Appendix for the corresponding results of the Hausman test.

existing autocorrelation and heteroscedasticity in the dataset, the standard errors are clustered by the identifier variable country-sector.

The concerns about reverse causality remain but may be mitigated in our study by several factors specific to the nature and market of ETS allowances. Firstly, ETS prices are often determined by regulatory frameworks, not solely by market dynamics, which reduces the direct influence individual sectors can have on these prices. Additionally, the market for ETS allowance is large, meaning the actions of the firms of a single sector, unless exceptionally large, are unlikely to significantly affect the market price. Any changes in behaviour in response to ETS prices are also expected to have a lagged effect on the market, further reducing the immediate impact. Moreover, ETS prices are subject to a variety of influences such as regulatory adjustments and external market pressures, which can offset strong demand shifts. This is in line with Marin and Vona (2017), who argue that energy prices are nationwide and thus uncorrelated with firm-specific demand shocks, which can be replicated onto our study. These aspects suggest that the direct feedback effects between firm actions and ETS prices may be less pronounced, making our analytical approach viable.

The second step in our analysis involves a comparative approach, where we examine two distinct groups of sectors: One that is required to pay for ETS allowances and another that receives these allowances for free. The ideal experiment would necessitate a random allocation of free allowances to sectors or installations. However, we posit that the alteration in the allocation mechanism, as influenced by the carbon leakage risk status[14], furnishes a quasi-random allocation approach for free allowances. Figure 2 visually depicts the sector contribution concerning trade and emission intensity, a computation undertaken by the European Commission.


Free Allocation Rule
All Sectors

Source: European Comission

Free Allocation Rule
Subsample

Source: European Comission

(a) All Sectors **(b)** Selected Subgroup

Figure 2: Treatment and Control Group Allocation

Panel (a) displays all manufacturing sectors present in the dataset. Red dots signify sectors that were never categorised as carbon leakage sectors. Green dots represent sectors exclusively designated as carbon leakage sectors during Phase III, while the blue dots portray carbon leakage sectors during both Phase III and IV. Within this context, the treated group pertains to sectors previously classified as carbon leakage sectors in Phase III but relinquished that status upon the commencement of Phase IV (green dots). Notably, these sectors exhibit varying degrees of emission and trade intensity.

For sectors characterised by elevated emission intensity, the EU ETS allowance price assumes a particularly crucial role as a cost factor (Grubb et al., 2022). When establishing both a treatment and control group, a critical consideration lies in selecting sectors that exhibit comparable emission intensity levels. The box demarcated by a dotted line in Panel (a) of Figure 2 is subsequently depicted in Panel (b). Within this subset, the exclusion primarily targets sectors with exceedingly high emission intensity, ensuring sufficient statistical power for accurate estimations. Notably, a restrained number of sectors with significantly high trade intensity are also omitted to maintain estimation power. Sectors positioned below the dotted line constitute the treatment group, while those above represent the control group.

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[14] Section A.3 of the Appendix provides a detailed elaboration on the carbon leakage status.

Another important consideration when using this approach lies in the assumption that the criteria used to determine the carbon leakage status of manufacturing sectors are not influenced by the sectors' own characteristics. In simpler terms, the criteria should divide the sectors in a somewhat random manner within their local context.

Equally vital for our analysis is the notion that sectors cannot manipulate the factors upon which the threshold classification is based. The reference year for calculating trade and emission intensity precedes the initial announcement of the new threshold in 2015. Alongside the quantitative rule, there exists a qualitative criterion as well. Sectors have the option to request carbon leakage status, which is then thoroughly evaluated by the European Commission. However, it is important to note that very few sectors are granted carbon leakage classification based on qualitative criteria, and these have been excluded from our analysis. This ensures that the interpretation of causality remains robust and credible. It is essential to recognise that the emission data under study is exclusively drawn from a specific subset of the sector, encompassing installations that fall within the purview of EU ETS regulations. In contrast, variables such as turnover, which contributes the computation of carbon efficiency, and the control variables account for the whole sector. During our analysis, we make the necessary assumption that alterations observed within this subset of installations can serve as a meaningful approximation for the behaviour of the entire sector. Additional evidence about this assumption is provided in Section A.2 of the Appendix.

In order to achieve a valid causal interpretation, the Stable Unit Treatment Value assumption (SUTVA) must be upheld. This essentially signifies that the control group should remain unaffected by the treatment. It is worth clarifying that if the treated sectors share direct competition or are intricately tied within the supply chain of the control sectors, the treatment could potentially exert some influence on the control group, albeit to a minor extent. While acknowledging this possibility, we proceed under the assumption that any such influence remains limited.[15]

Aside from these considerations, we should also account for general equilibrium effects on allowance prices, which could impact the control group dynamics. Specifically, the control group might benefit from elevated allowance prices if they are enabled to sell their free allowances at higher value. Consequently, this could elevate the marginal cost of emissions and intensify incentives to invest more rigorously in emission abatement efforts.

Considering the careful derivation of the estimation model and the unique context of the EU ETS, the risks associated with OVB and reverse causality in our study are significantly limited. The transition to Phase IV of the EU ETS introduces a quasi-random variation between sectors that have to pay for allowances and those that receive them for free. We use a restricted sample bases on emission and trade intensity, as shown in Figure 2, to ensure comparable groups. In Section A.4 of the Appendix we provide additional evidence about the selected subgroup. Overall, our approach allows for a nuanced examination of the differential impacts of ETS pricing between the treatment and control group. To this end, we render our baseline specification with a moderation effect, in which we interact our treatment variable with the dummy variable indicating whether the sector belongs to the treatment or the control group:

$$ln(Y_{cst}) = \beta_{p^e} ln(P^e_{t-1}) * Treatment + \delta ln(\mathbf{X_{cst-1}}) + \beta_{ep} ln(EP_{ct-1}) + \alpha_{cs} + \epsilon_{cst} \tag{6}$$

where we regress the same outcome variables on as before to enhance our understanding of economic and environmental implications between regulated and non-regulated sectors.

