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Emission Reductions and Firm Performance under the EU Emission Trading System: Evidence from the European Manufacturing Sector

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Abstract

This thesis analyses the environmental and economic effects of the EU Emissions Trading System (EU ETS) with a specific focus on manufacturing activities across the European Union. Using EU-wide panel data at both the installation and firm levels, the study employs regression-based empirical analysis to examine how emissions and firm performance respond to carbon pricing and regulatory exposure over different phases of the EU ETS. The installation-level analysis investigates the relationship between carbon prices, free allowance allocation, and verified emissions. In contrast, the firm-level analysis compares the profitability and productivity outcomes of ETS-regulated manufacturing firms with those of comparable non-regulated firms. The results show that emission reductions become more significant across successive regulatory phases and are especially notable for installations with less free allocation protection. At the firm level, ETS exposure is associated with modest profitability pressures but higher labour productivity, suggesting efficiency improvements rather than economic contraction. The effects are more noticeable in the low-protection sector. Overall, the results indicate that the EU ETS has enhanced environmental effectiveness in the manufacturing sector while avoiding major economic disruption. This underscores the importance of regulatory design in influencing both environmental and economic results.

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Introduction

Climate change represents one of the most pressing global challenges of the twenty-first century. Rising greenhouse gas emissions have intensified environmental degradation, increased the frequency of extreme weather events, and increased economic and social costs globally. Reducing carbon emissions is therefore essential not just for protecting the environment but also as a key focus for economic policy and long-term human well-being. In this context, industrial activity plays a central role. Manufacturing, power generation, and other energy-intensive sectors remain among the main sources of human-induced emissions and industrial pollution. Because of this, policymakers face the complex task of designing instruments that can achieve environmental goals without undermining economic sustainability.

Market-based mechanisms have become more prominent among the tools available to combat climate change. These instruments set a clear price on carbon emissions to internalise environmental externalities and motivate firms to cut emissions most cost-effectively. Over the past two decades, carbon pricing has increasingly emerged as a central policy instrument to address greenhouse gas emissions at the global level. Today, an increasing number of jurisdictions across Europe, Asia, North America, and Oceania have adopted emissions trading systems or carbon taxes as part of their climate policies. These systems vary widely in scope, design, and stringency, reflecting different economic structures and policy priorities. Within this global landscape, the European Union Emissions Trading System stands out as one of the largest and most established emissions trading schemes. In terms of both geographical coverage and volume of regulated emissions, the EU ETS surpasses other carbon markets, covering multiple countries and a broad range of industrial sectors. As a result, it has become a key reference point for the design and evaluation of carbon pricing systems worldwide.

Despite its central role in European climate policy, the EU ETS remains a topic of ongoing debate. While economic theory predicts that carbon pricing can reduce emissions cost-effectively, concerns persist about its potential impact on firms' economic and financial performance. These issues are particularly important in the manufacturing industry. Manufacturing activities account for a large share of regulated emissions outside the power sector. They are often characterised by limited cost pass-through, high capital intensity, and exposure to international competition. As a result, manufacturing companies might perceive carbon pricing as both an environmental signal and a direct expense that impacts their profitability, productivity, and investment choices.

A substantial empirical literature has examined the effects of the EU ETS on emissions and firm performance. However, much of this evidence focuses on the early phases of the system, when carbon prices were relatively low and regulatory stringency was limited. Evidence combining installation-level emission responses with firm-level economic outcomes, especially in an EU-wide manufacturing context, is still limited. This thesis aims to contribute to this literature by providing a comprehensive empirical assessment of the environmental and economic effects of the EU ETS in the manufacturing sector. Using a two-level empirical approach, the analysis examines emission outcomes at the installation level and financial and productivity performance at the firm level.

By focusing on manufacturing activities and the more recent phases of the EU ETS, this thesis provides evidence on how carbon pricing operates under increased regulatory stringency. The analysis contributes to the ongoing debate on whether market-based climate policies can reduce emissions while preserving economic resilience. It emphasises how regulatory design and effective exposure to carbon pricing influence both environmental and economic results.

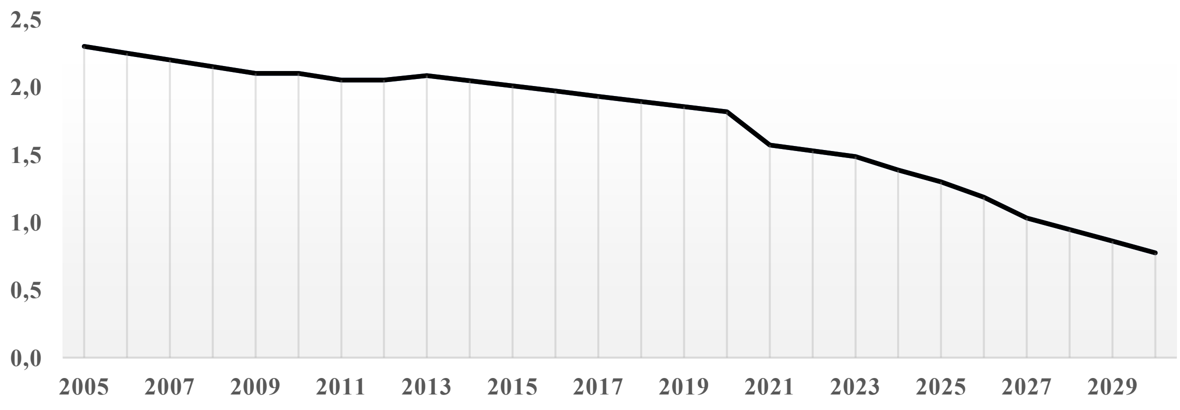
The remainder of the thesis is structured as follows. Chapter 1 provides the institutional background of the EU ETS and outlines its main design features and reforms. Chapter 2 reviews the empirical literature on the environmental and economic effects of the EU ETS, with particular attention to emissions outcomes, firm performance, carbon leakage, and innovation, and highlights the specific relevance of the manufacturing sector. Chapter 3 introduces the research questions and explains their conceptual and empirical motivation. Chapter 4 presents the data, variable construction, and empirical methodology, detailing the installation-level analysis of emissions and the firm-level analysis of financial performance. Chapter 5 reports the empirical results, including descriptive statistics, regression outcomes, and robustness checks. Chapter 6 discusses the findings in light of the existing literature and derives policy and financial implications.

Chapter 1°: Institutional Background

The EU Emissions Trading System (EU ETS) has been functioning on a cap-and-trade basis since 2005. Under this framework, the European Union issues a limited number of European Union Allowances (EUAs), each granting the right to emit one tonne of CO_2 or an equivalent amount of nitrous oxide (N_2O) or perfluorocarbons (PFCs). By placing a market price on greenhouse gas emissions, the system incentivises firms to adopt cleaner technologies and reduce emissions whenever the marginal abatement cost falls below the carbon price (Hintermann et al., 2016).

The "cap" represents the total quantity of allowances issued annually, effectively the maximum volume of greenhouse gases that participants can emit. This cap gradually decreases over time, as shown in Figure 1, which illustrates the development of the EU ETS cap from 2005 to 2030 and emphasises the faster decrease in allowances during the system's latest phases. This decrease aligns the system with the EU's more ambitious climate goals, which aim to reduce greenhouse gas emissions by at least 55% by 2030 (compared to 1990 levels) and to achieve climate neutrality by 2050 (European Commission, 2020).

Figure 1. Evolution of the EU ETS Cap (billion tonnes of CO_2), 2005- 2030



Note: Data are reported in million tonnes of CO_2. To ensure temporal consistency, the figure includes only stationary installations under the EU ETS. Aviation and maritime sectors are excluded, as they were incorporated into the system at later stages. Source: European Commission (EU ETS dataset)

The inclusion of a firm in the EU ETS is determined by the sector in which it operates and the type of greenhouse gases it emits[1]. The system mainly addresses CO_2 emissions from electricity and heat production, as well as major energy-intensive industries such as steel, cement, chemicals, and pulp and paper. Recently, it also regulates CO_2 emissions from aviation and maritime transportation. Participation in the EU ETS is mandatory for companies engaged in these regulated activities, although certain exceptions exist. In most sectors, the EU ETS applies only to large installations exceeding process-specific capacity thresholds defined in EU legislation, such as minimum thermal input or production capacity requirements. Smaller installations below these thresholds are not required to participate. Importantly, compliance obligations under the EU ETS are defined at the installation level rather than at the firm level. Each regulated installation must surrender allowances corresponding to its verified emissions, even when multiple installations belong to the same firm.

Geographically, the system applies across EU Member States and associated EEA countries[2]. According to the European Commission, the system today regulates emissions from approximately 16,000 installations[3].

1.1 Functioning of the EU ETS

A clear understanding of the EU ETS requires distinguishing between three conceptually different but closely related elements: the allocation of emission allowances, the measurement of actual emissions, and the compliance obligation that links the two. There are two channels for allocating these allowances: those granted free and those sold through auctions. Taken together, they represent the total annual supply of allowances available to regulated entities.

Figure 2 illustrates the evolution of allowance allocation under the EU ETS between 2005 and 2024, highlighting the gradual shift from free allocation towards auctioning and

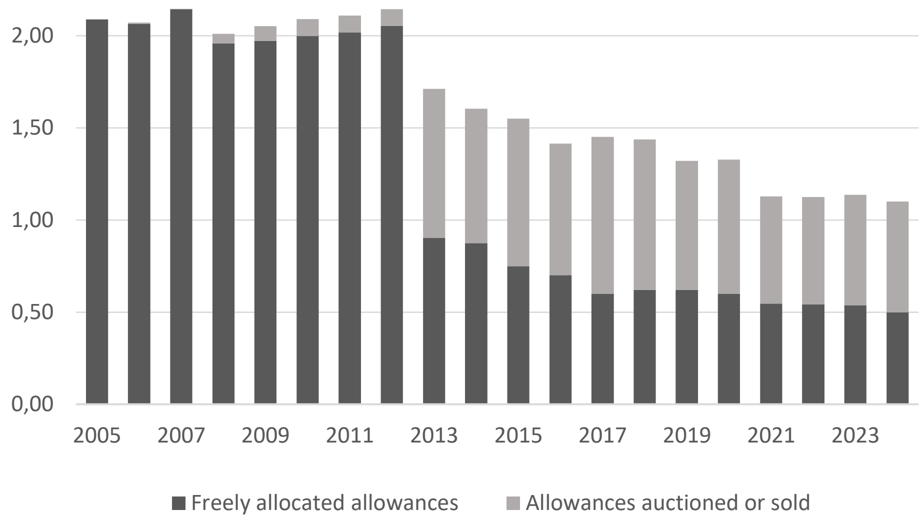
[1] The scope of the EU ETS and the sectors covered are defined by Directive 2003/87/EC and its subsequent amendments, including Directive 2008/101/EC (aviation) and Directive (EU) 2023/959 (maritime transport)

[2] Iceland, Liechtenstein and Norway

[3] Maritime activities account for approximately 16% of regulated installations and aviation for about 10% (European Environment Agency)

other forms of sale. These allocation methods are discussed in detail in the following section.

Figure 2. Evolution of allowance allocation in the EU ETS (2005–2024)



Note: Data are reported in million tonnes of CO_2. To ensure temporal consistency, the figure includes only stationary installations under the EU ETS. Aviation and maritime sectors are excluded, as they were incorporated into the system at later stages. Source: European Environment Agency (EEA)

(a) Free Allocation:

In the initial phases of the EU ETS, almost all emission allowances were distributed for free, reflecting a cautious policy approach aimed at facilitating firms' adjustment to carbon pricing. Over time, the allocation framework has been progressively reformed to better target sectors most exposed to international competition and carbon leakage risks, such as the relocation of production to regions with weaker climate policies. Today, free allowances have progressively assumed a secondary role, mainly allocated to energy-intensive and trade-exposed companies, where passing on carbon costs along the value chain is more challenging. Free allowances have been distributed in accordance with harmonised EU rules and sector-specific benchmarks. Benchmark values are regularly updated to capture technological progress, ensuring that free allocation does not reward inefficiency but instead preserves incentives to decarbonise. Overall, the system balances climate ambition with industrial competitiveness by protecting vulnerable sectors while steadily strengthening incentives to decarbonise.

(b) Auctioning:

By contrast, auctioned allowances are sold via public auctions conducted under harmonised EU rules that guarantee transparency and non-discrimination. Over time, the allocation of emission allowances has increasingly shifted toward auctioning as the core mechanism of the EU ETS. Auctioning takes place on regulated electronic platforms three times a week, with allowances sold at a uniform clearing price. These allowances can be purchased not only by operators of installations covered by the EU ETS, but also by banks, investment firms, and financial intermediaries bidding on their own behalf or on behalf of clients. In parallel, the use of auctioning revenues has become an integral part of the EU's climate policy framework. Since 2023, Member States have been required to use all the revenues generated from the auctioning of emission allowances for climate and energy-related purposes[4]. These funds are used to finance a broad range of measures, including the deployment of renewable energy, improvements in energy efficiency, the decarbonisation of transport, the modernisation of district heating systems, forest protection, and investments in carbon capture and storage. By linking allowance auctions to targeted climate expenditure, the EU ETS reinforces its role not only as a market-based emissions-reduction instrument but also as a key funding mechanism for the low-carbon transition.

Beyond their initial allocation, allowances circulate on the European carbon market. Companies with surplus allowances may sell them, while those facing shortfalls may purchase additional units or bank them for future years. The EU ETS operates as a fully integrated financial market governed by the EU's broader financial regulatory framework. Since 2018, EUAs have been classified as financial instruments under MiFID II[5]. The main market participants include energy companies, industrial firms with compliance obligations, and financial intermediaries that trade on behalf of clients. All transactions are recorded in the Union Registry and supervised via the European Union

[4] Directive (EU) 2023/959 of the European Parliament and of the Council, amending Directive 2003/87/EC, Article 10(3)

[5] Directive (EU) 2014/65/EU

Transaction Log (EUTL), which ensures transparency, reliability, and full traceability of all allowance movements.

While allocated allowances determine how many emission rights enter the system, they are conceptually distinct from verified emissions. Verified emissions refer to the actual quantity of greenhouse gases emitted by an installation during a given calendar year. These emissions are measured in accordance with harmonised monitoring, reporting, and verification (MRV) rules and must be independently certified by accredited third-party verifiers. Verified emissions are not allowances, nor do they confer any right to emit; they represent an ex post measurement of environmental output expressed in tonnes of CO_2 equivalent.

Compliance with the EU ETS is achieved by surrendering allowances. Each year, by 30 April, operators are required to surrender a number of allowances equal to their verified emissions from the previous year. At this point, regulations require a direct correspondence, where verified emissions must be paired exactly with surrendered allowances. Non-compliance results in significant financial penalties and mandatory surrender of missing allowances. The surrendered allowances could originate from different sources: free allocation, auction purchases, secondary market transactions, or allowances banked from previous years.

This annual compliance cycle clarifies the economic decision that regulated firms face. Firms can either emit greenhouse gases and surrender allowances to legitimise those emissions, or they can reduce emissions through abatement activities such as fuel switching, energy efficiency improvements, process innovation, or the development of less carbon-intensive products. The optimal compliance strategy depends on comparing the market price of allowances with the firm's marginal abatement costs. When abatement costs less than buying allowances, firms are motivated to cut emissions. Conversely, if allowance prices are low, firms might choose to comply by surrendering allowances.

1.2 Development and Reforms of the EU ETS

The origins of the EU ETS are rooted in the commitments established under the 1997 Kyoto Protocol, which, for the first time, imposed legally binding emission-reduction targets on industrialised countries[6]. To fulfil its commitment to cut greenhouse gas emissions by 8% relative to 1990 levels during the 2008–2012 period, the European Commission evaluated alternative policy instruments, including carbon taxes and emissions trading. Political constraints surrounding EU tax harmonisation made an EU-wide tax difficult to implement, while the success of the U.S. SO_2 trading programme demonstrated the potential of market-based approaches. As a result, cap-and-trade emerged as the most feasible and politically acceptable solution.

