Is EU ETS Exposure Associated with Renewable Energy Use in Industry?

Evidence from European industrial sectors, 2005-2024

Casper Ahlström

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Casper Ahlström

Supervisor:	**Marc Paul Yeterian, Swedish University of Agricultural Sciences, Department of Environmental and Natural Resource Economics**
Examiner:	Shon Ferguson, Swedish University of Agricultural Sciences , Department of Economics

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Abstract

This thesis examines whether stronger exposure to the European Union Emissions Trading System (EU ETS) is associated with higher renewable energy shares across industrial sectors. Using panel data covering European industrial sectors between 2005 and 2024, the analysis combines sector-level measures based on verified emissions and freely allocated allowances with EU ETS carbon prices to construct a continuous measure of effective carbon-cost exposure.

The empirical results indicate a positive relationship between effective ETS exposure and renewable energy shares. The preferred specification suggests that stronger carbon-cost exposure is associated with modest but economically meaningful increases in renewable energy use relative to the sample average. Dynamic specifications further indicate that these adjustments occur gradually over time, with the strongest responses emerging approximately two to three years after changes in exposure. Robustness checks show that the positive relationship remains broadly consistent across alternative specifications, although the estimated magnitudes vary depending on sample composition, lag structures, and the treatment of negative exposure values.

The findings suggest that carbon pricing may contribute not only to emissions reductions, but also to gradual changes in the composition of industrial energy use. More broadly, the results imply that firms may respond to carbon-cost incentives by adjusting their own energy systems over time, highlighting the potential role of emissions trading systems in supporting industrial energy transitions. The estimated relationships should, however, be interpreted cautiously and not as definitive causal treatment effects.

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Abbreviations

EU	European Union
ETS	Emissions Trading System
EU ETS	European Union Emissions Trading System
EUA Price	European Union Allowance Price
EUA	European Union Allowance
EEA	European Environment Agency
FE	Fixed Effects
GDP	Gross Domestic Product
IHS	Inverse Hyperbolic Sine
RES	Renewable energy share

1. Introduction

Renewable energy use in European industrial sectors has increased substantially over the past several decades. As illustrated in Figure 1, the average renewable energy share (RES) across industrial sectors increased steadily between the early 1990s and 2024, particularly following the mid-2000s. Understanding the drivers of this transition is important because long-run industrial decarbonization requires not only lower emissions, but also changes in the energy sources used in production. While carbon pricing is primarily designed to reduce emissions, it may also influence how firms adjust energy systems and fuel choices over time. This raises an important question: to what extent has carbon pricing contributed to changes in industrial energy use and fuel substitution?

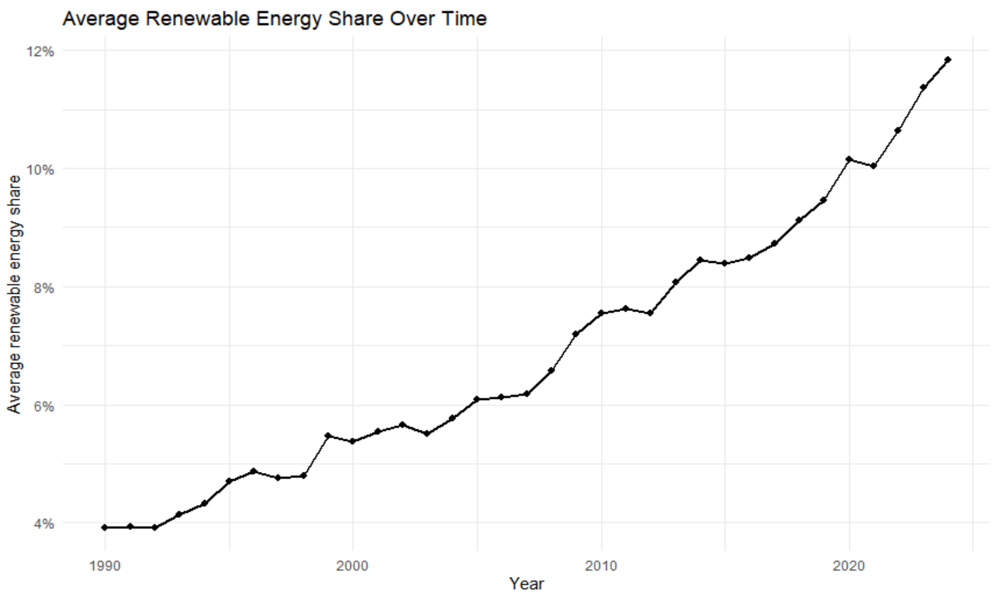

Figure 1. Average renewable energy share across industrial sectors over time

The European Union Emissions Trading System (EU ETS), introduced in 2005, is the world's largest carbon market and a central component of European climate policy. By placing a price on carbon emissions, the system increases the cost of fossil-fuel-intensive production and may encourage firms to improve energy efficiency, adopt renewable energy technologies, or substitute away from fossil fuels toward lower-carbon energy sources. Understanding whether carbon pricing contributes to broader changes in industrial energy use is important because industrial energy transition plays a central role in achieving long-run decarbonization objectives.

This thesis examines whether stronger carbon-cost exposure under the EU ETS is associated with higher renewable energy use across industrial sectors. The analysis combines sector-specific exposure measures with EU ETS carbon prices to construct a continuous measure of effective carbon-cost exposure across sectors and over time. Using panel data covering European industrial sectors between 2005 and 2024, the empirical analysis estimates fixed-effects models examining whether sectors facing stronger ETS exposure subsequently exhibit higher RES.

A large empirical literature examines whether the EU ETS reduced emissions while limiting adverse effects on competitiveness and industrial performance (Abrell et al. 2011; Petrick & Wagner 2014; Martin et al. 2016; Colmer et al. 2025). Other studies examine innovation and technological adaptation responses to carbon pricing (Calel & Dechezleprêtre 2016; Boungou & Dufau 2024). Although a smaller literature examines fuel substitution, energy-use adjustment, and changes in energy mixes (Zhu et al. 2019; Müller & Teixidó 2021; Kim & Bae 2022), considerably less attention has been given to renewable energy use directly compared with the extensive literature on emissions, competitiveness, and innovation outcomes.

Building on this literature, the present analysis examines whether carbon-cost exposure under the EU ETS is associated with renewable energy adoption across industrial sectors. The empirical results indicate a generally positive relationship between effective carbon-cost exposure and RES. The preferred specification suggests that a one-standard-deviation increase in ETS exposure is associated with approximately a 0.5 percentage-point increase in RES, corresponding to roughly 5 percent of the sample mean RES. The dynamic specifications further suggest that industrial energy adjustment may occur gradually over multiple years rather than immediately.