As a final step, we employ a mediation analysis to investigate the mechanism through which investment drive firms to improve their carbon efficiency under the EU ETS, with the modernisation effect as its theoretical foundation. Other studies, such as Dlugosch and Kozluk (2017) and Colmer et al. (2023), have investigated the role of investment as a mechanism by analysing the impact of energy prices on firm level investment. They regressed firm level investment on the first two trading phases and the pre-ETS phase using a difference-in-differences analysis. Our study is thus unique by being, to the best of our knowledge, the first study who scrutinises the channel effect of investment on carbon efficiency of regulated sectors and undertakes this study in context of the transition to Phase IV. The basic idea behind the mediation effect is that higher allowance prices increase the energy costs of regulated firms, inducing them to increase their investment in renewable energy sources and carbon emission abatement technologies, which in turn improves their carbon efficiency. Investment thus mediate the impact of allowance prices on carbon efficiency into an indirect and direct effect. A graphical visualisation of the mediation effect is depicted by Figure 3.

In line with Wahba and Elsayed (2015), we examine the mediation effect of investment in panel data setting with two-step procedure. First, we regress the mediator variable, *net investment*, on the treatment and control variables,

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[15] In Section A.4 of the Appendix, we elaborate on this in more detail.

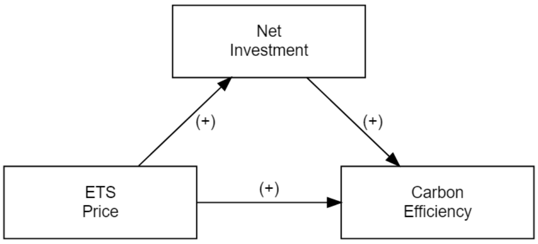


Figure 3: Mediation Effect of Investment on Carbon Efficiency

using fixed effects as outlined in the baseline specification:

$$ln(INV_{cst}) = \beta_{p^e} ln(P^e_{t-1}) + \delta ln(\mathbf{X_{cst-1}}) + \beta_{ep} ln(EP_{ct-1}) + \alpha_{cs} + \epsilon_{cst} \tag{7}$$

As a second step, we regress the outcome variable on the baseline specification 5, with carbon efficiency as the outcome variable, while also including this time the mediator:

$$ln(CE_{cst}) = \beta_{p^e} ln(P^e_{t-1}) + \delta ln(\mathbf{X_{cst-1}}) + \beta_{ep} ln(EP_{ct-1}) + \alpha_{si} + \beta_{inv} ln(INV_{cst}) + \epsilon_{cst} \tag{8}$$

To prove the mediation effect of investment, we expect the coefficient of the treatment in regression 7 to be significant and have the expected directional correlation as depicted in Figure 3. In the second regression 8, the coefficient of the mediator is projected to be significant and exhibit the right directional correlation, whilst the treatment becomes insignificant (Wahba and Elsayed, 2015).

6. Results and Discussion

6.1. Results

Our study employs three analytical steps. First, we use the empirical model summarised by specification 5 to estimate the overall effect of ETS prices on economic and environmental outcomes. Second, we repeat the first step for two groups of sectors. One has to pay for the emission allowances, the other – which has obtained its carbon leakage status – receives them for free. Due to the policy shock of implementing Phase IV of the EU ETS, the two groups are comparable in any other aspect except for the payment status as explained in Section 5. Together these methodologies offer a robust examination of the interplay between ETS pricing and its implications on economic activities and environmental policies, highlighting the multifaceted effects of the ETS on the manufacturing sector especially with variation in the payment status. Finally, we scrutinise the mediation effect of investment to better understand the mechanisms through which the EU ETS induces firms to improve their carbon efficiency.

The results of specification 5 are displayed in Table 1. In terms of the environmental impact, our analysis reveals a positive correlation between our treatment ETS prices and firms' carbon efficiency, significant at the 1% level. Specifically, a 1% increase in ETS prices is associated with 0.04% rise in carbon efficiency. This result is a significant indicator of the EU ETS' effectiveness in encouraging cleaner production processes. The improvement in carbon efficiency and thus the reduction in emission intensity is a key objective of the ETS, aiming to decouple economic growth from emissions. One could argue that this result is primarily driven by an increase in turnover with constant remaining amount of carbon emissions. To confirm our findings and verify that the reduction in emissions drives the result, we run the same regression with just direct emissions as outcome variable. A 1% increase in ETS prices results, on average, in a reduction of direct emissions by 0.05% (significant at the 0.1% significance level), corroborating our findings that rising ETS prices lead firms to increase their carbon efficiency by reducing the amount of emissions emitted per produced unit.