The first concrete step came in 2000, when the European Commission outlined the initial design of a European emissions trading system[7]. Following extensive consultations with stakeholders, the EU ETS Directive (2003/87/EC) was adopted in 2003, and the system was officially launched on 1 January 2005 across all Member States. The development of the EU ETS is structured around four major phases, each representing a distinct stage in the system's maturation and reform. The following sections examine these phases in turn, highlighting their main institutional features and implications.

I. Phase (2005-2007)

Phase 1 is a three-year pilot phase, from 2005 to 2007, intended as a "*learning by doing*" exercise to test the fundamental components of a carbon market, including the price-setting mechanism, the functioning of allowance trading, and the infrastructure for monitoring the movement of allowances[8]. This phase covered only CO_2 emissions, primarily from power generators and energy-intensive industrial installations. The cap during this phase was set at the national level through National Allocation Plans (NAPs), which defined the total number of allowances available in each Member State and their distribution among sectors. Because the EU lacked reliable historical emissions data at the time, these caps were based largely on estimates. This decentralised approach meant that the overall EU cap was not known until all NAPs were approved, and the estimates used by Member States tended to overstate expected emissions.

[6] United Nations, Kyoto Protocol to the UNFCCC, 1997, Articles 3 and 4
[7] Green Paper COM(2000) 87
[8] Directive 2003/87/EC

Nearly all allowances in this first phase were allocated free of charge, both to protect European industries from competitive disadvantages and potential carbon leakage and to reflect the experimental nature of the system. In the early months of 2005, the carbon price reached around €8 per tonne, and trading expanded rapidly as the market took shape. However, once verified emissions data became available in 2006–2007, it became clear that emissions were significantly lower than anticipated and that Member States had issued too many allowances (Aatola et al., 2013). Total supply exceeded actual emissions by a considerable margin, resulting in a substantial surplus of EUAs. Because allowances from Phase 1 could not be banked for use in Phase 2, market participants had no incentive to hold onto them. This caused a sharp drop in the carbon price in 2007, decreasing from €25–30 per tonne just months before to nearly zero by the end of the phase (Vlachou, 2014).

Despite its shortcomings, Phase 1 achieved several crucial objectives. It established a functioning carbon market across the EU, created a price signal for CO_2, and put in place the regulatory, institutional and technical infrastructure needed for monitoring, reporting and verifying emissions, foundations essential for the more robust and effective phases that followed. Above all, it provided invaluable practical experience, demonstrating the importance of accurate emissions data, centralized cap setting and banking provisions, lessons that shaped the reforms implemented in subsequent phases to strengthen the credibility and environmental effectiveness of the EU ETS.

II. Phase (2008-2012)

Phase 2 of the EU ETS, from 2008 to 2012, overlapped with the initial Kyoto Protocol commitment period, during which EU Member States were subject to legally binding emission reduction targets. During this, the policy broadened its geographical and sectoral scope, incorporating Iceland, Liechtenstein, and Norway in 2008, and including aviation in the scheme in 2012[9]. A key change was the introduction of a tighter emissions cap, set approximately 6.5% below 2005 verified emissions, made possible by the availability of reliable emissions data collected during Phase 1[10]. In terms of allocation,

[9] Directive 2008/101/EC. The inclusion of aviation initially applied only to flights within the European Economic Area (EEA). Flights to and from non-EEA countries were temporarily exempted and later addressed through a limited scope
[10] Directive 2003/87/EC

Phase 2 retained a high share of free allocation, though slightly lower than in Phase 1, with around 90% of allowances distributed free of charge. Importantly, auctioning was introduced, albeit on a limited scale, accounting for roughly 10% of allowances in some Member States.

The global financial crisis of 2008 constituted the defining external shock of Phase 2, profoundly affecting both emissions levels and allowance demand. As industrial production declined sharply across Europe, greenhouse gas emissions fell well below expectations, resulting in a significant surplus of allowances and credits. This excess supply, combined with inflows of international credit and lingering design flaws inherited from Phase 1, pushed carbon prices downward. Prices dropped significantly, hitting approximately €10 per tonne in early 2009, and stayed low for much of the period. Although allowances could be banked into Phase 3, partially reducing price volatility, the ongoing oversupply of allowances continued to limit the system's ability to generate strong decarbonisation incentives (Aatola et al., 2013).

Institutionally, Phase 2 introduced a centralised and harmonised compliance system through the establishment of a single Union Registry, which replaced the national registries, and the EU Transaction Log (EUTL). In summary, Phase 2 represented a transitional stage: more stringent and comprehensive than Phase 1, more aligned with climate policy goals, yet still characterised by structural imbalances that limited its price signal. Its experience influenced many of the major reforms in Phase 3, aimed at enhancing the system's effectiveness and resilience.

III. Phase (2013-2020)

Phase 3 of the EU ETS, from 2013 to 2020, marked the most substantial structural transformation of the system since its creation[11]. The scope of the ETS expanded further during this phase, both geographically, with Croatia joining the system, and in terms of sectors and greenhouse gases. This increased the system's potential to drive emissions reductions across the European economy. Unlike earlier phases, which relied largely on national discretion, Phase 3 introduced a fully harmonised, centralised framework to advance environmental goals, improve market efficiency, and address initial design issues. A defining innovation was the introduction of a single EU-wide emissions cap,

[11] Directive 2003/87/EC, as amended by Directive 2009/29/EC

replacing the fragmented system of national caps. The new cap declined annually at a linear rate of 1.74%[12].

While free allocation continued for sectors vulnerable to carbon leakage, Phase 3 represented a decisive shift toward auctioning as the primary method of allocating allowances. The power sector moved almost entirely to full auctioning beginning in 2013, reflecting both its limited exposure to international competition and its relatively lower abatement costs. Meanwhile, free allocation for the manufacturing sector was progressively reduced over the phase, falling from around 80% of their needs in 2013 to approximately 30% in 2020, except for installations classified as highly exposed to carbon leakage. Aviation, accounting for a small share of ETS emissions, remained largely covered by free allocation[13].

In parallel, dedicated support mechanisms, such as the New Entrants Reserve (NER300), were introduced to finance the deployment of innovative renewable energy technologies. They signalled the EU's intention not only to price carbon but also to foster low-carbon innovation and early-stage clean energy development[14]. Despite these reforms, Phase 3 initially inherited a substantial surplus of allowances accumulated during Phase 2, driven by the economic recession and persistent structural imbalances (Borghesi et al., 2016). Consequently, carbon prices remained low for several years, often below €10 per tonne from 2013 to 2017, thereby reducing the system's capacity to influence investment decisions. (Hintermann et al., 2016). In response, the EU introduced corrective measures, including the temporary backloading of auction volumes and, more importantly, the creation of the Market Stability Reserve (MSR)[15]. The MSR is the EU's primary instrument for maintaining balance between the supply of allowances and the demand for compliance, addressing structural oversupply and stabilising the carbon market.

Starting in 2018, these reforms significantly changed market expectations: surplus allowances were slowly absorbed, confidence in the system grew, and carbon prices increased markedly. By the end of Phase 3, the EU ETS had evolved from a system constrained by excess supply and weak price signals into a more resilient and credible

[12] Directive 2009/29/EC
[13] Directive 2008/101/EC
[14] Decision No 2010/670/EU
[15] Decision (EU) 2015/1814 (MSR)

market-based instrument, better positioned to steer long-term decarbonisation. Moreover, this phase coincided with a significant external shock, the COVID-19 pandemic, which temporarily decreased industrial activity and emissions independently of regulatory pressure, complicating causal attribution in the later years of this phase. Overall, Phase 3 constituted a decisive turning point in the evolution of the EU ETS, laying out the institutional and market foundations for the more ambitious Phase 4.

IV. Phase (2021-2030)

Phase 4 of the EU ETS, running from 2021 to 2030, represents the most far-reaching reform of the carbon market since its creation[16]. This phase aims to bring the system in line with the EU's reinforced climate targets, which include achieving climate neutrality by 2050 and reducing net greenhouse gas emissions by 55% by 2030. The system now covers 30 countries and approximately 10,000 energy and industrial installations, while extending regulation to new sectors, most notably maritime transport, which is gradually included from 2024[17]. A central feature of Phase 4 is the accelerated tightening of the emissions cap. The annual linear reduction factor was increased to 2.2%, compared to 1.74% in Phase 3, ensuring a faster and more predictable decline in emissions from ETS-covered sectors and strengthening the credibility of the carbon price signal[18]. This enhanced stringency is intended to drive emissions reductions of around 62% relative to 2005 levels by 2030. At the same time, the Market Stability Reserve (MSR) plays a strengthened role by absorbing and permanently cancelling surplus allowances, thereby preventing renewed oversupply and reinforcing carbon price signals and the overall credibility of the EU ETS.

In terms of allocation, Phase 4 consolidates auctioning as the dominant mechanism. Free allocation remains in place but is more narrowly targeted, reflecting a clearer trade-off between protecting sectors at high risk of carbon leakage and strengthening decarbonisation incentives. This phase also consolidates and expands the system's financial architecture to support the transition to a low-carbon economy. Auctioning revenues are channelled into major funding instruments, notably the

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[16] Regulation (EU) 2021/1119
[17] Directive (EU) 2023/959
[18] Directive (EU) 2018/410

Innovation Fund, Modernisation Fund, and Social Climate Fund, which support industrial decarbonisation, breakthrough clean technologies, and energy-system upgrades. Policy reforms adopted in 2023 further reinforced Phase 4 by increasing the emissions-reduction target for ETS sectors and introducing the Carbon Border Adjustment Mechanism (CBAM). The progressive phase-out of free allocation alongside CBAM aims to equalise carbon costs between EU producers and foreign competitors, fundamentally reshaping the EU's approach to carbon leakage prevention[19].

Overall, Phase 4 is characterised by significantly greater market stringency. Carbon prices have risen markedly, passing €100 per tonne in 2023, reflecting both a tighter cap and strengthened market-stability instruments. At the same time, policymakers increasingly recognise that the ETS must operate alongside complementary policies, including renewable energy regulations, energy-efficiency standards, and sector-specific measures. The EU ETS is thus positioned not as the sole driver of decarbonization, but as a central market-based pillar within a broader climate policy framework. The following table summarizes the key design features and market outcomes of the EU ETS across phases.

[19] Regulation (EU) 2023/956; Directive (EU) 2023/959

Key Features	Phase I	Phase II	Phase III	Phase IV
Time Period	2005-2007	2008–2012	2013–2020	2021–2030
Geography	EU27	EU27 - Norway, Liechtenstein, Iceland	EU27 - Norway, Liechtenstein, Iceland, Croatia	EU27 - Norway, Liechtenstein, Iceland, Croatia; Exit of United Kingdom
Sectors	Power stations and other combustion plants exceeding 20MW, along with oil refineries, coke ovens, iron and steel plants, cement clinker production, glass, lime, bricks, ceramics, pulp paper, and board	Same as Phase I, with the addition of Aviation starting from 2012	Same as Phase II, with the addition of Aluminium and Petrochemicals	Same as Phase III, with the addition of maritime transport
Greenhouse gases	CO_2	CO_2, N_2O, PFC	CO_2, N_2O, PFC	CO_2, N_2O, PFC
Cap Setting	Decentralised national caps	Tighter cap (-6.5% vs 2005) verified emissions	Single EU-wide cap, declining annually at a linear rate of 1.74%	Single EU-wide cap, declining annually at a linear rate of 2.2%
Allocation method	Free allocation only	Mostly free; limited auctioning introduced	Auctioning dominant; limited free allocation	Auctioning dominant; reduced free allocation
Market issues	Over-allocation; no banking; price collapse	Allowance surplus; financial crisis	Inherited surplus; initially weak prices; Covid-19	Carbon leakage risk; policy interaction
Key reforms	None (pilot phase)	Banking to Phase III; Union Registry; EUTL	Backloading measures; Market Stability Reserve (MSR); NER300	Strengthened MSR; climate funds; Carbon Border Adjustment Mechanism (CBAM)
Carbon Price signal	Initial rose (€8/t in early 2005; €25–30/t in 2006), then collapsed to near zero	Weak and volatile (around €10/t)	Initially weak, strengthened after 2018	Strong and credible (>€100/t)

1.3 Future Developments of the EU ETS

Looking toward 2030 and the decades ahead, the EU carbon pricing architecture is set to evolve into a broader, more integrated system combining the existing EU ETS with the newly established ETS II. Scheduled to begin operation in 2027, ETS II will extend carbon pricing to sectors closely linked to everyday energy consumption, including fuel use in buildings, road transport, and small industrial installations [20]. Together, these systems will support the EU's journey toward net-zero emissions, as increasing carbon prices are expected to strengthen incentives for deep technological change. However, the long-term trajectory remains uncertain: while the Commission has recommended a 90% emissions reduction target for 2040, the post-2030 linear reduction factor for the ETS has not yet been established. This leaves open various possible pathways, from a near-zero cap in the late 2030s to complete decarbonisation by 2050[21].

In parallel, policymakers face an increasingly delicate trade-off between environmental ambition and economic considerations. Carbon prices must remain sufficiently strong to stimulate innovation and long-term investment, while avoiding excessive distributional impacts on households and firms, particularly as ETS II begins to affect the energy costs consumers face directly. In this emerging dual-system architecture, the ETS and ETS II together will shape the core of Europe's long-term climate strategy, while operating alongside complementary measures that remain essential to achieving the Union's 2040 and 2050 commitments.

1.4 Price Drivers of EU Allowances (EUAs)

The price of European Union Allowances (EUAs) is determined through the interaction of supply and demand in a centralised carbon market. Although the demand for allowances mainly reflects compliance obligations from verified emissions of regulated installations, over time, the EU ETS has gradually expanded the range of factors that affect carbon prices. As the system matured, and particularly since Phase III, the EUA price has increasingly incorporated not only contemporaneous compliance demand, but also expectations about future regulatory stringency, developments in energy markets, macroeconomic conditions, and financial market dynamics.

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[20] Directive (EU) 2023/959

[21] European Commission, Communication on the EU's 2040 climate target

On the demand side, economic activity in regulated sectors remains a fundamental long-run driver of allowance demand. Periods of economic growth usually lead to higher industrial output, more energy use, and increased emissions. This results in greater demand for allowances and upward pressure on prices. Conversely, economic downturns, such as the COVID-19 crisis, reduce emissions and compliance needs, contributing to lower allowance demand (Hintermann et al., 2016). Short-term factors such as weather conditions and renewable energy availability further contribute to demand fluctuations by affecting electricity demand and the composition of generation technologies.

On the supply side, the emissions cap established by EU legislation represents the primary determinant of allowance scarcity. Reforms tightening the cap, such as increases in the linear reduction factor, directly affect expectations about future allowance availability and tend to raise current prices. In addition, since 2019, the Market Stability Reserve (MSR) has become a key institutional mechanism shaping effective supply (Dechezleprêtre et al., 2023). By adjusting auction volumes in response to the total number of allowances in circulation, the MSR reduces structural oversupply and strengthens the credibility of the scarcity signal embedded in the EU ETS. The possibility of banking allowances across compliance periods further links current prices to expectations of future policy stringency, allowing firms to smooth compliance costs over time.

Finally, the growing financialization of the EU ETS has contributed to shaping carbon price dynamics. As EUAs have been classified as financial instruments and increasingly traded by banks, investment funds, and other financial actors, market liquidity has improved, but short-term price volatility has also increased. Financial participation may amplify price movements in response to energy market shocks, geopolitical events, or changes in regulatory expectations. However, current evidence indicates that in the medium to long term, EUA price movements are mainly driven by policy-imposed scarcity and core market fundamentals rather than speculation (Ponti & Romagnoli, 2022).