This thesis contributes to the EU ETS literature in several ways. First, unlike much of the existing literature focusing primarily on emissions reductions, competitiveness effects, or innovation outcomes, the analysis examines industrial energy-mix adjustment directly through RES. Second, the analysis combines sector-level exposure measures with EU ETS carbon prices to construct a continuous measure of effective carbon-cost exposure across sectors and over time. Third, the dynamic specifications examine whether industrial energy adjustment occurs gradually following changes in carbon-cost exposure.

The remainder of the thesis is structured as follows. Section 2 provides institutional background on the EU ETS. Section 3 reviews the relevant literature. Section 4 presents the conceptual framework, while Section 5 discusses the identification strategy and empirical challenges. Section 6 outlines the estimation strategy. Section 7 describes the data and construction of the final panel dataset. Section 8 presents the empirical results, followed by a discussion in Section 9. Section 10 concludes.

2. Institutional Background: The European Union Emissions Trading System

Understanding the institutional design of the EU ETS is important because the empirical analysis exploits differences in sector-level exposure to carbon-cost pressure across regulated industries.

The European Union Emissions Trading System (EU ETS) was introduced in 2005 and is currently the world's largest carbon market by market value, trading volume, and auction revenue, although China's national ETS covers a larger volume of greenhouse gas emissions. The system regulates approximately 1.1 billion tons of CO_2-equivalent emissions annually and covers around 40 percent of total greenhouse gas emissions within the European Union. The EU ETS includes approximately 10,000 installations across electricity generation, energy-intensive manufacturing industries, aviation, and, more recently, maritime transport. The system was initially established to help the European Union meet its commitments under the Kyoto Protocol, but it has gradually become a central instrument for achieving the EU's broader climate objectives under the European Green Deal and the European Climate Law, including the target of reducing net greenhouse gas emissions by at least 55 percent by 2030 relative to 1990 levels and achieving climate neutrality by 2050 (European Commission, 2025a).

The EU ETS operates through a cap-and-trade framework in which a cap determines the total number of emission allowances available within the system. Firms covered by the EU ETS must surrender allowances corresponding to their verified emissions each year, while allowances may be traded between firms in secondary markets. The system has developed through several policy phases involving progressively stricter regulation and broader sector coverage. (European Commission, 2025b).

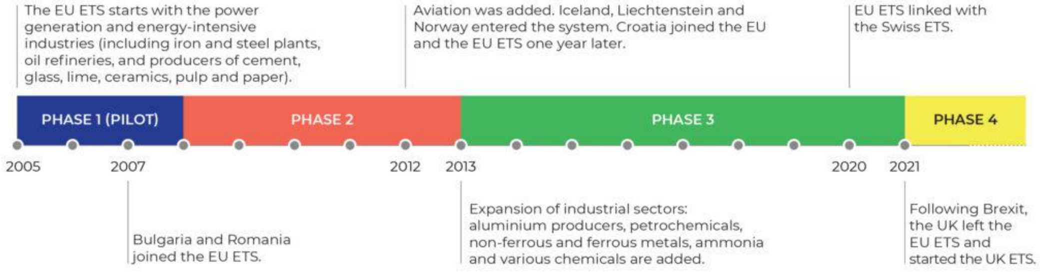

Figure 2. Timeline of major EU ETS phases and reforms. Source: adapted from ETXtra (2025).

Phase I (2005–2007) functioned mainly as a pilot phase and was characterized by substantial overallocation of allowances, contributing to low carbon prices toward the end of the period. Phase II (2008–2012) coincided with the Kyoto commitment period but was heavily affected by the global financial crisis, which reduced industrial output and created a large surplus of allowances. More substantial reforms were introduced beginning in Phase III (2013–2020), including a centralized EU-wide cap, increased auctioning, and a stronger annual reduction in allowance supply. Under Phase IV (2021–2030), the annual Linear Reduction Factor increased from 1.74 percent to 2.2 percent and was later strengthened further under the "Fit for 55" reforms, while maritime transport was gradually incorporated into the system and a separate ETS2 framework for buildings and road transport was introduced (European Commission, 2025a; European Commission, 2025b).

Allowance allocation within the EU ETS combines auctioning with free allocation based on sector-specific benchmarks. Since Phase III, electricity producers have generally been required to purchase allowances through auctions, while energy-intensive industrial sectors exposed to international competition continue to receive a substantial share of allowances for free. As a result, sectors differ considerably in their effective exposure to carbon pricing. Firms with emissions exceeding their freely allocated allowances must purchase additional permits, while sectors receiving relatively generous allocation face lower effective carbon costs. In some cases, firms receiving allowances in excess of verified emissions may sell surplus allowances on the carbon market, generating additional revenue and potentially transforming carbon-cost pressure into a net financial benefit.

This heterogeneity in carbon-cost exposure forms the basis of the empirical strategy used in this thesis. Although firms within the EU ETS face a common carbon market price at a given point in time, sectors differ substantially in the extent to which they are exposed to permit shortages. The analysis therefore combines sector-level exposure measures with changes in EU ETS carbon prices to examine whether sectors facing stronger carbon-cost pressure subsequently experience larger increases in RES.

An important institutional feature of the EU ETS is that major reforms, cap reductions, and allocation rules are often announced before implementation through EU legislative processes. This creates a relatively predictable regulatory environment in which firms may gradually adjust long-term investment and production decisions over time (European Commission, 2025a).

3. Literature Review

The existing literature suggests several channels through which carbon pricing may influence industrial behavior. Firms may respond through technological innovation, adjustments in energy use, fuel substitution, and broader changes in production systems. At the same time, the strength of these responses may depend on firms emissions intensity, allowance allocation, and effective exposure to carbon costs. This section reviews the literature most relevant to these adjustment mechanisms and highlights how the present thesis contributes to the existing evidence.

3.1 Innovation, technological adaptation, and energy adjustment

A growing literature examines how firms adjust energy use, production technologies, and innovation activity in response to carbon pricing. Several studies find that carbon pricing contributed to energy-efficiency investments, industrial energy adjustment, and broader technological change (Teixidó et al. 2019; Löfgren et al. 2013; Boungou & Dufau 2024). Other studies suggest that firms respond through fuel substitution and adjustments in energy inputs, including changes in fuel mixes and transitions toward lower-carbon energy sources (Zhu et al. 2019; Kim & Bae 2022; Müller & Teixidó 2021).

These findings are particularly relevant for the present thesis because they identify mechanisms through which carbon pricing may influence industrial energy use. If firms respond to higher carbon costs by altering fuel choices, investing in alternative energy sources, or adjusting production processes, sectors facing stronger carbon-cost exposure may be expected to exhibit higher renewable energy share (RES) over time.