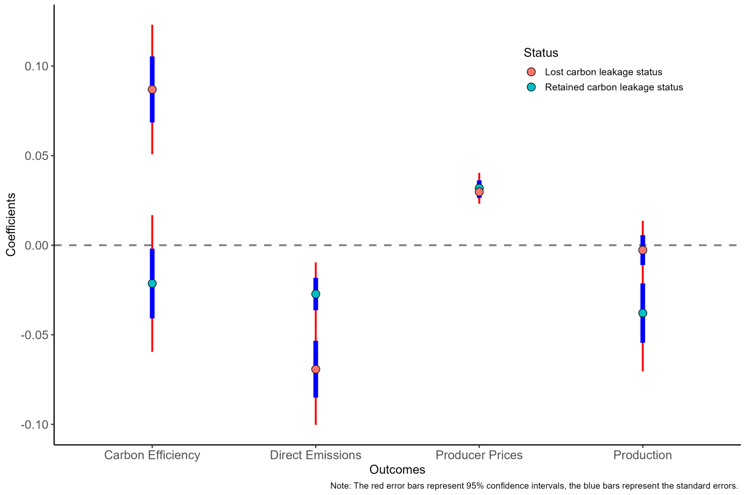
In terms of the impact of our treatment on the economic behaviour of regulated sectors, we see that our treatment has a statistically significant effect on the economic outcome variables with the expected directional correlation. However, production levels and producer prices show minimal effects, with a slight 0.02% decrease in production levels and a 0.03% increase in producer prices, indicating the relative resilience of production activities in the face of evolving environmental policies. At the same time, the results suggest that the contribution of ETS prices to the pass-through of costs to consumers is limited in firms' pricing strategies.

Table 1: Effects of ETS Prices

Dependent Variables: Model:	Carbon efficiency (log) (1)	Direct emissions (log) (2)	Production (log) (3)	Producer prices (log) (4)
Variables				
ETS price (log, t-1)	0.0394^{**}	-0.0490^{***}	-0.0198^{*}	0.0306^{***}
	(0.0137)	(0.0089)	(0.0097)	(0.0027)
Direct emissions (log, t-1)	-0.3943^{***}	0.5241^{***}	0.0195	-0.0006
	(0.0605)	(0.0571)	(0.0252)	(0.0099)
Net investment (log, t-1)	0.0360^{**}	0.0123	0.0155^{*}	0.0050
	(0.0124)	(0.0089)	(0.0066)	(0.0047)
Electricity prices (log,t-1)	-0.5321^{***}	0.0076	-0.1866	-0.0118
	(0.1280)	(0.0995)	(0.1216)	(0.0343)
Employees per enterprise (log, t-1)	0.1806^{**}	0.0331	0.0277	-0.0083
	(0.0547)	(0.0220)	(0.0185)	(0.0136)
Fixed-effects				
Country-Sector	Yes	Yes	Yes	Yes
Fit statistics				
Observations	1,493	1,720	1,347	1,591
R^2	0.99196	0.99385	0.54126	0.44865
Within R^2	0.15504	0.26897	0.03226	0.13205

Clustered (Country-Sector) standard-errors in parentheses
*Signif. Codes: ***: 0.001, **: 0.01, *: 0.05*

In the second part of the analysis, we compare sectors that transitioned from receiving ETS allowances for free to purchasing them against those that continued obtaining them without charge. This comparative analysis is presented by Figure 4 and offers valuable insights into the wider effects of a more stringent environmental policy shift. The findings show stark differences in the coefficients between the two groups, highlighting the distinct impacts of ETS pricing on sectors that pay for allowances and those receiving them for free. By looking at Figure 4 it becomes evident that sectors, which lost their carbon leakage status during Phase IV improve their carbon efficiency in larger magnitude than sectors, that retained their carbon leakage status. At the same time, sectors now obliged to buy allowances under Phase IV of EU ETS on average tend to have lower direct emissions than firms with carbon leakage status, underscoring the observation that sectors seem to improve their environmental performance when faced with more stringent environmental regulations. Notably, we observe that sectors subjected to more stringent environmental policies under the EU ETS tend to decrease their production to a lesser extent in response to higher ETS prices. This suggests that sectors within the treatment group face higher market competition after the transition to Phase IV and thus offer their goods at lower prices to remain competitive.



Note: The red error bars represent 95% confidence intervals, the blue bars represent the standard errors.

Figure 4: Moderated effect of log ETS Prices

We employed a t-test to verify whether the differences displayed in Figure 4 are statistically significant. The results indicate a significant disparity in how ETS pricing affects carbon efficiency across the two groups.[16] The statistically significant difference in emissions, where sectors that lost their carbon leakage status in Phase IV emit less direct emissions than those still exempted from paying allowance prices, confirms the previous findings. Additionally, the results reveal that the transition to Phase IV had no significant impact on regulated sectors' economic performance, as there are no significant differences in terms of production and producer prices between sectors receiving allowances for free and those paying for allowances. Overall, the environmental impact of Phase IV thus seems to be greater than its economic downsizing effect.

In the third part of our analysis, we turn our attention to investigating investment as one of the channels through which the EU ETS induces regulated sectors to improve their carbon efficiency, using a mediation analysis. The corresponding results of the analysis are displayed in Table 2. Under Model 1, our treatment variable has a statistically significant effect on the mediator net investment with the expected directional correlation, as we assume surging allowance prices entice firms to increase their investment in clean technology. In the second step analysis, displayed under Model 2, the coefficient of the ETS prices becomes insignificant, whilst the coefficient of the mediator net investment has a statistically significant effect on carbon efficiency at the 1% significance level with the expected positive correlation. The mediation or in other words indirect effect is 0.009, which is computed as product of the treatment coefficient in Model 1 and the mediator coefficient in Model 2. Despite only being modest in magnitude, our results reveal indeed the expected mediation effect of net investment between allowance prices and carbon efficiency, thus providing empirical evidence to the modernisation theory. To confirm the existence of a statistically significant mediation effect, we employ the Sobel-Goodman Test, which shows the mediation to be statistically significant (Z=2.795, p=0.005).[17] As further robustness check, we run the same mediation analysis but replace net investment with investment intensity[18] as alternate measure for investment as mediator. The corresponding results displayed in Models 3 and 4 also demonstrate the existence of a statistically significant mediation effect of investment.

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[16] Please refer to the Appendix for the results of the employed t-test.

[17] For a detailed description of the Sobel-Goodman test please refer to (Preacher and Leonardelli, 2001).