The EUA price serves as a primary indicator of the carbon pricing incentives that regulated installations encounter. Although it incorporates regulatory, economic, and market influences, it mainly functions as the main incentive signal through which the EU ETS transmits policy stringency to firms' emission decisions.

Chapter 2°: Literature Review

Since its launch in 2005, the EU ETS has been a subject of scholarly debate regarding its environmental impact and overall economic effects. Conceptually, the ETS is rooted in Coasian market-based regulation. By imposing a binding emissions cap and allowing firms to trade allowances, the system aims to equalise marginal abatement costs and achieve emissions reductions at minimum societal cost (Coase & Virginia, 1960). Nevertheless, the actual effectiveness of this mechanism in practice heavily relies on design elements like allocation rules, carbon price fluctuations, and market liquidity, all of which influence firms' adjustment strategies and the overall policy efficiency.

The expectations surrounding the EU ETS have always been dual. On one hand, the system was designed to deliver cost-effective emissions reductions and stimulate low-carbon technological change. On the other hand, both policymakers and scholars have long expressed concerns about potential adverse effects on firms' competitiveness, particularly in energy-intensive and trade-exposed industries. Traditional environmental economics suggests that environmental regulations lead to compliance costs, which may decrease productivity and incentivise polluting activities to move to areas with more lenient climate policies, often called the pollution haven hypothesis (Levinson & Taylor, 2008).

In contrast, the Porter hypothesis suggests that well-designed environmental regulations can enhance long-term competitiveness by encouraging firms to innovate, cut inefficiencies, and adopt new technologies that they might not pursue without policy support (Porter & Linde, 1995). This view has been widely supported by EU policymakers, who see the ETS not just as a tool for climate action but also as a potential driver for green innovation and sustainable economic growth. Empirical research has examined these dynamics, assessing if the EU ETS has successfully cut emissions, influenced firms' financial and competitive performance, caused carbon leakage, and fostered innovation. However, the findings of this research are often heterogeneous and depend on the sector, the ETS phase, the empirical methodology, and the stringency of regulation (Martin et al., 2016; Verde, 2020).

1.5 Emissions under the EU ETS

A substantial body of empirical research has evaluated whether the EU ETS has effectively reduced greenhouse gas emissions since its introduction in 2005. The evidence accumulated over the four trading phases shows a system whose environmental impact has strengthened over time, though with significant variation across sectors, countries, and methodological approaches.

Phase I (2005-2007) is widely regarded as a pilot period, characterised by substantial over-allocation of allowances and by carbon prices that were too low and volatile to induce strong emissions reduction incentives. Nevertheless, several aggregate studies estimate that emissions fell between 2.5% and 6% relative to business-as-usual, though reductions vary considerably across sectors (Dechezleprêtre et al., 2023; Martin et al., 2016). Using a generalised synthetic control method, Bayer & Aklin (2020) find that Phase I delivered considerably weaker impacts than subsequent phases. Country-level micro-evidence is broadly consistent with these findings, with studies for France, Germany, Norway, Lithuania and the United Kingdom generally failing to identify statistically significant emissions reduction effects during this phase (M. Klemetsen et al., 2020; Martin et al., 2014). This heterogeneity mainly results from the decentralised cap-setting process within National Allocation Plans, leading to significant variation across countries in policy stringency. It is also influenced by early methodological limitations, including short pre-treatment periods, limited control groups, and the development of monitoring, reporting, and verification systems.

Environmental impacts become clearer in Phase II (2008–2012), when allowance allocation tightened, emission monitoring and verification enhanced, and carbon prices, despite the global financial crisis, remained high enough during parts of the period to prompt behavioural changes. As a result, most empirical studies attribute significantly larger reductions to this phase. Cross-country evaluations suggest approximately 10% reductions in countries like France, the Netherlands, Norway, and the United Kingdom. (Dechezleprêtre et al., 2023). Sector-specific studies identify the largest reductions in chemicals, non-metallic mineral products, and electricity, indicating that emissions reductions were more substantial in sectors with relatively higher carbon intensities or greater ability to adjust fuel mixes. A broader synthetic-control analysis by Bayer & Aklin (2020) strengthens this assessment, concluding that EU ETS sectors emitted 11.5% less carbon than they would have in the absence of the system, with Phase II showing significantly stronger effects than Phase I. At the same time, several authors caution that part of the observed emissions reductions during Phase I may reflect the sharp contraction in industrial activity associated with the 2008–2009 financial crisis rather than purely policy-induced behavioural change (Bel & Joseph, 2015).

The picture becomes more differentiated in Phase III (2013–2020), a period marked by the progressive shift from free allocation toward auctioning, the introduction of the Market Stability Reserve, and a more persistent carbon price signal. Using country-level data for all the EU Member States over the period 2005–2020 and a counterfactual matrix completion approach, Biancalani et al. (2024) estimate that the EU ETS reduced CO_2 emissions in regulated industries by approximately 15.4% on average, providing statistically significant evidence of the scheme's effectiveness during its more stringent and mature phases. Consistent with these results, Bayer & Aklin (2020) find that emissions reductions increased substantially after 2013, once allowance oversupply was addressed through structural reforms such as the Market Stability Reserve and carbon prices rose. Their results suggest that firms responded more strongly to the clearer long-term incentives embedded in the post-2013 design, which reduced the uncertainty that had characterised earlier phases. However, Phase III also overlaps with major exogenous shocks, most notably the COVID-19 pandemic, which temporarily suppressed industrial activity and reduced emissions independently of regulatory pressure, complicating causal attribution in the final years of the phase (Bruninx & Ovaere, 2022).

Phase IV (2021–2030), although still ongoing, has already generated a preliminary wave of empirical assessments suggesting stronger environmental effects than in any previous phase. The sustained increase in carbon prices, the tightening of caps, and reforms aimed at reducing allowance surpluses have sharply enhanced the emissions reductions. Moreover, the post-pandemic rebound was accompanied by a surge in energy prices and a sharp increase in allowance prices, both of which strengthened the marginal incentive to reduce fossil-fuel use. These market dynamics intensified emissions reductions in sectors with flexible fuel-switching capabilities (Biancalani et al., 2024).

Across all these periods, a unifying pattern emerges: the effectiveness of the EU ETS increases as the system becomes more stringent and fewer allowances are freely allocated. While Phase I produced limited and uneven impacts, Phase II delivered widespread and statistically robust reductions, Phase III consolidated these trends through institutional reforms and a more persistent price signal, and early Phase IV evidence points toward an increasingly disciplined and effective carbon market. At the same time, the literature highlights substantial heterogeneity across firms, sectors and national contexts, reflecting differences in energy systems, regulatory environments and firms' capacity to adopt cleaner technologies. This heterogeneity underscores the importance of policy design, complementary measures, and sufficient stringency to enable carbon pricing to achieve its full environmental potential.

1.6 Economic and Financial Performance under the EU ETS

Since its introduction, the EU ETS has generated an intense policy debate regarding its potential impact on firms' economic and financial performance. Although traditional economic theory suggests that carbon pricing could raise production costs and reduce competitiveness, the Porter Hypothesis presents a different perspective. It argues that properly designed environmental regulations can drive innovation, improve efficiency, and ultimately strengthen firm performance. Across the empirical literature, the economic effects of the EU ETS are typically assessed using standard firm-level indicators, including employment, revenues, value added, turnover, labour productivity, and, in some cases, total factor productivity (TFP) or returns on capital. These results are typically examined by comparing two groups of firms: those affected by the ETS and those not covered. Matching techniques are used to create comparable firms and develop credible counterfactuals. Nevertheless, a broad pattern emerges across the four trading phases: the EU ETS has consistently reduced emissions without systematically harming firms' economic and financial performance (Dechezleprêtre et al., 2023).

Evidence from Phase I generally indicates limited or non-significant economic impacts. Early firm-level studies, such Chan et al. (2013) analysis report largely insignificant effects on output and employment in cement and steel, with the main exception being positive turnover effects in electricity generation, likely reflecting firms' ability to pass through opportunity costs into output prices. Research on employment echoes this pattern. Most studies find no systematic job losses, except for a small, temporary decline, consistent with the regulatory uncertainty of the early years. (Dechezleprêtre et al., 2023; Marin et al., 2018) . Overall, evidence from Phase I suggests that generous free allocation and immature market conditions prevented the ETS from imposing substantial cost pressures on firms, mitigating both negative and positive performance effects.

In Phase II, more sophisticated empirical strategies begin to identify clearer patterns, despite the confounding effects of the global financial crisis and persistent allowance surpluses. Marin et al. (2018), using a large European firm-level dataset, found that regulated firms experienced increases in turnover, value added, and employment, with no indication of declining competitiveness. Cross-country-level evidence reinforces this perspective. Wagner et al., (2014) In France and Germany, documented substantial emission reductions during Phase II, while employment and output remained largely unaffected. At the same time, some studies highlight potential vulnerabilities for specific industry segments. Martin et al. (2016) reported small negative TFP and ROI effects in emission-intensive sectors, where firms may have faced limited pass-through opportunities. Taken together, Phase II studies reinforce the conclusion that the EU ETS achieved meaningful emission reductions without jeopardising firms' economic scale or financial stability, while also revealing sector-specific heterogeneity in adjustment responses.

Evidence for Phase III, although more limited due to data availability, broadly confirms the continuation of Phase II trends. D'Arcangelo et al (2022), analysing Italian manufacturing firms over a decade, found no adverse effects on TFP and observed that firms remained economically resilient under the ETS. Dechezleprêtre et al. (2023), using a large multi-country matched sample, similarly reported that regulated firms did not experience declines in profits, employment, or overall performance. Instead, these firms showed increases in revenues and fixed assets, suggesting that the ETS encouraged investment in low-carbon technologies and productivity-enhancing processes. Labour productivity effects remained robustly positive, consistent with earlier findings from Marin et al. (2018) and Klemetsen et al. (2020). Meanwhile, mixed evidence on TFP persisted: while some firms benefited from innovation-induced efficiency gains, others, especially those further from the technological frontier, experienced weaker performance (Koch & Themann, 2022). This suggests that the ETS could strengthen existing productivity frameworks, benefiting innovative, technology-driven companies, while imposing adjustment costs on those that fall behind. Overall, Phase III evidence suggests that the tightening of the ETS strengthened firms' incentives for technological upgrading without undermining economic performance.

Phase IV is still in progress, and empirical evidence remains scarce. Early reports indicate that concerns about competitiveness and carbon leakage continue to shape policy debates, particularly for energy-intensive, trade-exposed sectors. Nevertheless, the absence of systematic negative performance effects in earlier phases suggests that large-scale adverse economic impacts are unlikely (Marcu et al., 2025).

Across the four phases of the EU ETS, the most statistically significant empirical evidence converges on a clear conclusion: carbon pricing in Europe has achieved significant emission reductions without imposing substantial economic and financial burdens on regulated firms. Indicators such as revenues, value added, labour productivity, and investment have frequently improved or remained stable, while negative impacts, when present, tend to be modest, sector-specific, or statistically weak. Crucially, the distribution of impacts is highly heterogeneous and depends on firms' technological proximity to the industry frontier. Productivity gains are concentrated among more innovative firms, whereas technologically lagging firms experience a relative slowdown in productivity growth, helping to explain the mixed evidence reported in the literature. Recognising and addressing this heterogeneity is essential for designing future phases of the EU ETS that support both decarbonisation and industrial competitiveness.

1.7 Risk of Carbon Leakage

The risk that climate policies induce firms to relocate production or increase imports from less regulated regions, commonly referred to as carbon leakage, has been a central concern since the introduction of the EU ETS. According to the Pollution Haven Hypothesis, stringent environmental regulation may erode competitiveness by raising production costs, thereby encouraging firms to move carbon-intensive activities abroad (Levinson & Taylor, 2008).

Whether these mechanisms materialise under the EU ETS remains an empirical question. The strongest empirical data indicate minimal or no carbon leakage in the initial stages of the EU ETS. Using firm-level emissions data for multinational companies between 2007 and 2014, Aghion et al. (2016) directly test whether regulated firms relocated emissions outside the EU and find no systematic shift in the geographical distribution of emissions. Complementing this micro-level evidence, Naegele & Zaklan (2019) analyse embodied carbon in bilateral trade flows for European manufacturing sectors and examine whether ETS regulation led to higher net imports or increased carbon intensity of imports. Across multiple measures of regulatory stringency and using data spanning 2004–2011, they find no statistically significant impact of the EU ETS on trade patterns or embodied emissions.

Together, these results suggest that the EU ETS did not undermine competitiveness or trigger carbon leakage during its initial phases. An important contribution by Martin et al. (2014) helps reconcile these empirical findings with persistent political concerns over competitiveness. Using firm-level survey data from European manufacturing, the authors show that firms often believed their exposure to carbon leakage was much higher than what subsequent empirical evidence suggested. This gap between perceived and actual relocation risks played a significant role in shaping policy design, particularly by reinforcing political support for generous free allocation as a precautionary measure, despite limited evidence of realised leakage.

While most micro-empirical studies find negligible leakage, theoretical and ex-ante modelling approaches paint a more cautious picture. Computable General Equilibrium (CGE) models often predict substantial leakage rates, sometimes exceeding 20–30%, under unilateral carbon pricing (Carbone & Rivers, 2017). However, such predictions are highly sensitive to modelling assumptions, especially regarding market structure, emissions-reduction elasticities, and firms' mobility. Empirical evidence based on observed firm behaviour under the EU ETS does not corroborate these high leakage estimates.

More recent studies suggest that leakage risks may be sector-specific and become more salient as carbon prices increase. De Beule et al. (2022) analyse multinational investment decisions during Phase III, when carbon prices rose significantly, and free allocation declined. They find that firms operating in sectors unable to pass through compliance costs were more likely to invest in new foreign direct investment outside the EU, indicating incipient leakage risks under tighter carbon constraints.

At the same time, the progressive tightening of the ETS, combined with the phase-out of free allocation, raises legitimate questions about whether leakage risks might become more pronounced in the future. In sum, the overall empirical record remains broadly consistent: across the electricity, manufacturing, and industrial sectors, direct econometric evidence of carbon leakage under the EU ETS is limited, and when detected, highly context-specific. This aligns with the view that relocation decisions are driven far more by labour costs, market access, and infrastructure than by carbon costs, which typically represent a small share of total production expenses (Naegele & Zaklan, 2019). Nonetheless, isolated sectoral vulnerabilities, particularly in energy-intensive, trade-exposed industries, highlight the importance of accompanying policies such as free allocation reforms and the Carbon Border Adjustment Mechanism, designed to safeguard competitiveness while preserving the environmental integrity and credibility of the ETS.

1.8 Innovation under the EU ETS

The relationship between emissions trading and technological innovation constitutes one of the most widely debated dimensions of the EU ETS. Theoretically, two opposing mechanisms emerge. On the other hand, the Induced Innovation Hypothesis and the Porter Hypothesis suggest that environmental regulation, by increasing the cost of pollution, can motivate firms to innovate and implement cleaner technologies. On the other hand, standard neoclassical theory suggests that stricter regulation increases production costs and may crowd out R&D investments, especially when firms face uncertainty or when compliance can be achieved through less costly strategies such as allowance trading or optimising production inputs (Coase & Virginia, 1960). As a result, whether and to what extent the EU ETS has effectively incentivised innovation remains an empirical question.