Innovation represents another potential adjustment channel. Calel and Dechezleprêtre (2016) use patent data matched with EU ETS installations to examine whether carbon pricing stimulated low-carbon innovation among regulated firms. The authors find that the EU ETS increased low-carbon patenting activity by approximately 10 percent, suggesting that firms respond to carbon pricing not only through emissions reductions, but also through technological adaptation and changes in production systems.

Together, these studies suggest that firms may partly respond to carbon pricing through gradual changes in industrial energy systems, fuel substitution, and technological adaptation. This literature therefore provides an important motivation for examining RES as an outcome of carbon-cost exposure.

3.2 Heterogeneous exposure and industrial adjustment incentives

An additional literature emphasizes that firms' responses to carbon pricing may differ depending on emissions intensity, allowance allocation, and effective carbon-cost exposure. Zaklan (2023) exploits variation in free-allocation rules following the 2013 EU ETS reforms and finds that firms responded primarily to the market value of allowances rather than the quantity of free allocation received. Harstad and Eskeland (2010) show that when future free allocation depends on current emissions, firms may adjust behaviour strategically in anticipation of future allocation decisions, creating inefficiencies in permit markets. Other studies similarly suggest that firms facing tighter allowance constraints respond more strongly to carbon-pricing incentives (Abrell et al. 2011).

The broader energy economics literature also suggests that industrial firms can gradually substitute between energy inputs when relative prices change, although adjustment possibilities remain constrained in the short run by technological and capital limitations (Bjørner & Jensen 2002). As a result, sectors facing identical carbon prices may nevertheless experience different adjustment incentives depending on emissions intensity, production technologies, and allowance positions.

The strength of carbon-pricing incentives has also varied substantially across different phases of the EU ETS. Early phases of the system were characterized by substantial allowance overallocation and relatively low carbon prices, reducing effective carbon-cost pressure on regulated firms (Ellerman & Buchner 2008; Anderson & Di Maria 2011). Subsequent reforms gradually tightened allowance supply and strengthened carbon-pricing incentives.

While the existing literature provides substantial evidence that firms adjust technologies, energy use, and production systems in response to carbon pricing, relatively few studies directly examine how heterogeneous EU ETS exposure affects RES across industrial sectors over time. This thesis contributes to the literature by combining sector-level exposure measures with EU ETS carbon prices to construct a continuous measure of effective carbon-cost exposure. The thesis then examine whether sectors facing stronger ETS exposure subsequently exhibit higher RES.

4. Conceptual Framework

The empirical literature reviewed in the previous chapter suggests several mechanisms through which carbon pricing may affect firms' production decisions. Existing studies show that carbon pricing has contributed to technological adaptation, low-carbon innovation, changes in fuel use, and improvements in energy efficiency (Calel & Dechezleprêtre, 2016; Teixidó et al., 2019; Kim & Bae, 2022; Müller & Teixidó, 2021). Building on these findings, this section develops a conceptual framework describing how carbon-cost exposure may influence renewable energy shares within industrial sectors.

4.1 Economic mechanism

Standard production theory predicts that firms adjust input choices when relative prices change. Under the EU ETS, carbon pricing increases the effective cost of carbon-intensive production by requiring regulated firms to surrender emission allowances corresponding to their emissions. Firms minimizing production costs may therefore respond by adjusting production processes, reducing energy use, improving energy efficiency, or substituting away from fossil fuels toward renewable energy sources. These adjustment channels are consistent with the mechanisms identified in the empirical literature, where firms respond to carbon pricing through technological adaptation, fuel substitution, and changes in production processes.

A simple decomposition of industrial emissions can be written as

$$Emissions_{c,s,t} = Output_{c,s,t} \times EnergyIntensity_{c,s,t} \times CarbonIntensity_{c,s,t}, \qquad (1)$$

where energy intensity captures energy use per unit of output and carbon intensity captures the emissions generated per unit of energy use.

Equation (1) illustrates several channels through which firms may reduce emissions in response to carbon pricing. Firms may reduce output, lower energy intensity through energy-efficiency improvements, or reduce the carbon intensity of production through changes in fuel use and energy inputs. Since carbon pricing increases the relative cost of fossil-fuel-intensive production, firms may have incentives to substitute toward renewable energy sources to reduce effective production costs. Examples include replacing coal or gas boilers with biomass systems, electrifying industrial processes previously powered by fossil fuels, or increasing the use of renewable electricity within production. These adjustments reduce the carbon intensity of production and may increase the renewable share of total energy use. This thesis focuses specifically on this latter adjustment channel by examining whether stronger carbon-cost pressure is associated with higher RES across industrial sectors.

4.2 Carbon-cost exposure and sector heterogeneity

Although firms covered by the EU ETS face a common carbon market price at a given point in time, the effective impact of that price differs substantially across sectors. Sectors vary in emissions intensity, allowance allocation, production technologies, energy dependence, and possibilities for fuel substitution. As a result, firms face different effective allowance constraints. Sectors whose emissions are close to or exceed their freely allocated allowances are more exposed to changes in carbon prices because they must purchase additional permits when emissions exceed allocation. By contrast, sectors with larger allowance surpluses face weaker adjustment incentives because changes in carbon prices have a smaller effect on their effective costs. The same carbon price may therefore generate very different adjustment incentives across sectors depending on their allowance position and the extent to which they are constrained by the need to purchase additional permits.

Carbon-cost exposure may conceptually be positive or negative depending on the relationship between emissions and freely allocated allowances. Firms whose emissions exceed freely allocated allowances must purchase additional permits, increasing marginal production costs. Conversely, firms receiving allowances in excess of emissions may sell surplus permits on the carbon market, implying that allowance surpluses may partly offset production costs. Negative exposure therefore reflects weaker effective carbon-cost pressure and may in some cases function similarly to an implicit subsidy through allowance overallocation.

The expected response is also unlikely to be immediate. Installing a new biomass boiler, modifying production equipment for electrification, or constructing on-site renewable energy facilities often requires substantial capital investment, permitting processes, and production adjustments. Firms may therefore implement such changes gradually over several years rather than immediately following changes in carbon-cost pressure.

4.3 Causal framework

The conceptual mechanism can be summarized by the following causal chain

$$EU\ ETS\ Cap \rightarrow Carbon\ Price \rightarrow Firm\ Exposure \rightarrow Energy\ Mix\ Decisions \rightarrow Renewable\ Energy\ Share \tag{2}$$

where changes in the EU ETS cap affect allowance scarcity within the carbon market, influencing the market price of carbon emissions. Since sectors differ in emissions intensity and allowance positions, changes in carbon prices generate heterogeneous changes in effective carbon-cost pressure across sectors. Firms may then respond by adjusting fuel use, production technologies, or energy inputs, potentially affecting the renewable energy share (RES) within total industrial energy consumption.