[18] Investment intensity is defined as the ratio of net investment to the number of enterprises per sector.

Table 2: Effects of ETS Prices

Dependent Variables: Model:	Net investment (log) (1)	Carbon efficiency (log) (2)	Investment intensity (log) (3)	Carbon efficiency (log) (4)
Variables				
ETS price (log, t-1)	**0.1065*****	0.0304	**0.0483****	-0.0256
	(0.0271)	(0.0175)	(0.0192)	(0.0223)
Direct emissions (log, t-1)	0.1329	-0.4350***	0.0649**	-0.8530***
	(0.1036)	(0.0591)	(0.0251)	(0.0578)
Electricity prices (log,t-1)	-0.7969**	-0.4871***	-0.6166***	-0.4250***
	(0.2531)	(0.1251)	(0.2048)	(0.1378)
Employees per enterprise (log, t-1)	0.1329	0.1837**	0.1277***	0.3401***
	(0.0778)	(0.0645)	(0.0386)	(0.0812)
Net investment (log)		**0.0848*****		
		(0.0213)		
Investment intensity (log)				**0.1385*****
				(0.0524)
Fixed-effects				
Country-Sector	Yes	Yes	Yes	Yes
Fit statistics				
Observations	1,527	1,489	1,671	1,633
R^2	0.89907	0.99288	0.62541	0.95756
Within R^2	0.03833	0.19525	0.06494	0.63796

Clustered (Country-Sector) standard-errors in parentheses
*Signif. Codes: ***: 0.001, **: 0.01, *: 0.05*

6.2. Discussion

In summary, our findings underscore the critical role of EU ETS pricing in reducing direct emissions and improving the carbon efficiency of regulated sectors, highlighting the significant benefits of this pricing mechanism. Notably, the effect on carbon efficiency and direct emissions is considerably larger for sectors that are required to pay for their emission allowances, as consequence of them losing their carbon leakage status in Phase IV. This distinction emphasises the effectiveness of the EU ETS in incentivising reductions in emissions, particularly when sectors bear the direct cost of their emission. Hence, our results indicate that the latest revision of the EU ETS in Phase IV has effectively accelerated sectors' reduction of carbon emissions. Although the EU ETS was not initially a success story, achieving only modest reductions in carbon emissions in its early years, its latest policy revisions have made it more stringent. These changes have enhanced its effectiveness in pricing carbon emissions, thereby encouraging firms to reduce their emissions to avoid higher costs. Our paper complements the findings of previous studies by indicating that the effectiveness of the EU ETS in reducing carbon emissions among regulated firms has increased with successive revisions (Colmer et al., 2023; Dechezleprêtre et al., 2023). This demonstrates the importance for policymakers to adjust environmental regulations to maintain their effectiveness in reducing emissions in response to evolving market conditions and a changing context and environment.

On the economic side, our analysis indicates that higher ETS prices result in increased producer prices and reduced production. However, it is important to note that the magnitude of these effects is relatively small and does not significantly vary between sectors receiving allowances for free and those required to pay from them. Like many previous studies, our results thus suggest that the EU ETS has the potential to reduce carbon emissions through market-based regulations without imposing too heavy economic losses for the regulated sectors (Colmer et al., 2023; Marin et al., 2018).

At the same time, the lack of statistically significant difference between sectors retaining and losing their carbon leakage status in Phase IV portrays the effectiveness of the latest EU ETS revision in further reducing carbon emission without increasing the economic burden for regulated sectors. One can further infer from these findings that while the EU ETS system does influence cost structures and production levels, the impact is uniformly minimal across different sectors. Additionally, the findings imply that the financial burden imposed by ETS pricing, whether through direct costs or production adjustments, does not disproportionately affect sectors based on their allowance allocation status.

In the design of new policies and adjustment of existing environmental regulation it is crucial for policymakers to exactly know how and why existing environmental regulations have encouraged firms to reduce their emissions (Colmer et al., 2023). Of equal importance is identifying the unintended by-products induced by environmental regulation, which are encapsulated in the debate between the modernisation and downscaling effects in the literature on emission trading systems (Dlugosch and Kozluk, 2017). Our findings on the mediation effect reveal a pronounced positive impact of EU ETS pricing on net investment, suggesting promising implications for long-term economic and environmental sustainability and adding to the support of the modernisation effect. Hence, our study underlines the need for a balanced approach, which requires policymakers to ensure that regulations not only reduce emissions but also foster innovation and modernisation within industries. Moreover, given that effective carbon pricing has a positive impact on net investment, our results underline the importance of designing targeted incentives to encourage further investment in green technologies and sustainable practices.

7. Conclusion

In this study, we examined how a market-based approach like the ETS strikes a balance between industrial production performance and environmental sustainability. Using quasi-random variation, we examined how the ETS prices affect manufacturing sectors when their carbon leakage status change. For this purpose, we compared sectors that lost their carbon leakage status in Phase IV of the EU ETS (2021-2030) with those that kept their status. When conducting such study, we assumed that the two group of sectors would have followed a similar trend without the policy change.

Our findings demonstrate that higher ETS prices have improved the environmental performance of the manufacturing sector with limited impacts on their production. By making firms pay for their emission permits, the system creates strong incentives for firms to improve their carbon efficiency and to reduce their direct emissions without imposing major economic costs onto the regulated firms. At the same time, this system creates strong incentives for regulated firms to invest in low-carbon technologies, which is not only one of the main channels through which the EU ETS induces firms to reduce emissions but can also lower firms' production costs and improve their long-term competitiveness.