Early evidence, largely based on qualitative and sector-specific analyses, points to limited innovation effects during Phases I and II of the EU ETS. Studies focusing on the German electricity sector find that while the ETS increased awareness of carbon constraints, its direct impact on innovation was modest, especially during the pilot phase (Hoffmann, 2007). Similarly, Borghesi et al. (2016) show that although the ETS encouraged firms to initiate climate-related innovation activities, it did not provide strong enough incentives to trigger transformative technological change. Instead, firms primarily responded through incremental adjustments such as fuel switching, efficiency improvements, and enhanced monitoring practices. In a more recent review research, Mandaroux et al. (2023), synthesising results from 43 empirical studies, conclude that although the EU ETS can stimulate some forms of pro-environmental innovation, its overall effectiveness in promoting technological change has been limited. The authors attribute this to insufficient stringency, regulatory uncertainty, and the gradual nature of reforms that did not fully account for exogenous shocks such as the financial crisis. Lilliestam et al. (2021) similarly argue that the ETS has not yet generated strong incentives for radical or long-term innovation, even though it has contributed to incremental improvements. Across literature, regulatory uncertainty emerges as a key constraint: uncertainty regarding future allowance prices, cap trajectories, and allocation rules discouraged long-term investments, particularly in capital-intensive industries (Borghesi et al., 2016; Hoffmann, 2007).

In contrast, a growing body of quantitative micro-level evidence provides more robust support for a positive innovation effect of the EU ETS. A seminal contribution by Calel and Dechezleprêtre (2016) combines firm-level ETS participation data with patent records covering approximately 80% of regulated installations. Their analysis shows a 9.1% increase in low-carbon patenting among ETS firms, offering one of the strongest empirical validations of induced innovation under carbon pricing. Complementing this evidence, Aghion et al. (2016) show, using patent data across OECD countries, that higher carbon prices significantly increase clean innovation while reducing innovation in carbon-intensive technologies.

Crucially, their results highlight that the credibility and persistence of the carbon price signal, rather than short-run price fluctuations alone, play a key role in shaping firms' innovation incentives. More recent studies reinforce this conclusion. Calel (2020), exploiting delayed entry of some UK firms into the ETS, finds significant increases in low-carbon R&D and patenting despite limited short-run effects on carbon intensity. Goerger (2021) similarly documents substantial increases in climate-mitigation investments, around 25% during Phase II and close to 40% during Phase III, suggesting that innovation incentives strengthened as the system matured and allowance scarcity increased.

Across the literature, two main constraints consistently emerge: insufficient stringency and high policy uncertainty. Low allowance prices in Phases I and II decreased motivation for innovation. Meanwhile, regulatory volatility, frequent rule changes, changing expectations about free allocation, and unclear long-term price signals discouraged long-term R&D commitments. The introduction of the Market Stability Reserve and the centralisation of cap-setting in Phase III partially addressed these issues by stabilising prices and enhancing predictability. As allowance prices increased in recent years, innovation incentives appear to have strengthened.

In addition to market-driven price incentives, the EU ETS also supports innovation by recycling auction revenues into dedicated funding instruments. A substantial portion of revenue from auctioned allowances is directed to the Innovation Fund, Modernisation Fund, and Social Climate Fund, which offers specific financial support for developing and implementing low-carbon technologies. These funds can complement carbon pricing by strengthening firms' incentives to invest in clean technologies, even when price signals alone may be insufficient.

Overall, the empirical literature suggests that the innovation effects of the EU ETS are highly contingent on policy stringency and regulatory predictability. While early phases generated limited, mostly incremental innovation, more recent evidence indicates that higher, more stable carbon prices have begun to strengthen incentives for low-carbon technological change.

1.9 Focus on the Manufacturing Sector under the EU ETS

Manufacturing plays a central role within the EU Emissions Trading System, accounting for a substantial share of covered emissions outside the power sector and encompassing some of the most energy-intensive and trade-exposed industries, such as steel, cement, chemicals, and non-metallic mineral products. These sectors are responsible for a significant fraction of industrial CO_2 emissions in Europe and have therefore been a primary target of carbon pricing policies.

At the same time, manufacturing differs markedly from other ETS-covered sectors, particularly electricity generation, in terms of cost pass-through, technological constraints, and exposure to international competition. While power producers have generally been able to pass carbon costs on to consumers through higher electricity prices, manufacturing firms often operate in highly competitive global markets and face more limited pass-through opportunities (Petrick & Wagner, 2014; Klemetsen et al., 2016). As a result, carbon pricing in manufacturing may generate more complex and heterogeneous effects on emissions, profitability, employment, and investment decisions than in other ETS sectors.

These sector-specific characteristics have strongly influenced the design of the EU ETS. Manufacturing industries have historically received a large share of allowances for free, reflecting concerns about carbon leakage and competitiveness. Benchmark-based free allocation has played a central role in moderating short-term compliance costs, particularly during Phases I and II, when allowance prices were low and overallocation was widespread. Empirical evidence suggests that these design features mitigated cost pressures but may also have weakened abatement and innovation incentives for some firms (Martin et al., 2016; Borghesi et al., 2016).

As free allocation has been progressively reduced and auctioning expanded, especially from Phase III onwards, manufacturing firms have become increasingly exposed to explicit carbon costs. Falling from around 80% of their needs in 2013 to approximately 30% in 2020, except for installations classified as highly exposed to carbon leakage (European Commission, 2015). The empirical literature highlights that the effects of the EU ETS on manufacturing are highly heterogeneous. Emissions reductions are generally positive but smaller and more uneven than in the power sector, reflecting technological rigidity, capital intensity, and longer investment cycles (Colmer et al., 2022; Bayer & Aklin, 2020).

Economic performance effects are similarly mixed. Most firm-level studies find no systematic negative impacts on output, value added, or employment, while some document modest improvements in productivity or revenues, particularly among more efficient or technologically advanced firms (Petrick & Wagner, 2014; Klemetsen et al., 2016; D'Arcangelo et al., 2022). At the same time, less productive and more energy-intensive firms tend to experience relatively weaker performance, indicating that the ETS may amplify pre-existing productivity differences within manufacturing sectors (Koch & Themann, 2022).

Manufacturing is also central to the carbon-leakage debate. Despite persistent concerns, most micro-empirical studies find little evidence that the EU ETS has induced large-scale relocation of manufacturing activity or emissions. Firm-level and trade-based analyses show that carbon costs typically represent a small share of total production costs, especially when compared to labour costs, infrastructure, and market access considerations (Naegele & Zaklan, 2018; Dechezleprêtre et al., 2015). Nevertheless, recent evidence suggests that leakage risks may become more salient in specific sectors as carbon prices rise and free allocation declines, particularly for firms with limited cost pass-through capacity (De Beule et al., 2022).

Finally, manufacturing provides a particularly informative empirical setting for evaluating the EU ETS. A common practice in the literature typically excludes power generation due to its distinct regulatory treatment, near-complete auctioning, and fundamentally different abatement technologies. Morover, the system's inclusion of thresholds create variation in treatment status within narrowly defined industries, as regulated and unregulated firms often coexist within the same sectors. This feature has been widely exploited in the literature to identify causal effects using matching strategies, strengthening the credibility of empirical findings in manufacturing contexts (Petrick & Wagner, 2014; Lutz, 2016; Löschel et al., 2016). Recent policy developments further reinforce the relevance of manufacturing-focused analysis. The tightening of the emissions cap in Phase IV, the progressive reduction of free allocation, and the introduction of the Carbon Border Adjustment Mechanism (CBAM) fundamentally reshape the incentives faced by manufacturing firms.

Overall, focusing on manufacturing allows for a more nuanced assessment of how the EU ETS operates under conditions of limited cost pass-through, high international exposure, and strong reliance on allocation rules. The sector therefore constitutes a key testing ground for evaluating both the environmental effectiveness of the EU ETS and its economic and financial implications for regulated firms.

Chapter 3°: Research Questions

The EU ETS represents the cornerstone of European climate policy and one of the largest carbon markets worldwide. Since its introduction in 2005, the EU ETS has undergone multiple regulatory reforms aimed at strengthening carbon pricing incentives while mitigating adverse economic effects on regulated firms. Despite an extensive empirical literature, the majority of the studies are concentrated on the early phases of the EU ETS, when carbon prices were relatively low, and regulatory design features differed substantially from the current system. By contrast, empirical analyses focusing on the more recent phases, characterised by tighter caps, strengthened market-stability mechanisms, and higher, more volatile carbon prices, remain comparatively limited. This highlights a significant gap in the literature, since the behavioural responses of installations and firms under the current, more stringent EU ETS design remain insufficiently understood.

This issue is particularly salient in the manufacturing sector, where EU ETS regulation applies to highly heterogeneous production processes and abatement opportunities, and where differences in regulatory exposure can translate into markedly different cost pressures across firms and installations. Manufacturing activities are also at the centre of long-standing concerns related to competitiveness and carbon leakage, making them especially sensitive to variations in effective carbon pricing arising from free allowance allocation. Despite this relevance, empirical evidence focusing specifically on the manufacturing sector remains relatively limited, particularly in studies adopting an EU-wide perspective and covering the more recent phases of the EU ETS.

This thesis aims to contribute to this literature by providing a more comprehensive assessment of how manufacturing installations and firms respond to carbon pricing and incentives within the EU ETS. By focusing on stationary manufacturing activities and exploiting EU-wide variation in regulatory exposure, the analysis aims to offer a clearer and more nuanced view of emission and performance outcomes within this sector. Moreover, restricting the analysis to stationary manufacturing activities also helps avoid conflating industrial responses with dynamics specific to power generation or other regulated segments that differ substantially in allocation rules, pass-through mechanisms, and abatement technologies. Building on these considerations, this thesis addresses two interrelated research questions, each focusing on a different unit of analysis and outcome dimension.

3.1 Research Question 1 - Environmental effectiveness

RQ1: *How have emissions from manufacturing installations regulated by the EU ETS evolved across different phases of the system, and how do these emissions relate to carbon prices and regulatory exposure via free allowance allocation?*

This research question is important for evaluating how effective the EU ETS is environmentally, especially as its regulatory framework continues to develop. If the system functions as intended, the progressive tightening of emission caps and the strengthening of carbon-pricing incentives should be reflected in changes in emissions outcomes over time. Examining emission patterns across different ETS phases, therefore, provides insight into whether regulatory reforms have coincided with meaningful shifts in environmental performance. Moreover, examining emissions in relation to carbon prices while accounting for heterogeneity in free allowance allocation allows assessing whether differences in effective regulatory exposure are associated with different emission responses. This is particularly relevant in the manufacturing sector, where installations may face similar market prices but very different compliance incentives. Addressing RQ1 contributes to the literature by providing EU-wide, installation-level evidence on how carbon-pricing incentives and regulatory shielding interact to shape emission outcomes under the current design of the EU ETS.

3.2 Research Question 2 – Economic and Financial Performance

RQ2: *Do manufacturing firms regulated by the EU ETS exhibit different financial and productivity performances compared to similar non-regulated firms? Do these performance differences vary between sectors with high and low levels of protection?*

The second research question is relevant to addressing the economic and financial implications of environmental regulation under the EU ETS. While carbon pricing is designed to reduce emissions, it may also affect firms' profitability, productivity, and competitive positioning through compliance costs, investment decisions, and organisational adjustments. Understanding these effects is essential for evaluating the broader economic sustainability of the EU ETS. By comparing ETS-regulated manufacturing firms with otherwise similar non-regulated firms, this research question assesses whether exposure to the EU ETS is associated with measurable differences in economic and financial performance. Focusing on firm-level outcomes is particularly relevant in the manufacturing sector, where strategic responses to regulation, such as process optimisation, technological upgrading, or changes in production structure, are likely to materialise at the firm level. Addressing RQ2 therefore, contributes to the literature by providing EU-wide evidence on the economic and industrial implications of the EU ETS, complementing the analysis of environmental outcomes and informing the debate on competitiveness and carbon leakage.

Chapter 4°: Methodology

4.1 Data and Sample

This section describes the construction of the datasets used in the empirical analysis. Given the different nature of the research questions, the empirical strategy relies on two distinct datasets. The first dataset is constructed at the installation level and is used to examine the environmental effectiveness of the EU ETS. This choice reflects the fact that emissions, allowance allocation, and compliance obligations are defined, monitored, and verified at the installation level, making this level of analysis the most accurate and reliable for assessing emission outcomes. The second dataset is constructed at the firm level and is used to analyse the economic and financial performance associated with EU ETS exposure. Firm-level data are more appropriate for this purpose, as financial performance, productivity, and strategic responses to regulation are determined at the firm level, and individual firms may operate multiple ETS-regulated installations. Together, this two-level empirical design allows the analysis to remain consistent with both the regulatory structure of the EU ETS and the nature of the outcomes under investigation.

The analysis focuses on stationary manufacturing installations and excludes aircraft operators, maritime operators, power generation, and other non-industrial activities. Manufacturing installations are identified based on NACE Rev. 2 codes, restricting the sample to divisions 10–33. This restriction ensures sectoral comparability.

4.1.1 ETS Installation-Level Dataset (RQ1)

Data sources:

The primary data source is the EU ETS Registry, a processed and harmonised datasets provided by EUETS.INFO, which reconstructs the European Union Transaction Log (EUTL) in a relational database format. The EUTL is the official monitoring and reporting system for the EU ETS and provides annual information at the installation level on verified emissions, allowance allocation, surrender behaviour, and compliance status.

Specifically, the analysis relies on two core EUTL tables: the installation table, which provides information on installation characteristics (including country and economic activity), and the compliance table, which reports annual verified emissions, the amount of free and total allowance allocation, and surrendered allowances. The

EUETS.INFO dataset is particularly suited for empirical analysis, as it addresses the structural complexity of the raw EUTL data and enables consistent linking of installations across years and regulatory phases. Instead, carbon price information is obtained from publicly available data on the European carbon market. Annual carbon price data are merged to the installation-level dataset and measured as the yearly average price of EU Allowances (EUAs), expressed in euros per ton of CO.

Sample construction and Data cleaning:

Several data-cleaning steps are applied prior to estimation to ensure the dataset's consistency and reliability. Observations with missing installation identifiers, missing reporting years, or missing key compliance variables are removed. Additional consistency checks are performed to flag anomalous cases, such as free allocation exceeding total allocation or inconsistencies between verified emissions and surrendered allowances.

To mitigate the influence of extreme values while preserving the panel structure, emission and allocation variables are winsorized at the 1st and 99th percentiles. This approach caps extreme observations without dropping them from the sample and is commonly used in the empirical EU ETS literature. Installations that lack complete reporting histories are included in the sample to maintain variation within installations over time, as long as key variables are observed for at least 8 consecutive years. This criterion balances sample size and panel continuity while avoiding excessive attrition of smaller or later-entering installations. This requirement ensures sufficient within-installation time variation for fixed-effects estimation.

The sample covers the period 2005–2023, corresponding to all phases of the EU ETS, and includes all years with available and reliable data. After applying the sample selection criteria and cleaning procedures described below, the final dataset consists of 7,910 unique installations and 96,555 installation–year observations.

4.1.2 Firm-Level Dataset (RQ2)

Data sources

Firm-level financial data are obtained from ORBIS, which provides standardised balance sheet and income statement information for firms. Firms subject to the EU ETS are identified by matching installation-level records from the EU ETS Registry to firm-level financial data in ORBIS using Bureau van Dijk identifiers reported in the EUETS.INFO database. Based on this linkage, firms are classified as ETS firms (treated group) if they are associated with at least one EU ETS installation, and as non-ETS firms (control group) otherwise.

Sample construction, Data cleaning and Matching Strategy

To enable comparison between regulated and non-regulated firms, the empirical analysis relies on a matched sample in which non-ETS firms are selected from the same countries and NACE sectors as ETS firms and share similar key observable characteristics. The matching variables include firm-size proxies commonly used in the literature: logarithms of total assets and employees. Variables are standardised prior to matching, and nearest-neighbour matching with a caliper is applied to restrict matches to sufficiently similar firms. Each ETS firm is matched to the closest non-ETS firm within the same country and sector cell, subject to the caliper constraint, which limits the maximum allowed distance between treated and control units.