This framework argues that stronger effective ETS exposure may contribute to gradual increases in RES over time. However, the relationship is not mechanically causal. Sector exposure may itself be affected by firms' emissions and energy choices, while broader technological change, renewable energy policies, and energy market developments may simultaneously influence renewable energy adoption. These identification challenges are discussed further in the following section.

5. Identification Strategy

5.1 Construction of variables

This thesis examines whether stronger EU ETS carbon-cost exposure is associated with changes in renewable energy use within industrial sectors. Since the EU ETS carbon price is common across regulated sectors, variation in carbon prices alone cannot identify differences in incentives across industries. The empirical strategy therefore exploits variation in sector-specific exposure to carbon pricing.

The main outcome variable measures the renewable energy share(RES) within industrial sectors and is defined as

$$RenewableEnergyShare_{c,s,t} = \frac{RenewableEnergy_{c,s,t}}{TotalEnergy_{c,s,t}}, \tag{3}$$

where $RenewableEnergy_{c,s,t}$, denotes renewable energy use and $TotalEnergy_{c,s,t}$ denotes total industrial energy consumption in sector s, country c, and year t. Higher values therefore indicate a greater reliance on renewable energy sources within industrial production.

To operationalize differences in effective carbon-cost pressure empirically, the analysis constructs a sector-level measure of EU ETS exposure based on the relationship between verified emissions and freely allocated allowances. Sectors whose emissions exceed free allocation must purchase additional permits and therefore face stronger effective carbon-cost pressure, while sectors receiving allowances in excess of emissions face weaker effective exposure.

Sector exposure to carbon pricing incentives is defined as

$$Exposure_{c,s,t} = \frac{VerifiedEmissions_{c,s,t-1} - FreeAllowances_{c,s,t}}{VerifiedEmissions_{c,s,t-1}}, \tag{4}$$

where $VerifiedEmissions_{c,s,t-1}$ denotes lagged verified emissions and $FreeAllowances_{c,s,t}$ denotes freely allocated allowances. Higher values indicate that a larger share of emissions must be covered through permit purchases. Conversely, negative values indicate that freely allocated allowances exceed lagged emissions. In these cases, firms may be able to sell surplus allowances on the carbon market, implying that negative exposure values may still contain economically meaningful information about firms' effective incentives.

Lagged verified emissions are used to eliminate contemporaneous mechanical simultaneity between current renewable energy choices and measured exposure.

The logic is similar to that underlying shift-share designs, where exposure measures are constructed using predetermined characteristics measured prior to the outcome period. Using lagged emissions ensures that current renewable energy adjustments cannot mechanically influence the construction of the exposure variable (Borusyak, Hull, & Jaravel, 2025).

Exposure to carbon pricing incentives is therefore measured as

$$ETSExposure_{c,s,t} = Exposure_{c,s,t} \times CarbonPrice_t, \tag{5}$$

where $CarbonPrice_t$, captures the common market-wide price of emissions allowances and $Exposure_{c,s,t}$ captures how strongly sector s in country c is affected by carbon pricing incentives in year t. The interaction term therefore measures effective carbon-cost pressure across sectors and over time.

The exposure index can take both positive and negative values, which creates an important interpretation issue. The preferred specification retains negative values because allowance surpluses may still affect firms' incentives through the possibility of selling surplus permits. Alternative specifications therefore examine whether the results are sensitive to treating negative exposure differently: one specification recodes negative values to zero, while another excludes negative observations entirely. These alternatives are interpreted as robustness checks because they focus only on cases where emissions exceed freely allocated allowances and firms face clearer positive carbon-cost pressure.

5.2 Identification challenges and mitigation strategies

Several identification challenges remain despite the proposed empirical framework. First, free allowance allocation under the EU ETS is not randomly assigned. Allocation partly depends on historical emissions, sector benchmarks, and political decisions, implying that sectors facing different exposure levels may also differ systematically in unobserved characteristics affecting renewable energy use. To partially address these concerns, the empirical specifications include country-sector fixed effects, which absorb persistent differences across sectors and countries that remain constant over time.

Second, simultaneity remains a concern because changes in renewable energy use may themselves affect future emissions and exposure measures. To address contemporaneous mechanical feedback, the exposure variable is constructed using lagged verified emissions, thereby eliminating the possibility that current renewable energy choices directly influence the emissions component of the exposure measure within the same period.

An additional concern is that firms may adjust current behaviour if they expect future allowance allocations to depend on present emissions. As noted by Zaklan (2023), dynamic updating of free-allocation rules may create incentives to maintain higher emissions in anticipation of future allocation decisions. While the current exposure measure uses lagged verified emissions and therefore eliminates contemporaneous mechanical feedback between renewable energy choices and measured exposure, the possibility that firms respond strategically to expected future allocation rules cannot be fully excluded.

The analysis additionally explores lagged specifications of carbon-cost exposure, since investments in renewable energy technologies and industrial energy systems often occur gradually over time. Because the exposure measure already incorporates lagged emissions, the baseline specification reflects prior emissions conditions, while additional lagged specifications capture increasingly delayed adjustment responses.

Third, broader technological change, renewable energy policies, and developments in energy markets may simultaneously influence renewable energy adoption independently of the EU ETS. To address these concerns, the empirical specifications include country-sector fixed effects, control variables, and a common linear time trend. The latter captures gradual changes affecting all sectors over time. Figure 1 suggests that RES evolved in a broadly smooth manner throughout the sample period, supporting the use of a linear approximation. However, a linear trend may not fully account for discrete common shocks or institutional reforms. The analysis therefore additionally examines the sensitivity of the findings to the Phase III reforms through robustness checks.

The identifying assumption underlying the empirical strategy is therefore that, conditional on country-sector fixed effects, common time trends, and control variables, changes in sector-specific carbon-cost exposure are uncorrelated with unobserved determinants of RES contained in the regression error term. However, because allowance allocation, technological change, and firms' energy choices may still be jointly determined, the estimated relationships should be interpreted as conditional empirical relationships rather than fully exogenous causal treatment effects.

Table 1. Main identification challenges and mitigation strategies

Identification challenge	Mitigation strategy

Non-random allowance allocation: Free allocation depends partly on historical emissions, sector benchmarks, and political decisions, implying that sectors facing different exposure levels may differ systematically in characteristics affecting renewable energy use.	Country-sector fixed effects absorb persistent differences across sectors and countries that remain constant over time.
Simultaneity between renewable energy use and exposure: Current renewable energy choices could mechanically influence the construction of the exposure measure.	Lagged verified emissions eliminate contemporaneous mechanical feedback between current renewable energy choices and measured exposure.
Broader technological, policy, and energy-market trends: Developments unrelated to the EU ETS may simultaneously influence renewable energy adoption across sectors.	Control variables and a common linear time trend account for gradual developments affecting all sectors. However, linear trends may not fully capture discrete common shocks or institutional changes that year fixed effects would absorb. Robustness checks additionally examine sensitivity to the Phase III reforms.