We show that the allocation criteria in Phase IV significantly improved carbon efficiency, reduced direct emissions, and enhanced economic efficiency in affected sectors, indicating the policy's success in mitigating carbon leakage and maintaining environmental integrity. Our evidence shows that higher allowance prices and stricter allocation rules have had minimal economic impact on the manufacturing sector, suggesting that concerns about future ETS policies harming this sector may be overstated. However, considering that investment is a major mechanism through which the EU ETS has encouraged manufacturing sectors to reduce their emissions, policymakers could further address these concerns by designing policies and providing financial support aimed at scaling up innovative abatement technologies, particularly for hard-to-abate sectors.

Our research gives rise to further research on this topic to guide future policy decisions regarding the EU ETS and similar carbon pricing schemes. First, our research suggests investment to be one of the main channels through which the EU ETS encourages firms to reduce their emissions. Thus, future research could further investigate the types of investments firms undertake as a consequence of the EU ETS, building on the work of Calel and Dechezleprêtre (2016). As such, it could policymakers support in designing targeted policies in encouraging firms in investing in targeted innovation such as abatement technologies rather than just in operational innovation in form of mitigation technogologies. Since our study focused exclusively on the investment mechanism, future research could explore other mechanisms, similar to Colmer et al. (2023), such as the fuel-mix response and the potential outsourcing of production to regions with less stringent environmental regulations in the context of Phase IV. Finally, given the design of the EU ETS, our study primarily focused on the economic and environmental impact on firms under the scope of the EU ETS. However, to reach a carbon-neutral European economy by 2050, as set out by the European Green Deal, the decarbonisation of all firms is needed. Thus, another fruitful avenue for future research would be to explore possible spillover effects from the EU ETS on the environmental and economic performance of unregulated firms.

This would offer policymaker and industry stakeholders valuable information to assess the EU ETS's impact across sectors and regions and support them in crafting optimal policies that encourage innovation and investment in green technologies, thereby facilitating a transition towards a more sustainable future.

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Appendix

A.1. Additional Tables and Figures

Table A.1: Summary statistics of outcome variables and covariates

Variable	(1) Mean	(2) Std. Dev.	(3) Median	(4) 25th percentile	(5) 75th percentile	(6) N
CO_2 efficiency (€1Mio/kg)	316,876	1,332,458	30,712	3,709	132,348	2,048
ETS price	22.91	24.10	11.75	5.83	24.84	9,930
Direct emissions	574,713	1,852,916	57,240	5,762	239,009	3,330
Production (Index)	101.50	17.83	100.00	95.00	107.30	6,190
Producer prices (Index)	105.63	13.00	101.60	99.90	107.00	8,518
Net investment	83.35	473.63	33.30	9.15	98.80	6,663
Electricity prices	0.15	0.06	0.14	0.11	0.20	9,930
Employees per enterprise	3.15	1.14	3.11	2.41	3.98	7,227

Note: CO_2 efficiency - the inverse of emission intensity in terms of turnover - is measured in €1Mio/kg.
Source: EUTL (2013-2022), Eurostat (2013-2020), Bloomberg (2013-2020), own calculations.

Table A.2: Results of the simple t-test

Variable	t-test statistic
CO_2 efficiency	-4.04^{***}
Direct Emissions	2.3^{*}
Producer prices	0.39
Production	-1.89

*Signif. Codes: ***:0.001, **:0.01, *:0.05*

Table A.3: Results of the Hausman test

Outcome Variable	(1) Joint Impact Analysis	(2) Moderation Analysis	(3) Mediation Analysis
Carbon Efficiency (log)	1600.1^{***}	503.45^{***}	554.68^{***}
Direct Emissions (log)	343^{***}	340.36^{***}	-
Production (log)	17.65^{**}	19.8^{**}	-
Producer Prices (log)	12.46^{*}	11.16	-
Net Investment (log)	-	-	952^{***}

*Signif. Codes: ***:0.01,**:0.05,*:0.1*

Table A.4: Interaction model

Dependent Variables: Model:	Carbon efficiency (log) (1)	Direct emissions (log) (2)	Production (log) (3)	Producer prices (log) (4)
Variables				
ETS price (log, t-1)	-0.0253	-0.0264^{**}	-0.0409^{*}	0.0337^{***}
	(0.0193)	(0.0080)	(0.0184)	(0.0043)
Net Investment (log, t-1)	0.0320^{*}	0.0143	0.0133^{*}	0.0053
	(0.0123)	(0.0090)	(0.0062)	(0.0047)
Direct emissions (log, t-1)	-0.3860^{***}	0.5206^{***}	0.0254	-0.0012
	(0.0589)	(0.0561)	(0.0263)	(0.0098)
Electricity prices (log,t-1)	-0.5476^{***}	0.0147	-0.1951	-0.0112
	(0.1266)	(0.0993)	(0.1177)	(0.0341)
Employees per enterprise (log, t-1)	0.1887^{***}	0.0315	0.0287	-0.0084
	(0.0533)	(0.0216)	(0.0186)	(0.0136)
ETS price (log, t-1)*Treatment	0.1164^{***}	-0.0420^{*}	0.0374	-0.0059
	(0.0263)	(0.0168)	(0.0196)	(0.0055)
Fixed-effects				
Country-Sector	Yes	Yes	Yes	Yes
Fit statistics				
Observations	1,493	1,720	1,347	1,591
R^2	0.99215	0.99390	0.54752	0.44939
Within R^2	0.17559	0.27382	0.04546	0.13322

Clustered (Country-Sector) standard-errors in parentheses
*Signif. Codes: ***: 0.001, **: 0.01, *: 0.05*