In ORBIS, firm-level financial information prior to 2016 exhibits a high incidence of missing values for key balance sheet and income statement items, hindering consistent measurement of baseline firm characteristics. To address this limitation, the matching procedure relies on firm characteristics averaged over the years 2016–2018. This multi-year baseline window helps smooth short-term fluctuations. Consequently, the empirical analysis is restricted to the post-2016 period to maintain consistency between the matching stage and the regression sample. This data constraint also shapes the interpretation of the empirical design. Although the regression framework resembles a difference-in-differences specification, the analysis does not rely on a classical pre-treatment versus post-treatment comparison.

Several data cleaning procedures are applied prior to estimation to ensure the consistency and comparability of firm-level observations. The dataset is restricted to non-branch firms reporting unconsolidated or partially consolidated accounts in ORBIS, to avoid double counting and to ensure that financial outcomes reflect firm-level economic activity. Observations with missing or non-positive values for key financial statement items are excluded, as these prevent meaningful logarithmic transformations and may indicate reporting inconsistencies. Firm-level financial variables are converted to a consistent panel format and aligned across reporting years. To mitigate the influence of extreme values while preserving the full matched sample, financial variables are winsorized at the 1st and 99th percentiles.

The resulting cleaned dataset consists of 2,484 firms, including 1,449 ETS firms (treated group) and 1,035 non-ETS firms (control group). It is an unbalanced panel, reflecting firm entry and exit as well as incomplete financial disclosure over time. Firms with partial reporting histories are retained provided that sufficient information is available for the matching period, to preserve sample size and avoid mechanically excluding smaller or younger firms.

4.2 Variables Definition

This section defines all variables used in the empirical analysis. All continuous variables used in the analysis are winsorized at the 1st and 99th percentiles. This treatment limits the influence of extreme observations while preserving the full sample size. Rather than dropping observations, winsorization caps extreme values, ensuring that estimates are not driven by a small number of atypical installations.

4.2.1 Variables – Installation-Level Analysis (RQ1)

Verified Emissions - Dependent Variable: The main outcome variable of the RQ1 is the natural logarithm of verified CO_2 emissions at the installation–year level. Verified emissions are reported annually in the EU ETS compliance records and represent the quantity of emissions that installations are legally required to cover with emission allowances. Emissions are expressed in natural logarithms in order to reduces skewness and limits the influence of extreme values.

Key Independent Variables:

- **Carbon Price**: Carbon pricing incentives are captured by the natural logarithm of the annual average price of EU Allowances (EUAs), expressed in euros per ton of CO_2. The EUA price reflects the marginal cost of emitting one additional ton of CO_2 under the EU ETS and constitutes the primary economic incentive for abatement within the system. Because allowance trading takes place in an integrated EU-wide market, the price is common to all installations within a given year and varies only over time. The annual average price is used rather than higher-frequency measures to align the price variable with the annual reporting frequency of emissions and to smooth short-term volatility unrelated to compliance decisions. The price is expressed in natural logarithms to ensure consistency with the transformation applied to emissions and to allow coefficients to be interpreted as proportional responses.

- **Free Allocation Intensity:** Exposure to free allocation is measured using lagged free allocation intensity, defined as:

$$FA\_Intensity_{i,t-1} = \frac{Free\ Allowances_{i,t-1}}{Verified\ Emissions_{i,t-1}}$$

This measure indicates how installations are protected from carbon pricing thanks to free allocation. Lower values reflect greater exposure to the carbon price. Measuring exposure through allocation intensity allows capturing heterogeneity across installations that face the same market price but different regulatory constraints. The use of lagged values serves an important methodological purpose. Allocation decisions are based on historical activity levels and are predetermined with respect to contemporaneous emissions. Therefore, lagging the variable reduces mechanical correlations between current emissions and current allocation and mitigates concerns related to reverse causality.

Table 1. Summary of Key Variables in RQ1

Variable	Definition	Unit/ Transformation	Source
ln_verified	Log of verified CO_2 emissions	Natural log	EU ETS Registry (EUETS.INFO)
ln_price	Log of annual average EUA price	Natural log, EUR/ton	European carbon market (ICAP)
FA_intensity	Lagged ratio of free allowances allocated to an installation relative to its verified emissions.	Lagged Ratio	EU ETS Registry (EUETS.INFO)

4.2.2 *Variables – Firm-Level Analysis (RQ2)*

Dependent Variables:

Firm performance is measured using three complementary outcomes, each capturing a distinct financial and economic margin. The selection highlights both their importance in the corporate finance literature and their empirical relevance in the ORBIS dataset, where these variables have relatively higher coverage than other indicators that tend to have more missing data.

- **Return on Assets (ROA):** Overall firm profitability is measures using ROA, defined as:

$$ROA_{i,t} = \frac{Profit\ Before\ Tax_{i,t}}{Total\ Assets_{i,t}}$$

ROA captures a firm's ability to generate earnings from its asset base. An important advantage of ROA in this context is that it is not mechanically driven by firm size and therefore avoids the inclusion of "bad controls" related to scale. ROA is also widely adopted in studies on the firm-level impacts of regulation, enabling comparability with the existing empirical literature.

- **EBITDA Margin:** Operating profitability is measured using EBITDA margin and is computed as:

$$EBITDA\ Margin_{i,t} = \frac{EBITDA_{i,t}}{Operating\ Revenue_{i,t}}$$

This metric provides valuable insight into environmental policies as it measures profitability at the operating level, prior to considering financing costs (interest), tax policies, and non-cash accounting elements (depreciation and amortisation). As a result, it is well-suited to detect margin compression associated with compliance costs (e.g., abatement expenditures, monitoring/reporting, or allowance purchasing) while remaining less sensitive to heterogeneity in capital structure across firms.

- **Labour Productivity:** Labour productivity is measured as the logarithm of operating revenue per employee:

$$\ln\left(Productivity_{i,t}\right) = \ln\left(\frac{Operating\ Revenue_{i,t}}{Number\ of\ Employees_{i,t}}\right)$$

  This indicator captures firms' ability to generate output per unit of labour input and is particularly relevant for assessing whether carbon-pricing incentives are accompanied by efficiency improvements rather than simple reductions in activity. Labour productivity is included to capture a dimension of firm performance that is distinct from profitability. While profitability measures reflect the net impact of regulatory costs on firm margins, productivity provides information on firms' operational efficiency and their ability to generate revenue relative to labour input. This distinction is particularly relevant in the context of environmental regulation, where firms may face higher compliance costs while simultaneously responding through process optimisation, technological upgrading, or organisational adjustments. From an empirical perspective, labour productivity, measured as the logarithm of operating revenue per employee, is a widely used and parsimonious proxy for efficiency and competitiveness. Compared to alternative productivity measures, revenue per employee provides a favourable balance between economic interpretability and data availability.

Key Independent Variables:

- ETS Exposure: Exposure to the EU ETS is captured by a binary treatment indicator equal to one if the firm operates at least one installation regulated under the EU ETS, and zero otherwise. This variable identifies firms subject to carbon regulation and serves as the basis for comparing regulated (treated) and non-regulated (control) firms.

- **Sectoral Protection Indicator**: Sectoral protection is measured using a dummy variable identifying highly protected sectors based on NACE Rev. 2 three-digit industry codes. These sectors correspond to those classified as exposed to a significant risk of carbon leakage and thus eligible for more generous free allocation under EU

ETS carbon leakage rules for the period 2021–2030[22]. Sectors on this list are deemed to face a relatively larger risk of relocation due to carbon costs and are granted additional regulatory protection in the form of full or enhanced free allocation. This indicator allows the analysis to assess whether the economic impact of ETS exposure differs systematically across sectors with different degrees of regulatory protection and carbon leakage risk.

Table 2. Summary of Key Variables in RQ2

Variable	**Definition**	**Unit / Transformation**	**Source**
ROA	Profit before tax / total assets	Ratio	ORBIS
EBITDA_margin	EBITDA / operating revenue	Ratio	ORBIS
ln_prod	Log of operating revenue per employee	Natural log	ORBIS
ETS_exposure	Firm regulated under EU ETS	Dummy	EU ETS registry matched to ORBIS
HighProtectionSector	Sector with high carbon leakage protection	Dummy	NACE classification/sector mapping

4.3 Empirical Strategy

This section outlines the empirical strategy adopted to address the research questions of this thesis. The analysis employs regression models, which examine how variables change over time within the same installation or company. Instead of only comparing different firms or plants to each other, the analysis focuses on how each one evolves year by year. This approach helps reduce the influence of hidden differences that

[22] COMMISSION DELEGATED DECISION (EU) 2019/708 supplementing Directive 2003/87/EC

do not change over time, such as location, production technology, or general business structure. It also accounts for events that affect everyone in the same year, such as economic crises or energy price shocks. In simple terms, the model tries to compare each firm or installation to itself over time, while also considering broader changes that affect all units.

The analysis aims to detect consistent patterns linking EU ETS exposure with emissions and financial results. However, the empirical strategy is not designed to establish strict cause-and-effect relationships. Emissions and economic outcomes are influenced by many factors, including firms' own production, investment, and compliance decisions, and some of these influences may not be fully observable in the data. Furthermore, while the carbon price is set at the European level rather than by individual firms, it is connected to broader economic factors that influence emissions and performance. For these reasons, the estimated results are interpreted as statistical associations that are consistent with the economic mechanisms of the EU ETS, rather than as direct causal impacts.

4.3.1 General Panel Regression Framework

The empirical analysis is based on a general panel regression model with fixed effects, which is applied throughout the thesis to both installations and firms. The model is:

$$Y_{i,t} = \beta X_{i,t} + \alpha_i + \lambda_t + \varepsilon_{i,t}$$

Where:

- $\boldsymbol{Y_{i,t}}$ is the outcome variable for unit *i* (installation or firm) in year *t*
- $\boldsymbol{X_{i,t}}$ contains the explanatory variables of interest
- $\boldsymbol{\alpha_i}$ represents unit-specific fixed effects, capturing characteristics of each firm or installation that do not change over time
- $\boldsymbol{\lambda_t}$ represents year fixed effects, which account for shocks affecting all units in the same year (e.g., macroeconomic conditions, energy prices, crises)
- $\boldsymbol{\varepsilon_{i,t}}$ represents random fluctuations and all other factors affecting the outcome variable that are not included in the model

This panel regression model focuses on how changes within the same firm or installation over time are related to changes in explanatory variables. By doing so, it removes the influence of permanent differences across units and controls for common yearly shocks. Standard errors are clustered at the unit level to account for the fact that observations belonging to the same firm or installation over time may be affected by common unobserved factors, making their errors correlated rather than independent.

4.3.2 Application to Installation-Level Analysis (RQ1)

i. Baseline specification: emissions across EU ETS phases

$$ln(Emissions_{i,t}) = \alpha + \beta_2 PhaseII_t + \beta_3 PhaseIII_t + \beta_4 PhaseIV_t + \mu_i + \varepsilon_{i,t}$$

where:

- $\boldsymbol{\beta_2}$ difference in average verified emissions in Phase II compared to Phase I
- $\boldsymbol{\beta_3}$ difference in Phase III vs Phase I
- $\boldsymbol{\beta_4}$ difference in Phase IV vs Phase I
- $\boldsymbol{\mu_i}$ represents installation fixed effects;
- $\boldsymbol{\varepsilon_{i,t}}$ is the idiosyncratic error term, capturing other factors affecting emissions that are not included in the model.

The first specification provides a descriptive assessment of how emissions evolve across the different regulatory phases of the EU ETS. It is intended to document broad temporal patterns in emissions that coincide with the evolution of the regulatory framework. Phase indicators absorb a wide range of time-varying factors, including technological progress, macroeconomic shocks, structural changes in industrial activity, and changes in the scope and enforcement of the EU ETS. As such, the estimated phase effects are interpreted as descriptive indicators of structural shifts in emissions over time, motivating the more targeted analyses that follow.

ii. Core specifications: carbon price and heterogeneous exposure

$$ln(Emissions_{i,t}) = \alpha + \beta(ln(Price_t) \times FA_{Intensity}{}_{i,t-1}) + \mu_i + \lambda_t + \varepsilon_{i,t}$$

where:

- $\boldsymbol{\beta}$ measures how the relationship between carbon prices and emissions varies with free allocation intensity
- $\boldsymbol{\lambda_t}$ are year fixed effects, controlling for shocks that affect all installations in the same year

The second specification focuses on the relationship between carbon prices and emissions conditional on exposure to free allocation. The dependent variable remains the logarithm of verified emissions. The key explanatory variable is the interaction between the logarithm of the EU allowance price and lagged free allocation intensity. This interaction reflects a central feature of the EU ETS design: although the carbon price is common across installations, the effective regulatory pressure may differ depending on how much of an installation's emissions are covered by free allowances. Installations that are less shielded by free allocation may face stronger cost incentives associated with carbon pricing, while more heavily shielded installations may experience weaker incentives. The model therefore tests whether the association between carbon prices and emissions differs systematically with the level of free allocation, without imposing a specific causal interpretation.

iii. Reform specification: changes in price sensitivity after Phase III

$$\begin{aligned} ln(Emissions_{i,t}) \\ &= \alpha + \beta_1(ln(Price_t) \times FA_{Intensity}{}_{i,t-1}) \\ &+ \beta_2(Post2013_t \times FA_{Intensity}{}_{i,t-1}) + \mu_i + \varepsilon_{i,t} \end{aligned}$$

where:

- $\boldsymbol{Post2013_t}$ is a dummy variable equal to 1 for Phase III–IV (post-2013 reform), and 0 otherwise
- $\boldsymbol{\beta_1}$ indicates how the association between carbon prices and emissions changes with the degree of free allocation protection

- $\boldsymbol{\beta_2}$ indicates whether the post-2013 regulatory regime is associated with different emission patterns depending on free allocation intensity.

  The third specification examines whether the Phase III reform of the EU ETS altered the sensitivity of emissions to carbon pricing. To do so, the interaction between the carbon price and lagged free allocation intensity is augmented with an additional interaction term capturing the post-2013 period. In this specification, installation fixed effects are retained, while year fixed effects are excluded to allow identification of changes in sensitivity through the post-reform interaction term. This modelling choice reflects the fact that year fixed effects would otherwise absorb all post-2013 variation common across installations, preventing the identification of differential sensitivity associated with the reform.

4.3.3 Application to Firm-Level Analysis (RQ2)

i. Baseline Firm-Level Specification

$$Y_{i,t} = \beta ETS_i + \delta_t + \gamma_s + \varepsilon_{i,t}$$

where:

- $\boldsymbol{Y_{i,t}}$ indicates firm-level performance outcomes for firm *i* in year *t*
- $\boldsymbol{ETS_i}$ is a dummy variable equal to 1 if the firm operates at least one EU ETS installation, and 0 otherwise.
- $\boldsymbol{\beta}$ measures the average difference in firm performance between ETS and non-ETS firms
- $\boldsymbol{\delta_t}$ represents year fixed effects, controlling for shocks that affect all firms in the same year (e.g., macroeconomic conditions, energy prices, crises)
- $\boldsymbol{\gamma_s}$ represents sector fixed effects (NACE sector), controlling for structural differences across industries (e.g., capital intensity, competition, technology)
- $\boldsymbol{\varepsilon_{i,t}}$ is the error term capturing other factors affecting firm performance that are not included in the model

  This specification is used to assess whether firms exposed to the EU ETS systematically differ in economic and financial performance from comparable firms that are not regulated, after accounting for sectoral characteristics and common macroeconomic conditions. It allows the analysis to isolate the association between ETS participation and firm-level outcomes, net of industry structure and year-specific shocks. Firm fixed effects are not included in the baseline specification because the key explanatory variable, ETS exposure, is time-invariant over the sample period for most firms. Including firm fixed effects would therefore absorb the treatment indicator and prevent identification. Instead, firm-level heterogeneity is addressed through the matching procedure and sectoral controls.

ii. Heterogeneous Effects by Sectoral Protection

$$Y_{i,t} = \beta_1 ETS_i + \beta_2 (ETS_i \times HighProtectionSector_s) + \delta_t + \gamma_s + \varepsilon_{i,t}$$

where:

- $\boldsymbol{\beta_1}$ measures the difference in performance between ETS and non-ETS firms in low-protection sectors (baseline sectors).
- $\boldsymbol{\beta_2}$ indicates how this difference changes in high-protection sectors

To assess whether the economic impact of ETS exposure differs across sectors, the baseline model is augmented with an interaction between ETS exposure and a sectoral protection indicator. It tests whether firms in highly protected sectors experience different performance patterns compared to ETS firms in less protected sectors, after controlling for industry structure and common macroeconomic conditions. From a financial perspective, this extension is crucial. Firms operating in protected sectors may experience weaker profitability or productivity effects due to the partial insulation from compliance costs, whereas firms in less protected sectors may face stronger incentives to adjust production, pricing, or investment decisions.