6. Estimation Strategy

The following section outlines the empirical specifications used to examine the relationship between ETS exposure and renewable energy use across industrial sectors. The models are estimated using ordinary least squares (OLS) on a country-sector-year panel dataset, with country-sector clustered standard errors to account for heteroskedasticity and serial correlation within panel units over time.

6.1 Main estimating equation

The baseline specification relates renewable energy share(RES) to effective ETS exposure while controlling for country-sector fixed effects, a common linear time trend, and additional control variables. The main estimating equation is given by

$$RenewableEnergyShare_{c,s,t} = \beta ETSExposure_{c,s,t} + \gamma_{c,s} + \mu t + X'_{c,s,t}\theta + \varepsilon_{c,s,t} \quad (6)$$

where RenewableEnergy$Share_{c,s,t}$ measures the renewable energy percentages in country c, sector s, and year t, $ETSExposure_{c,s,t}$ captures effective carbon-cost pressure as defined in Equation (5), $\gamma_{c,s}$ denotes country-sector fixed effects, μt captures a common linear time trend, and $X'_{c,s,t}$ represents additional control variables. The coefficient of interest is β, which captures the relationship between effective carbon-cost pressure and RES. The analysis considers three alternative definitions of ETS exposure: a preferred specification retaining both positive and negative exposure values, a non-negative specification in which negative values are recoded to zero, and a specification excluding negative observations entirely.

6.2 Variable transformation

Because negative exposure values can be substantially larger in absolute magnitude than positive values, the analysis applies an inverse hyperbolic sine (IHS) transformation to the exposure. Unlike logarithmic transformations, the IHS transformation accommodates zero and negative values while reducing the influence of extreme observations. The transformation is defined as:

$$IHS(x) = \ln\left(x + \sqrt{x^2 + 1}\right) \quad (7)$$

The transformed exposure measure is used throughout the main empirical specifications.

6.3 Dynamic specifications

The analysis additionally estimates dynamic specifications using lagged measures of ETS exposure to account for delayed adjustment responses in industrial energy systems. Because the exposure measure itself is constructed using lagged verified emissions, the baseline specification already reflects prior emissions conditions, while additional lagged specifications capture increasingly delayed responses over time.

The joint lag specification is estimated as

$$RenewableEnergyShare_{c,s,t} = \beta_1 ETSExposure_{c,s,t} + \beta_2 ETSExposure_{c,s,t-1} + \beta_3 ETSExposure_{c,s,t-2} + \beta_4 ETSExposure_{c,s,t-3} + \gamma_{c,s} + \mu t + X'_{c,s,t}\theta + \varepsilon_{c,s,t} \quad (8)$$

where lagged specifications additionally help reduce simultaneity concerns by ensuring that exposure precedes observed changes in RES.

The interpretation of the dynamic coefficients requires particular attention because the exposure measure itself is constructed using lagged verified emissions. Consequently, the contemporaneous exposure coefficient (β_1) approximately reflects a one-year delayed response between emissions-based exposure and renewable energy outcomes. The subsequent coefficients (β_2–β_4) capture increasingly delayed responses occurring approximately two, three, and four years after the underlying emissions conditions used to construct the exposure measure. Positive coefficients therefore indicate that stronger carbon-cost exposure is associated with higher RES emerging gradually over time rather than immediately.

7. Data

7.1 Eurostat energy data

The empirical analysis combines three main data sources. Sectoral energy-use data are obtained from the Eurostat energy balances database (`nrg_bal_c`), which provides annual energy consumption by country, sector, and energy source measured in terajoules. Renewable energy consumption is identified using the Eurostat code `RA000`, while total energy consumption is measured using the aggregate category `TOTAL`.

Data on verified emissions and freely allocated allowances are obtained from the European Environment Agency EU ETS database. Installation-level observations are aggregated to the country-sector-year level to match the structure of the Eurostat energy data. Annual EU ETS carbon prices are obtained from the World Bank carbon pricing database and measured as average annual EUA prices.

The final dataset covers industrial sectors participating in the EU ETS between 2005 and 2024. The analysis focuses on electricity and heat generation, refineries, iron and steel, non-ferrous metals, non-metallic minerals, chemicals, and pulp and paper. These sectors correspond to the major stationary industrial sectors covered by the EU ETS and for which consistent emissions, allowance allocation, and energy-use data could be harmonized across the different data sources. The sectors were selected based on the EEA EU ETS sector classification and data availability. Aviation was excluded because it entered the EU ETS later and operates under different regulatory and energy-use conditions. Some smaller activity categories could not be consistently matched between the EU ETS and Eurostat energy data. The sector classifications used to merge the Eurostat and EU ETS datasets were matched using the activity mappings reported in Gores et al. (2024) in the EU Emissions Trading System data viewer: Background note. How sectors where match is shown in Appendix Table 13.

7.2 EU ETS emissions and allowance data

The Eurostat energy data, EU ETS emissions and allowance data, and carbon price series are merged at the country-sector-year level using common identifiers for country, sector, and year. The resulting dataset combines information on renewable energy use, emissions, allowance allocation, and carbon prices across sectors participating in the EU ETS.

The final panel is unbalanced because data availability differs across countries, sectors, and years. Aviation is excluded from the main analysis because it entered the EU ETS later than most stationary industrial sectors and operates under different regulatory and energy-use conditions. The number of observations therefore varies across specifications depending on data availability and lagged variables.

7.3 Descriptive statistics

Table 2 presents descriptive statistics for the main variables used in the empirical analysis. The table is restricted to observations with non-missing exposure values, leaving 3,078 country-sector-year observations. This ensures that the descriptive statistics for RES and ETS exposure are based on the same sample.

The average RES is 0.098(9.8%), while the median is 0.005(0.5%). This indicates that renewable energy use remains relatively low across many industrial sector observations, although some sectors exhibit substantially higher RES. The exposure variables display considerable dispersion, reflecting large differences in emissions intensity and allowance allocation across sectors. The baseline exposure measure has a negative mean, while the nonnegative exposure measure has a mean of 0.154, indicating that allowance overallocation is present in parts of the sample. At the same time, the inverse hyperbolic sine (IHS) transformation substantially compresses extreme negative observations, resulting in a transformed exposure measure centred relatively close to zero and reducing the influence of extreme observations in the main specifications. These patterns help motivate the distinction between the baseline exposure measure and the alternative nonnegative specifications used later in the analysis.