A.2. Emission Measure

As previously explained, the carbon leakage status depends on the four-digit NACE code classification. The emission data for the whole sector is only available for a small subset of four-digit classified sectors. Thus, this data cannot be used for our analysis. However, the data from the regulated installations can be compared to the data of the whole sectors, for which the whole-sector emissions are available at the two-digit NACE level. For this purpose, we collapsed our dataset to the two-digit NACE level to compare emissions from the regulated installations with the emission levels of the whole sector at the two-digit NACE level, obtained from Eurostat. Figure A.2 shows the relationship between the overall emissions in the manufacturing sectors (blue) and the regulated installations of the same sectors (red), based on emission intensity and absolute emission levels. The total difference is small, and the movements are very similar. Table A.5 shows a simple OLS regression relating the log emissions of the whole sector to the regulated emissions in logged terms. The two measures are very strongly correlated. An increase of 1% of all emissions of a sector is associated with an increase of 0.62% of regulated emissions. The same regression, when run in terms of emission intensity, resembles these results, showing that both measures are highly correlated. A 1% increase in emission intensity using all sectors is associated with a 0.58% increase in emission intensity in terms of regulated installations' emissions (Table A.6). As an additional robustness check, we plotted the share of emissions from regulated installations relative to the total emissions of the respective manufacturing sector at the two-digit NACE level. (Figure A.1). Throughout the analysed period, the share of regulated installations' emissions remains consistently above 76%, corroborating our assumption that regulated installations are a valid approximation of the emissions of the whole sector.

Table A.5: Relationship of total and partially measured emissions

Dependent Variable:	Emissions of the whole sector (log)
Model:	(1)
Variables	
Constant	5.895***
	(0.0922)
Emissions of regulated installatios (log)	0.6190***
	(0.0072)
Fit statistics	
Observations	2,440
R^2	0.74943
Adjusted R^2	0.74932

IID standard-errors in parentheses
*Signif. Codes: ***: 0.001, **: 0.01, *: 0.05*

Table A.6: Relationship of total and partially measured emissions in the context of emission intensity

Dependent Variable: Model:	Emission intensity using all sectorial emissions (log) (1)
Variables	
Constant	-3.358***
	(0.0669)
Emission intensity using regulated installations' emissions (log)	0.5798***
	(0.0060)
Fit statistics	
Observations	2,440
R^2	0.79140
Adjusted R^2	0.79131

IID standard-errors in parentheses
*Signif. Codes: ***: 0.001, **: 0.01, *: 0.05*

Figure A.1: Share of partial emissions

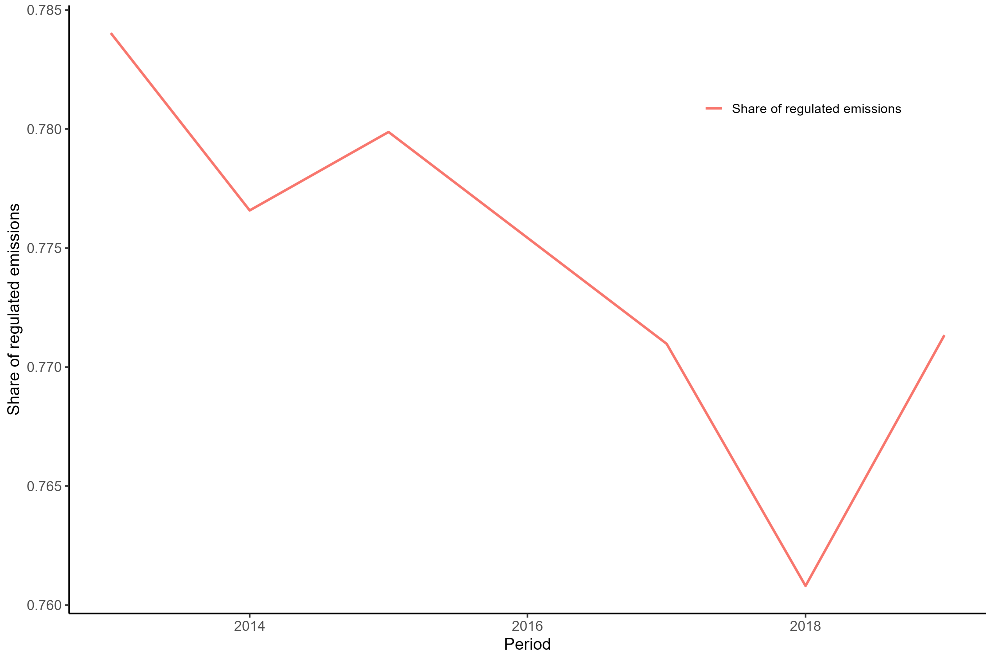
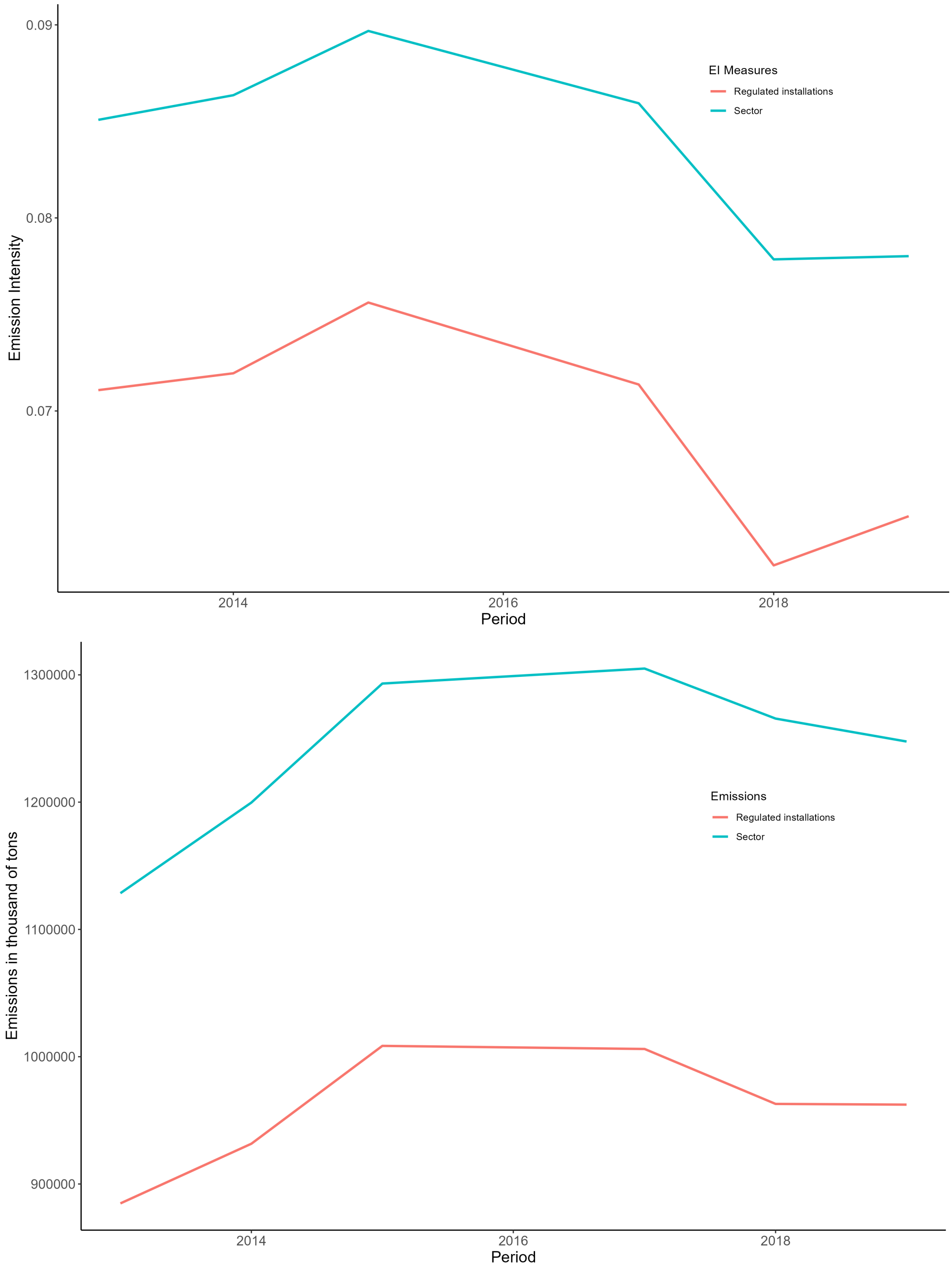