4.4 Identification Issues and Limitations

This section discusses the main identification challenges and limitations of the empirical analysis. Across both research questions, the empirical strategy is designed to estimate robust associations consistent with the incentive mechanisms of EU ETS, rather than to identify causal effects. While the use of panel data, fixed effects, lagged variables, and matching improves internal validity, several sources of endogeneity and data-related constraints cannot be fully eliminated.

4.4.1 Endogeneity and identification at the installation level (RQ1)

At the installation level, a primary concern relates to the potential endogeneity between emissions, allocation outcomes, and production decisions. Although free allocation is determined based on historical activity levels and regulatory benchmarks, emissions may still respond to unobserved shocks, such as changes in demand, technology adoption, or energy input prices, that simultaneously affect allocation profiles and emission outcomes. The inclusion of installation fixed effects mitigates bias arising from time-invariant characteristics, such as baseline technology or structural differences in production processes. Year fixed effects further control for aggregate shocks common to all installations, including macroeconomic fluctuations and EU-wide policy developments. In addition, the use of lagged allocation measures improves temporal ordering and reduces mechanical contemporaneous correlations between emissions and regulatory exposure.

Nevertheless, residual endogeneity concerns remain. Emission reductions may reflect unobserved firm-level investment decisions or technological upgrades that are correlated with exposure to carbon pricing but not directly observable in the data. Moreover, while the EU-wide carbon price can be considered exogenous from the perspective of individual installations, it may still be correlated with broader economic or regulatory dynamics that affect emissions system-wide. For these reasons, the installation-level estimates are interpreted as conditional associations between carbon pricing, regulatory exposure, and emissions, rather than as causal estimates of the impact of the EU ETS.

4.4.2 Selection and identification at the firm level (RQ2)

At the firm level, identification challenges are primarily driven by non-random selection into EU ETS participation. Firms operating ETS-regulated installations are not randomly assigned but are concentrated in specific industries characterized by higher energy intensity, capital intensity, and exposure to international competition. These structural differences may independently affect firm performance, profitability, and productivity. The matching procedure addresses part of this concern by restricting the analysis to a subset of ETS and non-ETS firms that are comparable along observable pre-matching characteristics, such as firm size and scale. Sector fixed effects further control for persistent differences across industries, while year fixed effects absorb macroeconomic shocks affecting all firms simultaneously.

Within this framework, the coefficient associated with ETS exposure captures the average difference in performance between ETS and non-ETS firms, conditional on matching, sectoral characteristics, and common time effects. While this strategy reduces selection bias arising from observable characteristics, it cannot eliminate endogeneity from unobserved firm-level factors, such as managerial quality, innovation capacity, long-term investment strategies, or access to finance, that may be correlated with both ETS participation and economic outcomes. For this reason, the firm-level estimates are interpreted as conditional associations rather than causal effects of EU ETS regulation.

4.4.3 Data limitations and measurement issues

The empirical analysis is subject to several data-related limitations. At the installation level, while emissions and allocation data are drawn from verified compliance records, measurement error may still arise from reporting practices, aggregation across activities within installations, or changes in regulatory coverage over time. The analysis is further constrained to manufacturing installations to ensure sectoral comparability, which may limit external validity.

At the firm level, financial data are obtained from ORBIS, where reporting coverage varies across countries and over time. In particular, firm-level financial information prior to 2016 exhibits a high incidence of missing values for key accounting variables, restricting the construction of consistent baseline firm characteristics and motivating the focus on the post-2016 period. Panel attrition is driven by firm entry and exit, incomplete disclosure, and mismatches between ETS and ORBIS identifiers. To mitigate the influence of extreme observations arising from accounting noise or firm restructuring, financial variables are winsorized at conventional thresholds. While this approach improves robustness, it may attenuate variation at the tails of the distribution.

4.5 Robustness and Validation Strategy

To assess the reliability and internal validity of the empirical findings, a comprehensive set of robustness and validation checks is conducted. Robustness analyses are implemented separately for each dataset, reflecting the different sources of variation, identification challenges, and data structures underlying Research Question 1 and Research Question 2. The purpose of these checks is not to generate additional results, but to verify that the main findings are not driven by specific modeling choices, variable definitions, or sample restrictions. In particular, the robustness strategy is designed to assess the sensitivity of the estimates to alternative specifications, measurement choices, and potential sources of bias.

4.5.1 Robustness checks – Installation-level analysis (RQ1)

Several robustness checks are conducted for the installation-level analysis to validate the relationships among carbon pricing, regulatory exposure, and verified emissions.

- **Alternative regulatory phase specification:** To ensure that the baseline results documenting emission patterns across EU ETS phases are not driven by the specific use of phase dummies, an alternative specification replaces the full set of phase indicators with a single post-2013 dummy. This check verifies that the observed temporal patterns are robust to a more parsimonious representation of regulatory changes and are not sensitive to the exact partitioning of ETS phases.
- **Alternative exposure measures:** The core installation-level model relies on lagged free allocation intensity to capture regulatory shielding. As a robustness check, alternative exposure proxies are employed, including a binary indicator identifying over-allocated installations. This validation step ensures that the estimated relationship between carbon prices and emissions is not driven by a specific functional form or normalization of the exposure variable.
- **Alternative price specification:** To assess whether results depend on contemporaneous price movements, alternative price specifications are considered, including lagged carbon prices. This check addresses concerns related to short-term price volatility and potential simultaneity between emissions and allowance prices.
- **Inference and clustering:** Alternative inference assumptions are considered by modifying the clustering structure of standard errors and by testing specifications with different combinations of fixed effects, where conceptually appropriate. These checks ensure that statistical inference is not sensitive to specific assumptions regarding error correlation.

4.5.2 Robustness and validation checks – Firm-level analysis (RQ2)

The firm-level analysis is subject to a distinct set of robustness and validation exercises, reflecting the use of matched panel data and treatment-style comparisons.

- **Validation of the matching procedure:** To assess the quality of the matching process, balance diagnostics based on standardized mean differences (SMDs) are reported for key matching covariates. These diagnostics verify that observable differences in firm size and scale between ETS and non-ETS firms are substantially reduced after matching, thereby improving comparability and mitigating selection bias on observables.
- **Alternative performance measures:** Firm performance is captured using multiple outcome variables—ROA, EBITDA margin, and labor productivity—to ensure that the results are not specific to a single dimension of economic performance. This strategy allows testing whether ETS exposure is consistently associated with firm outcomes across profitability and efficiency measures.
- **Alternative sample definitions:** Robustness checks are conducted by varying sample restrictions, including alternative time windows and exclusions of firms with incomplete reporting histories. These exercises verify that the results are not driven by specific subsamples or by firms with atypical reporting patterns.
- **Inference and clustering:** Standard errors are clustered at the firm level to account for serial correlation in firm performance over time. Robustness checks confirm that the results are not sensitive to alternative assumptions regarding error correlation.
- **Alternative sample window (2013–2022):** As a robustness check, the firm-level regressions are re-estimated over the period 2013–2022. This alternative time window allows assessing whether the results are sensitive to the choice of the baseline period used for matching and to the post-2016 data restriction. By extending the estimation sample closer to the beginning of Phase III, this check verifies that the estimated associations between ETS exposure and firm performance are not driven by a specific sample window or by the construction of the matched baseline.

Chapter 5°: Results

5.1 Descriptive Statistics

This section describes the samples used to address the two research questions. Table 3 summarises the main characteristics of the datasets for both research questions.

Table 3. Main Characteristics of Datasets

Characteristics	RQ1	RQ2
Observation	96,555	22,356
Entities	7,910	2,484
Countries	28	24
Sectors	188	172
Period	2005 - 2023	2016 - 2023

5.1.1 Installation-Level Descriptives (RQ1)

This subsection presents descriptive statistics for the installation-level dataset used to address RQ1, focusing on the sample composition and distributions of the main variables.

(a) Geographic and sectoral composition of the sample

Figure 3 displays the geographic distribution of ETS-regulated manufacturing installations across countries, together with the cumulative share of the sample. The distribution is highly concentrated. In particular, the first five countries represent around 60% of the total sample, while the remaining countries contribute relatively small shares.

Figure 3. Distribution of Installations by Country (%)

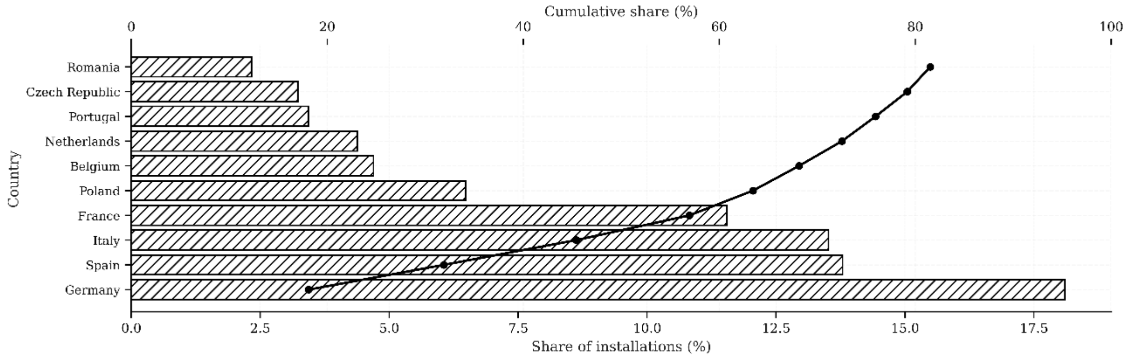
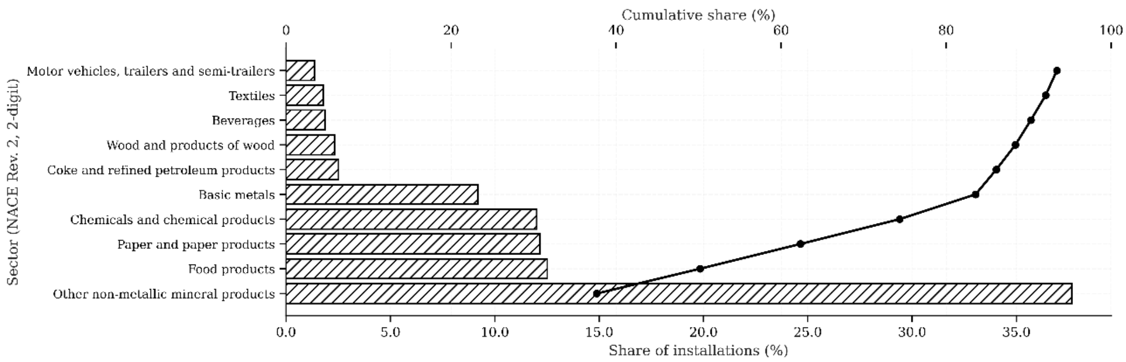


Figure 3 reports the distribution of installations across NACE Rev. 2 two-digit manufacturing sectors. The figure highlights strong sectoral concentration, with a small number of energy and material intensive industries accounting for a large share of ETS installations, while the remaining sectors individually represent relatively small proportions of the sample.

Figure 4. Distribution of Installations by Sector (%)



(b) Variable descriptive statistics

Table 4 reports descriptive statistics for the main variables used in the installation-level analysis. Variables are reported in the same functional form employed in the regression models to facilitate interpretation. Emissions and carbon prices are expressed in natural logarithms, while free allocation intensity is measured as a ratio. Verified emissions are highly skewed, which motivates the use of logarithmic transformation (see Appendix

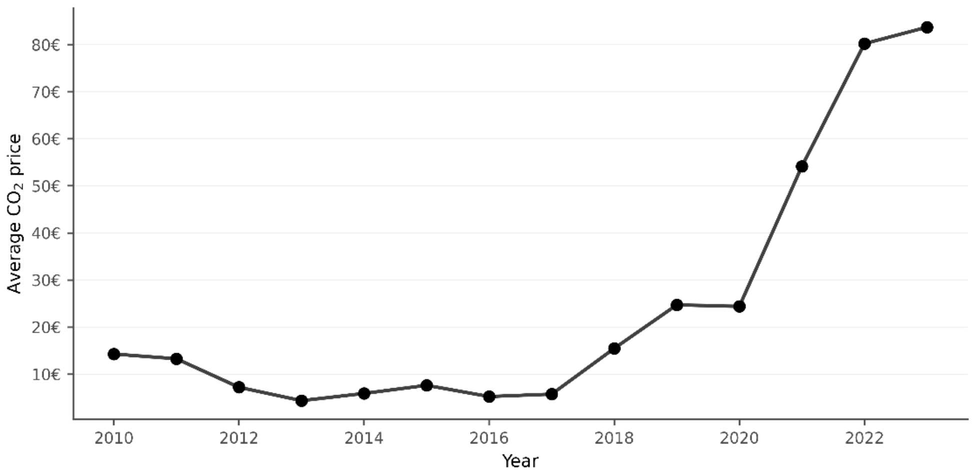
Figure A).

Table 4. Summary Statistics of the Main Variables

	Mean	*Std*	*Min*	*25%*	*50%*	*75%*	*Max*
ln_verified	9.979	1.827	0.693	8.958	9.925	10.982	16.305
ln_price	2.649	0.926	0.501	1.933	2.729	3.128	4.439
FA_intensity	0.822	0.542	0.000	0.582	0.711	0.878	3.873

Figure 5 reports the evolution of the EU allowance price over time. Carbon prices display substantial variation across phases of the EU ETS, reflecting changes in regulatory design, market conditions, and broader macroeconomic dynamics. As the price is common to all installations within a given year, its variation is entirely driven by time effects.

Figure 5. Evolution of the Average CO_2 Allowance Price



5.1.2 *Firm-Level Descriptives (RQ2)*

This subsection presents descriptive statistics for the firm-level dataset used to address RQ2, focusing on firm size, performance indicators, and the comparability between ETS and non-ETS firms in the matched sample.

(a) Firm Size and Structural Characteristics

To provide an intuitive benchmark for the economic scale of firms included in the analysis, Table 5 reports summary statistics for firm size variables for the overall matched sample, without distinguishing between ETS and non-ETS firms. The figures indicate that the sample predominantly consists of medium-sized and large manufacturing firms in terms of total assets, employment, and turnover. The distribution of firm size is highly right-skewed across all dimensions, as reflected by mean values substantially exceeding medians. This pattern suggests the presence of a limited number of very large firms alongside a broader group of medium-sized firms, a characteristic commonly observed in manufacturing datasets. Moreover, the statistics exhibit considerable heterogeneity.