Table 12 reports mean-difference tests comparing the pre- and post-2013 periods. This comparison is relevant because Phase III of the EU ETS introduced major reforms, including increased auctioning, a centralized EU-wide cap, and changes in allowance allocation rules. The average renewable energy share(RES) increased from 0.074 (7.4%) before 2013 to 0.110 (11.0%) after 2013, and the difference is statistically significant. The mean IHS-transformed exposure measure also shifted significantly, from -0.287 before 2013 to 0.014 after 2013, indicating stronger effective carbon-cost exposure after the Phase III reforms.

At the same time, average freely allocated allowances declined substantially, from approximately 23,618 to 8,110, and the corresponding mean-difference test indicates that this decline is statistically significant. Verified emissions also decreased from around 22,656 to 16,875, although this difference is only weakly statistically significant at the 10 percent level. Together, these patterns suggest that the typical sector moved from a position characterized by allowance overallocation toward one facing more positive effective carbon-cost exposure. These developments are consistent with the institutional evolution of the EU ETS, which gradually reduced allowance surpluses and strengthened carbon-pricing incentives across regulated sectors.

Figure 3 in the Appendix illustrates the evolution of average sector exposure over time and shows a clear shift from predominantly negative exposure values before 2013 toward increasingly positive exposure values after the Phase III reforms. While this pattern is consistent with the institutional reforms of the EU ETS, it also suggests that developments over time may not have been entirely smooth. This observation is relevant when interpreting specifications relying on a common linear time trend and motivates the robustness checks presented later in the thesis.

Table 2 Descriptive overview

	Obs	Mean	SD	Median	Min	Max
RES	3078	0.098	0.180	0.005	0.000	0.998
Exposure	3078	-0.868	25.847	-0.006	-1396	1.000
Exposure-nn	3078	0.154	0.260	0.000	0.000	1.000
Exposure,ihs	3078	-0.090	0.632	-0.006	-7.935	0.881
ETS-Exposure	3078	-0.010	23.624	-0.049	-521.231	84.875
ETS-Exposure, nn	3078	5.198	12.541	0.000	0.000	84.875
Emissions	3078	18880.93	87991.50	2608.740	0.001	1341993
Allocated Allowances	3078	13490.78	62897.65	2264.889	0.000	1306655
Electricity-price	2800	1.056	4.130	0.205	0.079	50.005
Gas price	2464	86.839	229.522	22.305	9.224	1476.159
ln(GDP)	2945	12.313	1.389	12.228	8.695	14.945
Observations	3078					

8. Results

8.1 Baseline specifications

Table 3 reports the main estimation results examining the relationship between EU ETS exposure and RES across industrial sectors. The preferred specification is reported in Column (4), which includes country-sector fixed effects, a common time trend, and control variables for electricity prices, gas prices, and GDP. The estimated coefficient on ETS exposure remains positive and statistically significant at the 10 percent level, suggesting that sectors facing stronger effective carbon-cost pressure tend to exhibit higher RES.

The estimated coefficient in Column (4) implies that a one-unit increase in ETS exposure is associated with approximately a 0.0216 percentage-point increase in the RES. Relative to the sample mean RES of 9.8 percent, this corresponds to an increase of approximately 0.22 percent. The positive relationship is furthermore consistent with the proposed mechanism that stronger carbon-cost exposure increases incentives for firms to substitute away from fossil-fuel-intensive energy inputs toward renewable energy sources.

Columns (1)–(3) present simpler specifications used to illustrate how the estimated relationship changes as additional controls are introduced. Column (1) reports a naïve specification without fixed effects or controls and produces a larger positive coefficient. Columns (2) and (3) sequentially introduce country-sector fixed effects and a common time trend, reducing both the magnitude and statistical significance of the estimated coefficient. This suggests that part of the raw correlation between ETS exposure and renewable energy transition reflects persistent differences in industrial structure, energy intensity, and broader long-run increases in renewable energy use across Europe rather than sector-specific carbon-cost incentives alone. At the same time, some reduction in statistical precision is mechanically expected as additional controls and fixed effects absorb variation and reduce the degrees of freedom available for estimation.

Table 3. Main Estimation Results

VARIABLES	(1) Naive	(2) FE	(3) FE + trend	(4) Controls
ETS-Exposure Approx. 1-year response	0.000520***	0.000442**	0.000231*	0.000216*
	(0.000137)	(0.000186)	(0.000121)	(0.000125)
Electricity price				0.000110
				(0.000692)
ln(GDP)				0.0605
				(0.0428)
Gas price				0.00000790
				(0.0000250)
Time trend			0.00363***	0.00271***
			(0.000585)	(0.000845)
Constant	0.0977***	0.0977***	-7.215***	-6.114***
	(0.00324)	(0.00000187)	(1.179)	(1.443)
Observations	3,078	3,078	3,078	2,457
R-squared	0.005	0.029	0.161	0.152
Country-sector FEs	NO	YES	YES	YES
Time trend	NO	NO	YES	YES
Controls	NO	NO	NO	YES
Clustered SEs	NO	YES	YES	YES
Number of country_sector_id		175	175	148

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

8.2 Dynamic specifications

Table 4 reports dynamic specifications examining whether the relationship between ETS exposure and RES persists over longer horizons. Because the baseline exposure measure already incorporates lagged verified emissions, the specifications approximately correspond to one-, two-, three-, and four-year delayed responses between emissions-based exposure and renewable energy outcomes.

The estimated coefficients remain positive across all specifications. The coefficient increases from 0.000216 in the baseline specification, corresponding approximately to a one-year response, to 0.000325 in the two-year specification and 0.000466 in the three-year specification. The estimated coefficient remains positive and statistically significant in the four-year specification at 0.000428.

Relative to the sample mean RES of 9.8 percent, these estimates correspond to increases of approximately 0.22, 0.33, 0.48, and 0.44 percent, respectively.

The results suggest that industrial adjustment to carbon pricing may occur gradually rather than immediately. This pattern is consistent with the substantial investment costs, technological rigidities, and adjustment frictions associated with industrial energy systems, where changes in energy inputs and production processes often require time. It may also reflect anticipatory behaviour. Because major EU ETS reforms are frequently announced before implementation, firms may begin planning investments and adjusting production strategies in advance of tighter future carbon constraints. The delayed responses observed in the dynamic specifications are therefore consistent with the broader conceptual framework presented earlier in the thesis, where firms gradually adapt production systems and energy mixes following changes in effective carbon-cost exposure.

Column (5) includes the baseline exposure measure together with the additional lagged exposure variables. Although only the approximately three-year response remains statistically significant when estimated jointly, all coefficients remain positive. A joint significance test including the baseline exposure measure and all additional lagged exposure variables rejects the null hypothesis that these coefficients are jointly equal to zero ($F(4,143) = 2.48, p = 0.0467$).

This provides evidence that ETS exposure over the broader one- to four-year adjustment window is jointly associated with renewable energy share(RES). However, because exposure measures are highly correlated over time, the jointly estimated lag coefficients should be interpreted cautiously. Each coefficient reflects the partial association of exposure at a given horizon conditional on exposure in other periods rather than an isolated adjustment effect.