Figure A.2: Comparison of total and partial emission intensity and absolute emissions



A.3. Carbon Leakage Exposure

For clarity, we shall denote sectors classified as exposed to carbon leakage as *carbon leakage sectors*. These sectors are entitled to receive *free allowances*, ensuring a 100% allocation of allowances up to the benchmark level.

In essence, a quantitative criteria is employed to determine the carbon leakage status of sectors, hinging on two pivotal factors: Carbon Intensity and Trade Intensity.[19] Carbon leakage sectors are characterised by a significant risk that elevated EU ETS prices cannot be fully passed on to consumers, and that the likelihood of production decline within Europe, relative to non-regulated countries, is substantial. Carbon intensity gauges the impact of the EU ETS price on the production cost of regulated installations. Meanwhile, trade intensity serves as a gauge of exposure to international competition. Goods that are readily tradable and significantly influenced by the carbon price tend to be more prone to be imported from non-regulated regions.

The carbon intensity of a sector quantifies the cost incurred by an EU ETS price of €30 per ton of CO2 relative to the gross value added at factor cost of the sector:

$$\text{Carbon intensity} = \frac{(\text{direct emissions} \cdot \text{auctioning factor} + \text{indirect emissions}) \cdot \text{€}30/\text{ton}CO_2}{\text{gross value added at factor costs}}$$

Here, *direct emissions* correspond to the verified emissions generated directly by the sector, such as emissions resulting from fuel combustion during the production process. On the other hand, *indirect emissions* encompass the emissions linked with electricity consumption. The trade intensity is straightforwardly calculated as the aggregate of non-EU imports and exports over the market size, which is computed as the sum of non-EU imports and the total production within a sector in the EU:

$$\text{Trade intensity} = \frac{\text{imports} + \text{exports}}{\text{imports} + \text{production}}$$

In Phase III, three thresholds defined carbon leakage sectors:

A. Carbon intensity $\geq 5\%$ and trade intensity $> 10\%$
B. Carbon intensity $\geq 30\%$
C. Trade intensity $\geq 30\%$

The initial panel of Figure A.3 illustrates that trade intensity carried greater significance in the determination of carbon leakage sectors. Throughout Phase IV, the quantitative criterion was further refined. Presently, the sole quantitative rule relies on the combined interaction of both factors:

$$\text{Trade intensity} \times \text{Carbon intensity} \geq 20$$

The subsequent panel of Figure A.3 delineates the quantitative criteria of Phase IV. Any sector situated above the stipulated threshold is designated as a carbon leakage sector. A number of manufacturing sectors previously classified as carbon leakage during Phase III due to their trade intensity relinquished this categorisation in Phase IV (depicted as green dots). A few sectors persist in being categorised as carbon leakage sectors, predominantly featuring relatively elevated carbon intensity.