Table 5. Summary Statistics of Firm Size Variables

	Mean	*Std*	*Min*	*25%*	*50%*	*75%*	*Max*
Total Assets (€)	141186.683	245689.298	857.000	22633.000	59911.500	148178.000	1735949.000
Turnover (€)	366.655	509.079	5.000	83.750	198.000	433.000	3306.000
N. of employees	176374.988	356987.944	363.000	23129.250	68925.000	168437.500	2673434.000

Table 6 reports average firm-size characteristics by ETS status, using logarithmic transformations, consistent with the matching procedure and the regression framework. Firms subject to the EU ETS are, on average, slightly larger than non-regulated firms in terms of total assets, employment, and turnover. This pattern is economically intuitive, as EU ETS regulation primarily applies to more capital-intensive and energy-intensive manufacturing activities.

Table 6. Difference in Mean of Firm Size

ETS Status	***ln_TotalAssets***	***ln_Employees***	***ln_Turnover***
ETS firms	11.027	5.258	11.053
Non-ETS firms	10.760	5.132	10.835

Table 7. Difference in Mean of Firm Size Variables

Variable	***SMD***
ln_TotalAssets	0.176
ln_Employees	0.096
ln_Productivity	0.105

To assess the quality of the matching procedure, standardized mean differences (SMDs) are reported for key size variables. Conventional thresholds consider values below 0.10 as indicative of excellent balance and values below 0.20 as acceptable. The reported SMD values in Table 7 indicate good overall covariate balance after matching, with only moderate residual differences in firm size between ETS and non-ETS firms. Although regulated firms remain somewhat larger on average, these differences are limited in magnitude and consistent with matching diagnostics. Overall, the results suggest that treated and control firms are broadly comparable in structural size characteristics, supporting the credibility of the matched sample used in the regression analysis.

(b) Performance Variable descriptive statistics

Table 8 summarises descriptive statistics for the main firm-level performance variables used in the empirical analysis. Profitability and operating performance exhibit substantial heterogeneity across firms.

Table 8. Summary Statistics of the Main Variables

	Mean	*Std*	*Min*	*25%*	*50%*	*75%*	*Max*
ROA	5.540	10.443	-29.573	0.482	4.356	10.272	40.401
EBITDA_margin	9.758	9.895	-23.934	4.180	8.674	14.689	41.229
ln_prod	5.853	0.981	3.046	5.271	5.889	6.460	8.409

ROA shows wide dispersion and includes both positive and negative values, while EBITDA margins are more stable but still variable. Labor productivity, expressed in logarithmic terms as operating revenue per employee, shows a more concentrated distribution. This pattern is consistent with interpreting productivity as a structural efficiency measure, which is less sensitive to short-term accounting fluctuations than profitability indicators. Overall, the descriptive evidence highlights substantial heterogeneity in firm performance within the manufacturing sector, motivating the use of panel methods that control for firm-specific and sectoral characteristics.

(c) Comparison between ETS and non-ETS firms

To provide a preliminary comparison between regulated and non-regulated firms, Table 9 reports summary statistics for performance variables separately for ETS and non-ETS firms. Average levels of profitability and productivity are broadly similar across the two groups, with no striking unconditional differences.

Table 9. Mean of Main Variables by EU Status

ROA	***Mean***
ETS firms	5.37
Non-ETS firms	5.78

EBIT_Margin	***Mean***
ETS firms	9.99
Non-ETS firms	9.35

ln_prod	***Mean***
ETS firms	7.88
Non-ETS firms	7.95

(e) Sector protection distribution

Table 10 presents the distribution of firms across sectors with different levels of regulatory protection under the EU ETS carbon leakage framework. It displays a fairly balanced distribution of firms across protection categories, with a slightly higher number of firms in the high protection sector that also have a greater share of free allowances. This relatively balanced distribution indicates meaningful variation in effective carbon cost exposure across firms, providing the basis for analysing heterogeneous performance effects in the regression analysis.

Table 10. Sectoral Protection Classification of Firms

Sector protection level	***Share of firms (%)***
Higher-protection sectors	59%
Lower-protection sectors	41%

5.2 Regression Results – Environmental effectiveness (RQ1)

This section presents the regression results for RQ1. The results are presented sequentially, moving from baseline phase patterns to the analysis of heterogeneous price responses.

(a) Emissions across EU ETS phases

The first specification provides a baseline assessment of how verified emissions evolve across the different regulatory phases of the EU ETS. Table 11 reports the results from a fixed-effects regression where the dependent variable is the logarithm of verified emissions at the installation–year level, and the explanatory variables are dummy indicators for EU ETS phases. Phase I (2005–2007) serves as the reference category. The model includes installation fixed effects to control for time-invariant heterogeneity across installations, while year fixed effects are excluded to allow identification of differences across regulatory phases.

Table 11: Parameter Estimates

	Parameter	Std. Err.	T-stat	P-value	LowerCI	UpperCI
const	10.276	0.0125	824.34	0.0000	10.251	10.300
phase_2008-2012	-0.3200	0.0127	-25.119	0.0000	-0.3449	-0.2950
phase_2013-2020	-0.3409	0.0171	-19.982	0.0000	-0.3743	-0.3075
phase_2021-2030	-0.4546	0.0200	-22.754	0.0000	-0.4938	-0.4155

The estimated coefficients on all phase dummies are negative and highly statistically significant. Relative to Phase I, emissions are lower in Phase II (2008–2012), decline further in Phase III (2013–2020), and reach their lowest levels in Phase IV (2021–2030). The magnitude of the coefficients increases monotonically across phases, indicating progressively lower emission levels in later regulatory periods. Overall, the baseline results establish a clear downward trend in emissions across successive EU ETS phases, motivating a more focused analysis of carbon pricing and heterogeneous regulatory exposure.

(b) Carbon price and heterogeneous exposure to free allocation

The objective of the second specification is to assess whether the association between carbon prices and emissions depends on the degree of regulatory exposure, measured by free allowance allocation. Table 12 reports the results from a two-way fixed effects model in which the dependent variable is the logarithm of verified emissions. The key explanatory variable is the interaction between the logarithm of the EUA price and lagged free allocation intensity. All specifications include installation fixed effects and year fixed effects, and standard errors are clustered at the installation level.

Table 12: Parameter Estimates

	Parameter	Std. Err.	T-stat	P-value	Lower CI	Upper CI
const	10.107	0.0059	1713.4	0.0000	10.095	10.118
price_x_FA_w	-0.0197	0.0011	-18.055	0.0000	-0.0218	-0.0175

The estimated coefficient on the interaction term between the carbon price and free allocation intensity is negative and highly statistically significant. This indicates that increases in the carbon price are associated with larger emission reductions for installations that are less shielded by free allocation. In contrast, installations receiving higher levels of free allowances exhibit substantially weaker responses to price changes. In terms of economic magnitude, the estimated effect is moderate but meaningful. The response is stronger for less shielded installations and weaker for heavily protected ones. These estimates provide strong evidence of heterogeneous price effects and align with the incentive design of the EU ETS, reinforcing the idea that free allocation reduces the carbon price incentives.

(c) Did the Phase III reform alter price sensitivity?

The third specification examines whether the Phase III reform of the EU ETS altered the sensitivity of emissions to carbon pricing by strengthening the role of regulatory exposure. Table 13 reports the results from a fixed-effects regression that interacts free allocation intensity with both the carbon price and a post-2013 indicator. Installation fixed effects are included, while year fixed effects are excluded to allow identification of changes in sensitivity through the post-reform interaction term.

Table 13: Parameter Estimates

	Parameter	Std. Err.	T-stat	P-value	Lower CI	Upper CI
const	10.109	0.0062	1640.3	0.0000	10.097	10.121
price_x_FA	-0.0166	0.0012	-13.676	0.0000	-0.0190	-0.0142
post2013_x_FA	-0.0147	0.0044	-3.3878	0.0007	-0.0233	-0.0062

The interaction between the carbon price and free allocation intensity remains negative and highly statistically significant. In addition, the interaction between free allocation intensity and the post-2013 indicator is also negative and statistically significant. The magnitude of the estimates suggests that emissions became more sensitive to regulatory exposure after 2013. These results indicate that the Phase III reform did not fundamentally change the nature of the price–exposure mechanism but reinforced it. The reform enhanced emissions responsiveness to carbon pricing by tightening allocation rules and increasing effective exposure to market-based compliance costs, especially for installations with lower free allocation.

5.3 Regression Results – Economic and Financial Performance (RQ2)

This section presents the regression results for RQ2. The results are presented sequentially, moving from baseline firm-level outcomes and then exploring heterogeneity by sectoral protection.

(a) EU ETS exposure and firm profitability

The first set of results examines the association between EU ETS exposure and firm profitability, measured by return on assets (ROA). Table 14 reports the results from a panel regression with year and sector fixed effects at the NACE Rev. 2 four-digit level.

Table 14: Parameter Estimates

	Parameter	Std. Err.	T-stat	P-value	Lower CI	Upper CI

const	5.8526	0.2345	24.961	0.0000	5.3931	6.3122
treated	-0.5358	0.3256	-1.6456	0.0488	-1.1741	-0.8024

The coefficient on the ETS exposure indicator is negative and statistically significant. This indicates that, on average, firms regulated under the EU ETS exhibit lower profitability than comparable non-regulated firms. The result aligns with the interpretation that compliance with carbon regulations imposes additional costs on regulated firms, potentially affecting their short-term profitability. At the same time, the relatively small magnitude and borderline statistical significance of the estimate suggest that the EU ETS's profitability impact is limited. This finding is consistent with the design of the EU ETS, which combines carbon pricing with protection mechanisms to limit competitiveness effects.

(b) EU ETS exposure and labour productivity

The second specification examines whether EU ETS exposure is associated with differences in firm-level labour productivity, measured as the logarithm of operating revenue per employee. Table 15 reports the results from a panel regression analogous to the profitability specification.

Table 15: Parameter Estimates

	Parameter	Std. Err.	T-stat	P-value	Lower CI	Upper CI
const	5.8178	0.0258	225.51	0.0000	5.7673	5.8684
treated	0.0638	0.0346	1.8416	0.0489	-0.0041	-0.0016

The coefficient on the ETS exposure indicator is positive and statistically significant. This indicates that ETS firms exhibit, on average, higher labour productivity than comparable non-ETS firms, conditional on sector and year effects. This result contrasts with the negative association observed for profitability, but it is not contradictory. Rather, it suggests that regulated firms may respond to carbon constraints by improving operational efficiency through process optimisation, technological upgrading, or changes in input composition. Importantly, higher productivity does not necessarily translate into higher profitability in the short run. Efficiency gains may be offset by compliance costs, allowance expenditures, or capital investments required for emissions reduction. The combination of lower profitability and higher productivity, therefore, points to an adjustment mechanism in which firms improve efficiency while absorbing part of the regulatory burden.

(c) Heterogeneous effects by sectoral protection

The final set of results explores whether the economic impact of EU ETS exposure differs across sectors with different levels of regulatory protection. Table 16 examines the heterogeneous effects of EU ETS exposure on firm profitability, measured by return on assets (ROA), across sectors with different levels of regulatory protection.

Table 16: Parameter Estimates

	Parameter	Std. Err.	T-stat	P-value	Lower CI	Upper CI
const	5.7832	0.2325	24.877	0.0000	5.3275	6.2389
treated	-1.1230	0.3869	-2.9025	0.0037	-1.8814	-0.3647
ets_highprot	1.1193	0.4109	2.7239	0.0065	0.3139	1.9248

The coefficient on ETS exposure is negative and statistically significant for firms operating in less protected sectors, indicating a reduction in profitability relative to non-ETS firms. The interaction term between ETS exposure and high sectoral protection is positive and statistically significant, partially offsetting the negative baseline effect. This suggests that firms operating in highly protected sectors experience substantially weaker profitability losses. These results provide consistent evidence that the economic effects of the EU ETS are not uniform across firms but are strongly mediated by sectoral protection. while ETS exposure is associated with modest reductions in profitability, these impacts are mainly seen in less protected sectors and are significantly reduced for firms operating in industries that have greater regulatory shielding.

5.4 Robustness Checks

This section reports a set of robustness checks conducted to assess the stability of the main empirical results presented in Sections 4.2 and 4.3. This section summarizes the key validation results.

5.4.1 Robustness checks – Installation-level analysis (RQ1)

Several robustness checks are performed to verify that the installation-level results linking carbon prices, regulatory exposure, and verified emissions are not driven by specific modelling choices.

First, the baseline specification that documents emission patterns across EU ETS phases is re-estimated using a simpler model of regulatory changes, replacing the full set of phase dummies with a single indicator for post-2013. The results remain consistent with the baseline findings, confirming that the observed decline in emissions is not sensitive to the exact partitioning of ETS phases.

Second, alternative measures of regulatory exposure are employed. In particular, the lagged free allocation intensity is replaced with a binary indicator identifying over-allocated installations. The interaction between carbon prices and regulatory exposure remains negative and statistically significant, indicating that the heterogeneous price response documented in the main analysis is robust to alternative exposure definitions.

Third, the sensitivity of the results to price measurement is assessed by using lagged rather than contemporaneous carbon prices. The estimated coefficients remain similar in sign and magnitude, suggesting that the main results are not driven by short-term price volatility or simultaneity concerns.

Finally, alternative inference assumptions are considered by modifying the clustering structure of standard errors and by testing specifications with alternative combinations of fixed effects, where appropriate. Across all cases, the main conclusions remain unchanged, and statistical significance is preserved. Overall, these robustness checks confirm that the installation-level results are stable across alternative specifications and support the reliability of the main findings.

5.4.2 Robustness checks – Firm-level analysis (RQ2)

Robustness and validation exercises are also conducted for the firm-level analysis. First, the quality of the matching procedure is validated using balance diagnostics based on standardised mean differences for key firm-size covariates. As documented in Section 4.1.2, observable differences between ETS and non-ETS firms are substantially reduced after matching, supporting the comparability of the treated and control groups.

Second, the main results are re-estimated using EBITDA margins as an alternative performance measure. The qualitative patterns observed in the baseline profitability analysis remain unchanged, indicating that the results are not specific to a single outcome variable. Third, robustness checks are conducted using alternative sample definitions, including modifications to the estimation window and exclusions of firms with incomplete reporting histories. Re-estimations over the 2013–2022 period yield coefficients with consistent signs and magnitudes.

Finally, inference robustness is assessed by confirming that the results are not sensitive to alternative clustering assumptions. Taken together, these checks confirm the stability of the firm-level findings across alternative outcome measures, sample definitions, and inference assumptions.

5.4.3 Multicollinearity diagnostics

Multicollinearity arises when explanatory variables are highly correlated, potentially inflating standard errors and undermining the interpretability of individual regression coefficients. To assess potential multicollinearity among the explanatory variables, Variance Inflation Factors (VIFs) are computed for the main regression specifications. All VIF values remain well below conventional threshold levels, indicating that multicollinearity does not pose a concern for the estimated models. In addition, pairwise correlations among the explanatory variables are generally. Taken together, these diagnostics suggest that the estimated coefficients are not driven by excessive collinearity and can be interpreted with confidence.

Chapter 6°: Discussion

5.1 Main Findings and Link to Literature

This thesis is structured around two research questions: environmental effectiveness at the installation level (RQ1) and economic and financial performance at the firm level (RQ2). Overall, the results provide consistent evidence that the effectiveness and economic impact of the EU ETS depend critically on regulatory stringency and on firms' exposure to carbon pricing incentives.

5.4.4 Environmental effectiveness of the EU ETS (RQ1)

The installation-level analysis reveals a clear and progressive decline in verified emissions across successive phases of the EU ETS. Emissions are significantly lower in later regulatory phases compared to the initial phases, with the strongest reductions observed during the most recent period, characterised by tighter caps and strengthened market-stability mechanisms. This pattern suggests that the environmental effectiveness of the EU ETS has increased over time as the system matured and regulatory design features were progressively reinforced.