The corresponding joint test for the nonnegative exposure specification strongly rejects the null hypothesis ($F(4,146)10.52, p < 0.001$), providing even stronger evidence of delayed adjustment responses when sectors face clearer positive carbon-cost incentives rather than periods characterized by persistent allowance overallocation.

Overall, the dynamic specifications provide evidence consistent with gradual industrial adjustment to carbon-cost pressure over multiple years. While uncertainty remains regarding the precise timing and magnitude of these responses, the results suggest that industrial energy adjustment may unfold over an extended period rather than occurring immediately following changes in effective carbon-cost exposure.

Table 4.Dynamic Specifications

VARIABLES	(1) Lag 1	(2) Lag 2	(3) Lag 3	(4) Lag 4	(5) All lags
ETS-Exposure Approx. 1-year response	0.000216* (0.000125)				0.0000725 (0.000134)
ETS-Exposure, Approx. 2-year response		0.000325** (0.000159)			0.000113 (0.0000993)
ETS-Exposure, Approx. 3-year response			0.000466** (0.000215)		0.000277* (0.000159)
ETS-Exposure, Approx. 4-year response				0.000428* (0.000252)	0.0000870 (0.000121)
Electricity price		0.0000772 (0.000670)	0.0000966 (0.000676)	0.000126 (0.000698)	0.000130 (0.000657)
ln(GDP)		0.0582 (0.0434)	0.0722 (0.0447)	0.0939* (0.0493)	0.0905* (0.0495)
Gas price		0.00000595 (0.0000253)	0.0000167 (0.0000271)	0.0000306 (0.0000276)	0.0000300 (0.0000272)
Time trend		0.00268*** (0.000856)	0.00225** (0.000891)	0.00185* (0.00101)	0.00173* (0.000971)
Constant		-6.040*** (1.459)	-5.328*** (1.510)	-4.810*** (1.663)	-4.519*** (1.608)
Observations		2,438	2,307	2,169	2,153
R-squared		0.161	0.162	0.152	0.166
Number of country_sector_id		149	149	149	147
Country-sector FEs		YES	YES	YES	YES
Time trend		YES	YES	YES	YES
Controls		YES	YES	YES	YES
Clustered SEs		YES	YES	YES	YES

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

8.3 Robustness checks

Several additional robustness checks are reported in Appendix Tables 5 - 10 to assess whether the estimated relationship between ETS exposure and RES is sensitive to alternative sample definitions, control specifications, lag structures, and assumptions regarding the treatment of negative exposure values.

Appendix Table 5 excludes Luxembourg, Malta, Cyprus, Iceland, and Liechtenstein from the sample to assess whether the baseline results are driven by small countries with limited sector coverage and potentially volatile observations. Small countries may exhibit greater volatility due to narrower sector coverage and smaller industrial bases, increasing sensitivity to outlier observations. The estimated coefficient remains positive, increases modestly in magnitude, and becomes statistically significant at the 5 percent level. The dynamic specifications similarly remain positive across lag structures, with somewhat stronger statistical significance relative to the full-sample baseline. Overall, these results suggest that the main findings are not driven by smaller countries.

Appendix Table 6 sequentially introduces additional control variables to examine whether the estimated relationship primarily reflects broader macroeconomic or energy-market conditions. The estimated ETS coefficient remains positive and statistically significant across specifications, suggesting that the baseline findings are not solely attributable to omitted macroeconomic factors.

Appendix Table 7 reports extended dynamic specifications including up to 4 additional lag structures, corresponding approximately to adjustment responses over up to 5 years. The estimated coefficients become less stable at longer horizons, and one longer-run lag coefficient becomes negative. However, these estimates are statistically weaker and based on substantially smaller samples, suggesting greater uncertainty regarding the persistence of longer-run adjustment responses. Moreover, because the lagged exposure measures are estimated jointly and are highly correlated over time, the individual coefficients should be interpreted cautiously as partial associations conditional on the other lagged exposures rather than as isolated adjustment effects.

Appendix Tables 8 and 9 examine alternative treatments of negative exposure values. Table 8 recodes all negative exposure values to zero while retaining the full sample, whereas Table 9 excludes negative observations entirely. Across both alternative specifications, the estimated coefficients remain positive, substantially larger in magnitude, and more statistically significant relative to the baseline specification. In the nonnegative specification, the baseline coefficient increases from 0.000216 to 0.00126 and becomes statistically significant at the 1 percent level.

These alternative specifications should nevertheless be interpreted cautiously. While the stronger estimated effects are economically intuitive under the assumption that firms respond primarily when emissions exceed freely allocated allowances, negative exposure values may still contain economically meaningful information. Firms receiving allowances in excess of emissions can sell surplus permits on the carbon market, implying that allowance surpluses may also influence firms' effective incentives. Because recoding or excluding negative exposure values removes this dimension of the EU ETS, the resulting estimates may approximate adjustment responses under conditions of clearer positive carbon-cost pressure rather than the full range of incentives embedded in the system. The baseline specification therefore remains the preferred interpretation of the overall relationship between ETS exposure and RES.

Finally, Appendix Table 10 reports separate estimations for the pre- and post-2013 periods to examine whether the results are sensitive to the major Phase III reforms of the EU ETS. The estimated coefficients are not statistically significant in either subsample. Given the substantially smaller sample sizes following the split, these results provide limited evidence of differential effects across periods but suggest that the main findings are not driven solely by either the pre- or post-reform period.

Overall, the robustness checks suggest that the positive relationship between ETS exposure and RES remains broadly consistent across alternative specifications. Although estimated magnitudes and statistical significance vary across samples and modelling choices, the direction of the estimated relationship remains remarkably stable.

9. Policy implications

The empirical results indicate that stronger EU ETS carbon-cost exposure is associated with higher renewable energy share(RES) across industrial sectors. The dynamic specifications further suggest that these adjustments occur gradually over approximately one to four years rather than immediately.

The delayed responses are consistent with the substantial investment costs and technological constraints associated with industrial energy systems. Firms often cannot alter their energy mix quickly, as adjustments require replacing existing capital equipment, modifying production processes, and making long-term investments under uncertainty. The findings therefore suggest that carbon pricing may influence industrial energy-use decisions over time rather than generating immediate responses.

The gradual adjustment pattern may also reflect anticipation and announcement effects. Major reforms of the EU ETS are frequently announced years before implementation, allowing firms to plan investments and adapt production strategies in anticipation of tighter future carbon constraints. In this sense, the credibility and predictability of climate policy may be almost as important as the contemporaneous carbon price itself. Expectations may, however, also create unintended incentives depending on policy design. Zaklan (2023) notes that firms may respond strategically to anticipated changes in allocation rules, drawing on the theoretical argument of Harstad and Eskeland (2010) that when future free allocation depends on current emissions, firms may have incentives to maintain higher present emissions in anticipation of receiving additional allowances in the future. Policymakers may therefore reduce such distortions by increasing the share of auctioned allowances or reducing the frequency with which free allocations are updated.