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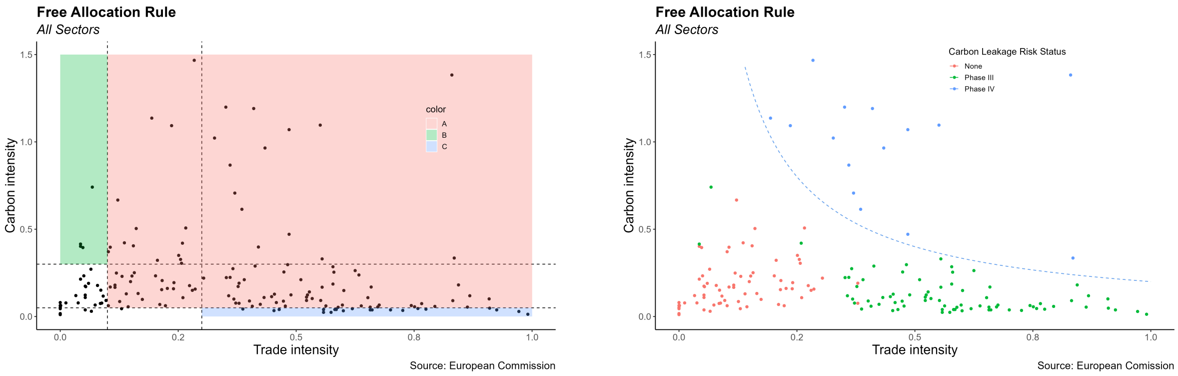
[19] For a comprehensive acccount of the carbon leakage assessment, see (Juergens et al., 2013).

Furthermore, in conjunction with the quantitative criteria, a qualitative criterion also comes into play. In this context, a sector must demonstrate a substantial risk of carbon leakage, supported by increasing import ratios. Such an evaluation may be initiated either by the sector itself or by the European Commission.

Figure A.3: Carbon leakage sector allocation rule



(a) In Phase III

(b) In Phase IV

A.4. Carbon Leakage Status

In our empirical analysis, we assume that two manufacturing sector groups are comparable and were not selected to control and treatment groups based on their own characteristics. This assumption cannot be tested directly through empirical methods. However, good reasons exist to believe the two groups do not suffer from selection. First, the quantitative rule used to assign carbon leakage status is a very simple rule[20]. Simple rules that apply to all sectors similarly have little scope to be adjusted to many sectors based on their characteristics. Second, some sectors receive exceptional carbon leakage status based on a qualitative criterion. The assignment based on this qualitative criterion is likely based on the sector's own characteristics and is therefore excluded from the analysis. It seems unlikely that manipulating the quantitative rule is necessary given the option of the qualitative criterion. Third, the assumption of comparability of treatment and control group is based on the fact that the sectors used in the analysis are close to the cutoff given by the quantitative criterion as shown in Figure 2. Sectors far from the cutoff are selected based on their own criteria. However, it seems plausible that status assignment is assigned quasi-random close to the cutoff. As in *Regression Discontinuity Designs*, which are based on the same assumption, we cannot provide formal proof of the assumption that sectors around the cutoff are not selected in some way. However, given the arguments above we are confident that our assumption holds. Finally, note that even though this assumption is necessary for interpreting the results of the *differential* effect of ETS pricing on the two groups, it is not crucial for identifying the *general* effect. For example, this assumption would be more essential in a Difference-in-Difference setting. As an additional robustness check we re-estimate the our baseline model with different sample restrictions which are shown in figure A.4. Figure A.5 shows that including sectors with much higher emission intensity does not change the results substantially.

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[20] Trade intensity × Carbon intensity $\geq 20\%$

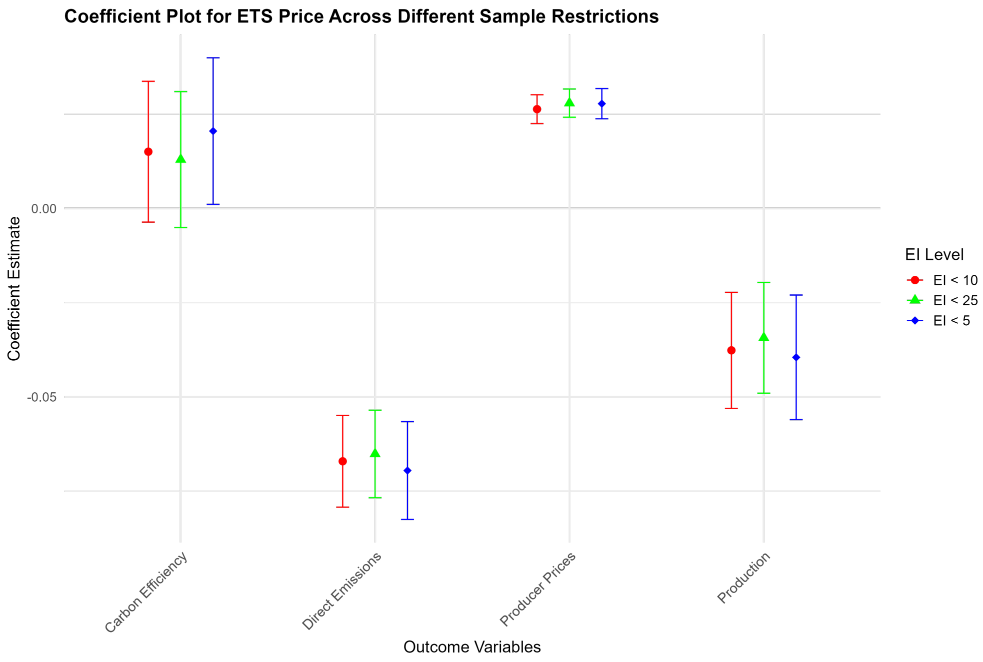
Figure A.4: Different Sample Restrictions

Source: European Comission

Source: European Comission

Source: European Comission

Figure A.5: Coeffients for Different Sample Restrictions



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