These findings closely aligns with existing empirical evidence discussed in the literature review, which documents weak and heterogeneous effects in Phase I, stronger reductions in Phase II, and increasingly robust environmental impacts following the institutional reforms introduced in Phase III and Phase IV. Studies such as Bayer and Aklin (2020) and Biancalani et al. (2024) show that emissions reductions became statistically stronger once allowance oversupply was addressed and the cap trajectory became more stringent. This analysis supports these findings by examining installation-level data on manufacturing activities across EU countries, further emphasising that regulatory maturity and institutional credibility are key factors in the effectiveness of ETS.

Importantly, the results not only document aggregate phase effects but also explicitly connect emission outcomes to carbon-pricing incentives and exposure to regulatory measures. While the carbon price is uniform across installations, the analysis shows that emission responses vary systematically with the intensity of free allocation . Installations that are less protected by free allowances exhibit stronger emission reductions in response to price increases, whereas heavily protected installations display significantly weaker responsiveness. This finding suggests that free allocation, while mitigating competitiveness and leakage risks, significantly moderates the effective price signal for regulated entities, reducing its impact.

The analysis further contributes to the literature by showing that this heterogeneous price responsiveness becomes stronger after the Phase III reform. After 2013, emissions became more responsive to carbon pricing, particularly for installations with lower levels of regulatory protection. This evidence points to an increase in the credibility and effectiveness of the carbon price signal in the post-reform period, consistent with the tightening of allocation rules and the introduction of market-stabilising instruments. This increased sensitivity of emissions to regulatory exposure in the post-2013 period is consistent with studies identifying Phase III as a structural turning point in the EU ETS. Bayer and Aklin (2020) argue that earlier phases suffered from credibility deficits caused by over-allocation, price volatility, and regulatory uncertainty.

This result is especially relevant for the manufacturing sector. Unlike power generation, where near-full auctioning and cost pass-through are common, manufacturing installations operate under highly heterogeneous allocation regimes and abatement opportunities. These finding complements sector-level studies documenting stronger ETS effects in industries with greater fuel-switching or process-adjustment flexibility, while highlighting that policy-induced heterogeneity plays a central role alongside technological factors.

Taken together, the results support the view that the environmental effectiveness of the EU ETS is not determined solely by the level of the carbon price, but by the interaction between price signals and allocation rules. While early phases delivered limited incentives due to excessive shielding, later reforms enhanced both price credibility and effective exposure, allowing carbon pricing to translate more consistently into emission reductions. In this sense, the findings align with the broader literature emphasizing that carbon markets function effectively only when scarcity is credible and regulatory protection is carefully targeted rather than pervasive.

5.4.5 *Economic and Financial Performance (RQ2)*

At the firm level, the analysis indicates that exposure to the EU ETS leads to diverse and nuanced economic outcomes rather than consistent negative impacts. On average, regulated firms show slightly lower profitability than similar non-regulated firms, suggesting that complying with carbon regulations entails short-term cost pressures. However, the magnitude of this effect is limited, suggesting that the EU ETS has not seriously threatened firms' financial stability.

This finding is consistent with studies documenting compliance and adjustment costs associated with carbon regulation, particularly in manufacturing sectors where cost pass-through is limited. Empirical evidence from Marin et al. (2018) and Dechezleprêtre et al. (2023) similarly reports small but statistically significant profitability effects, especially in the early years following regulatory tightening. The present results reinforce this interpretation by showing that, while carbon pricing imposes tangible costs, these do not translate into large or persistent losses in firm performance.

At the same time, ETS-regulated firms display higher labour productivity relative to non-regulated firms. This pattern suggests that firms subject to carbon pricing may respond by improving operational efficiency, reorganising production processes, or investing in productivity-enhancing measures. Importantly, increased productivity does not always lead to higher short-term profits, since efficiency gains might be offset by compliance costs, allowance spending, or necessary investments to cut emissions.

The analysis also reveals substantial heterogeneity across sectors. Profitability effects are concentrated in less protected sectors, where firms face greater exposure to carbon costs. In contrast, companies in sectors highly exposed to carbon leakage face considerably smaller impacts on profitability, highlighting the protective effect of free allowance allocation. These results underscore that the economic effects of the EU ETS are strongly mediated by sectoral characteristics and policy design, rather than being uniform across regulated firms.

Taken together, the findings suggest that the EU ETS has achieved meaningful emissions reductions without causing widespread economic disruption. Environmental effectiveness increases with regulatory stringency and effective exposure to carbon pricing, while economic impacts at the firm level remain limited and heterogeneous. The combination of declining emissions, modest profitability effects, and higher productivity points to an adjustment process in which firms tend to adapt to carbon constraints through efficiency improvements rather than large-scale contraction. These findings offer a clear basis for understanding the EU ETS as a policy tool that harmonizes environmental goals with economic stability.

The firm-level results contribute to the long-standing debate on the economic consequences of carbon pricing and, more specifically, on whether the EU ETS undermines firms' competitiveness and financial performance. Overall, the findings of this thesis align with a growing body of empirical literature suggesting that the economic impacts of the EU ETS are real but limited, heterogeneous, and strongly mediated by policy design and sectoral characteristics.

Importantly, the magnitude and distribution of profitability effects vary substantially across sectors. Firms operating in less protected industries face stronger negative impacts, whereas firms in sectors classified as highly exposed to carbon leakage display significantly weaker profitability responses. This pattern is fully consistent with the literature emphasizing the role of free allocation and leakage protection in cushioning regulated firms from carbon cost exposure. Rather than indicating a failure of the EU ETS, these results highlight how distributional outcomes are shaped by policy design choices. In this sense, the findings support the view that observed competitiveness effects are not inherent to carbon pricing per se, but depend on the degree of regulatory insulation embedded in the system.

At the same time, the analysis reveals a robust positive association between ETS exposure and labor productivity. Regulated firms exhibit higher productivity levels than comparable non-regulated firms, suggesting that carbon constraints induce behavioral and organizational responses aimed at improving efficiency. This result resonates with the literature documenting productivity-enhancing effects of environmental regulation, even in the absence of immediate profitability gains. Studies testing the Porter Hypothesis in the context of the EU ETS generally find limited support for strong win–win outcomes in terms of profits, but more consistent evidence of efficiency improvements and innovation responses. The findings of this thesis are closely aligned with this "weak Porter" interpretation, whereby regulation stimulates efficiency gains without necessarily generating short-term financial benefits.

The coexistence of higher productivity and lower profitability offers important insight into the adjustment mechanisms triggered by carbon pricing. Efficiency improvements may reflect investments in cleaner technologies, process optimization, or reallocation of resources within firms. However, these gains often require upfront expenditures and learning costs that weigh on short-term margins. As a result, productivity improvements do not automatically translate into higher profitability, particularly in the presence of allowance expenditures and compliance costs. This interpretation is consistent with recent firm-level studies showing that the economic benefits of decarbonization strategies tend to materialize gradually over time.

The manufacturing focus of this analysis further refines the existing literature. Unlike power generation, where cost pass-through and auctioning dominate, manufacturing firms operate under heterogeneous competitive conditions and face varying degrees of regulatory protection. By isolating manufacturing firms, the results demonstrate that productivity-enhancing responses to the EU ETS are observable even in sectors traditionally considered vulnerable to competitiveness losses. At the same time, the sectoral heterogeneity in profitability effects underscores that adjustment capacity differs markedly across industries, depending on technological flexibility and policy treatment.

Taken together, the firm-level findings suggest that the EU ETS has not generated widespread economic harm, but has instead reshaped firm performance along multiple dimensions. Carbon pricing imposes short-term financial pressures, particularly where regulatory protection is limited, while simultaneously encouraging efficiency improvements that enhance productive capacity. This nuanced pattern helps reconcile seemingly conflicting results in the literature and supports the interpretation of the EU ETS as a policy instrument that induces adaptation rather than deindustrialization. The evidence thus reinforces the view that economic outcomes under carbon pricing are best understood as transitional effects, shaped by both market incentives and regulatory design.

5.5 Policy and Financial Implications

The findings of this thesis carry important implications for climate policy design and for the financial assessment of firms operating under carbon pricing regimes. By jointly examining environmental outcomes at the installation level and economic performance at the firm level, the results provide a coherent basis for evaluating the effectiveness and distributional consequences of the EU ETS in its current form.

Implications for Climate and Industrial Policy

From a policy perspective, the results underline that the effectiveness of the EU ETS depends critically on the credibility and binding nature of the carbon price signal. Although higher carbon prices generally lead to greater emission reductions, the analysis indicates that these price signals result in environmental improvements only if firms and installations face enough compliance costs. Extensive free allocation, although justified by concerns over carbon leakage and competitiveness, systematically weakens the responsiveness of emissions to carbon prices and delays adjustment.

This finding suggests that the key policy challenge is not whether carbon pricing works, but under which design conditions it delivers meaningful environmental outcomes. The evidence shows that the post-2013 reforms, which include stricter caps, updated allocation rules, and mechanisms to stabilize the market, have reinforced the connection between prices and emissions without causing significant economic disruption.

At the same time, the results highlight the inherent trade-off embedded in leakage protection policies. While free allocation plays an important role in cushioning firms against short-term cost pressures, excessive or persistent protection reduces incentives for abatement and efficiency improvements. These findings endorse a policy approach where free allocation is slowly reduced or made more targeted, especially as additional tools like the Carbon Border Adjustment Mechanism are implemented to handle competitiveness issues externally instead of relying on internal shielding.

Implications for Firms

For regulated firms, the results suggest that exposure to the EU ETS should be understood as a structural constraint rather than a temporary cost shock. The combination of modest profitability pressures and higher productivity indicates that firms adapt primarily through efficiency-enhancing adjustments rather than contraction. This implies that long-term competitiveness under carbon pricing increasingly depends on firms' ability to reorganise production processes, invest in cleaner technologies, and integrate carbon costs into strategic decision-making.

The heterogeneity observed across sectors further implies that firms' responses are shaped by both technological characteristics and regulatory treatment. Firms operating in less protected sectors face stronger incentives to internalise carbon costs and adjust rapidly, while firms benefiting from regulatory shielding experience weaker short-term pressures. Over time, however, persistent exposure to carbon pricing is likely to shift competitive advantages toward firms with greater adaptive capacity, regardless of sectoral classification.

5.6 Limitations and Future Research

While this thesis provides novel empirical insights into the environmental and economic effects of the EU ETS, several limitations should be acknowledged. Recognising these constraints is essential for a correct interpretation of the results and for identifying promising avenues for future research.

First, the empirical analysis is based on observational data and econometric associations. Despite the inclusion of fixed effects, control variables, and robustness checks, the results should not be interpreted as fully causal. Residual endogeneity may persist, particularly with respect to carbon prices and firms' regulatory exposure, which are influenced by broader market and policy dynamics. As a result, the findings capture systematic relationships rather than definitive causal effects.

Second, data limitations constrain the scope of the analysis. Firm-level financial information is derived from ORBIS, which may suffer from reporting inconsistencies and limited coverage for certain firms and years, particularly in the post-2016 period. In addition, the analysis focuses on manufacturing firms and stationary installations, excluding sectors such as power generation and services. While this focus enhances internal consistency and sectoral comparability, it limits the generalizability of the results to the broader economy.

Third, the empirical framework does not explicitly account for major external shocks, such as the COVID-19 pandemic or the recent energy price crisis, which may have affected both emissions and firm performance independently of the EU ETS. Although fixed effects partially absorb these influences, future research could explicitly model the interaction between carbon pricing and macroeconomic shocks.

Future research could extend this analysis in several directions. First, the availability of more granular data on firm-level investments, innovation activities, and abatement technologies would allow a deeper investigation of the channels through which carbon pricing affects productivity and emissions. Second, future studies could examine longer-term dynamics to determine whether productivity gains under the EU ETS translate into improved profitability over time. Finally, as the EU climate policy framework evolves, further research could assess how instruments such as the Carbon Border Adjustment Mechanism interact with the EU ETS in shaping firm behaviour, competitiveness, and environmental outcomes.

Conclusion

This thesis has examined the environmental and economic effects of the EU Emissions Trading System by combining installation-level and firm-level evidence for the European manufacturing sector. By jointly analysing emissions outcomes and firm performance, the study provides a comprehensive assessment of how carbon pricing operates in practice under different degrees of regulatory stringency and protection.

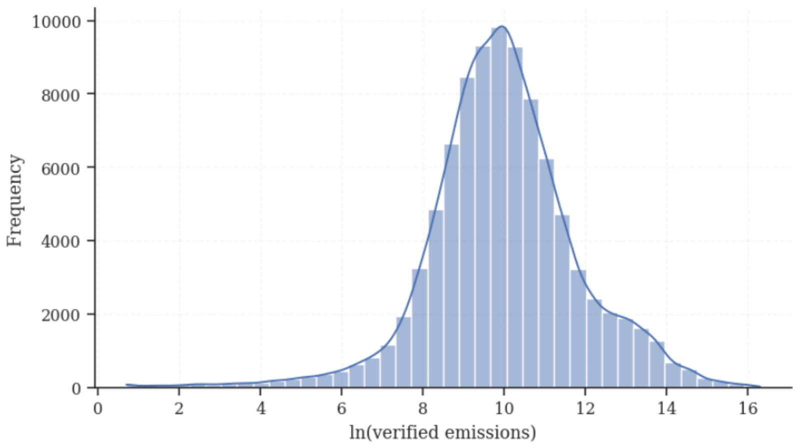
The results show that the environmental effectiveness of the EU ETS has strengthened over time and is closely linked to the credibility of the carbon price signal and to firms' effective exposure to it. Emission reductions are more pronounced in later phases of the system and are systematically larger for installations that are less shielded by free allowance allocation. This highlights that carbon pricing alone is not sufficient to induce abatement if regulatory protection remains extensive.

At the same time, the firm-level analysis indicates that exposure to the EU ETS has not led to widespread economic disruption. While regulated firms experience modest profitability pressures, they also exhibit higher labour productivity than comparable non-regulated firms. This pattern suggests that firms primarily adjust to carbon constraints through efficiency-enhancing responses rather than through contraction or relocation. Importantly, the economic effects of the EU ETS are highly heterogeneous and strongly mediated by sectoral protection, confirming that policy design choices shape the distribution of costs across firms.

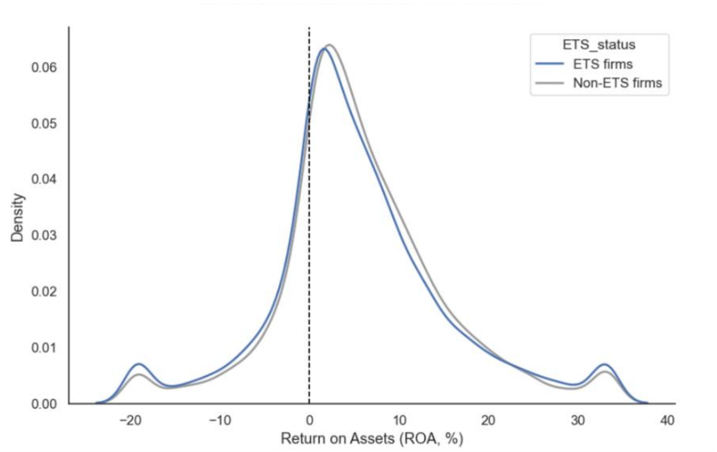
Taken together, the findings support the view of the EU ETS as a policy instrument capable of delivering meaningful emission reductions while preserving economic resilience in the manufacturing sector. Evidence indicates that the main challenge for upcoming EU ETS phases is not just implementing carbon pricing but optimizing its design to align environmental goals with specific protection strategies. In this context, the findings highlight the need to gradually lessen regulatory protection and enhance supporting tools to keep carbon pricing effective and economically sustainable in the long term.

Appendix

A. Distribution of log-verified emissions



B. Distribution of ROA for ETS and non-ETS firms



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