More broadly, this thesis results complement earlier studies finding that carbon pricing contributed to technological adaptation and low-carbon innovation (Calel & Dechezleprêtre, 2016; Teixidó et al., 2019; Kim & Bae, 2022; Müller & Teixidó, 2021), suggesting that these broader adjustment processes may also manifest through gradual increases in RES across industrial sectors.

Taken together, the findings highlight an important distinction between emissions reductions and broader industrial energy transition. While much of the existing EU ETS literature focuses on emissions outcomes, competitiveness effects, or innovation, the results in this thesis suggest that carbon pricing may also contribute to changes in industrial energy systems themselves. In terms of the conceptual framework presented in Equation (1), firms appear able to reduce the carbon intensity of production through changes in the composition of energy inputs. Importantly, this implies that industrial energy transition need not occur exclusively through direct government intervention or changes in the broader electricity system. Although firms often have limited influence over the energy mix supplied through national grids, they retain considerable scope to alter the carbon intensity of their own operations. For example, firms may replace fossil-fuel-fired boilers with biomass systems for industrial process heat, invest in electrification technologies, install on-site renewable generation such as solar panels, or enter long-term renewable electricity purchase agreements. The findings therefore suggest that carbon pricing may support industrial decarbonization not only by encouraging lower emissions directly, but also by creating incentives for firms themselves to identify and implement cost-effective changes in their energy systems.

Finally, the results suggest that the effectiveness of emissions trading systems may depend not only on the level of the carbon price, but also on the extent to which firms face meaningful effective carbon-cost exposure. This relates to the Coasean independence property of cap-and-trade systems, which predicts that the initial allocation of allowances should not affect firms' abatement decisions, provided allowances can be traded efficiently and firms face the same carbon price. By contrast, the results of this thesis suggest that firms' effective allowance positions may still influence adjustment behaviour in practice. In particular, the larger estimated effects observed under the alternative nonnegative exposure specifications are consistent with the idea that persistent allowance overallocation may weaken incentives for industrial energy adjustment. This interpretation should, however, be treated cautiously, since firms holding surplus allowances may still face economically meaningful incentives through the opportunity cost of selling unused permits. Rather than contradicting the Coasean benchmark, the findings may instead reflect real-world frictions, policy uncertainty, or institutional features of the EU ETS that influence how firms respond to carbon pricing. The preferred baseline specification therefore suggests that both positive carbon-cost pressure and allowance positions may shape firms' adjustment incentives.

The findings should nevertheless be approached with care, since the empirical strategy does not fully eliminate potential endogeneity concerns related to allowance allocation, sector-specific technological change, and industrial energy demand. The estimated relationships should therefore be interpreted as evidence consistent with industrial energy adjustment under carbon pricing rather than definitive causal treatment effects.

10. Conclusion

This thesis examined whether effective carbon-cost exposure under the European Union Emissions Trading System (EU ETS) is associated with changes in renewable energy share(RES) across industrial sectors. Using panel data covering European industrial sectors between 2005 and 2024, the analysis combined sector-level exposure measures based on verified emissions and freely allocated allowances with EU ETS carbon prices to construct a continuous measure of effective carbon-cost exposure.

The empirical results suggest that sectors facing stronger carbon-cost exposure tend to exhibit higher RES. Although the estimated annual effects are relatively modest in magnitude, they remain positive across most specifications and robustness checks. Relative to the sample average RES of approximately 9.8 percent, the preferred specification implies that stronger ETS exposure is associated with economically meaningful, albeit gradual, increases in renewable energy use over time. The dynamic specifications further indicate that these adjustments unfold over multiple years rather than immediately.

These findings contribute to the growing literature on the EU ETS by shifting attention from emissions reductions, competitiveness effects, and innovation outcomes toward industrial energy transition itself. The results suggest that carbon pricing may not only encourage lower emissions, but may also contribute to gradual changes in the composition of industrial energy use. Importantly, the findings imply that firms retain some capacity to alter the carbon intensity of their own operations through decentralized investment and energy-use decisions, even in settings where they have limited influence over the broader electricity system.

At the same time, the results highlight the importance of policy design. The findings suggest that the effectiveness of emissions trading systems may depend not only on the level of the carbon price, but also on the extent to which firms face meaningful effective carbon-cost exposure. Persistent allowance overallocation may weaken incentives for industrial adjustment, while credible and predictable policy signals may encourage firms to undertake long-term investments and adapt production systems over time.

Several limitations remain. First, the exposure measure is unlikely to be fully exogenous, and broader technological, economic, and policy developments may simultaneously influence renewable energy adoption. Although the preferred specification includes country-sector fixed effects and a common linear time trend, it does not include year fixed effects. Consequently, discrete shocks affecting all sectors simultaneously may not be fully accounted for. The supplementary pre- and post-2013 analyses nevertheless suggest that the estimated relationship is not driven exclusively by the major institutional reforms associated with Phase III of the EU ETS.

Second, the sector-level nature of the data limits the ability to identify the precise mechanisms through which firms adjust their energy systems. The observed changes in renewable energy share may reflect a range of responses, including investments in on-site renewable generation, electrification of industrial processes, fuel switching toward biomass, or contractual changes in electricity procurement, none of which can be distinguished using the aggregated data employed in this study.

The estimated relationships should therefore be interpreted as evidence consistent with industrial energy adjustment under carbon pricing rather than as definitive causal treatment effects.

Future research could build on these findings by employing alternative identification strategies, exploiting exogenous policy variation, or using firm-level data to better identify the mechanisms through which carbon pricing influences industrial energy choices and renewable energy adoption.

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Appendix

Table 5.No small countries

VARIABLES	(1) Main	(2) No small countries	(3) Lag 1	(4) Lag 2	(5) Lag 3	(6) All lags
ETS-Exposure Approx. 1-year response	0.000216*	0.000251**				
	(0.000125)	(0.000125)				
Electricity price	0.000110	0.000193	0.000158	0.000180	0.000211	0.000212
	(0.000692)	(0.000681)	(0.000661)	(0.000669)	(0.000692)	(0.000649)
ln(GDP)	0.0605	0.0554	0.0532	0.0680	0.0911*	0.0886*
	(0.0428)	(0.0426)	(0.0433)	(0.0446)	(0.0492)	(0.0493)
Gas price	0.00000790	0.00000909	0.00000683	0.0000175	0.0000314	0.0000304
	(0.0000250)	(0.0000247)	(0.0000250)	(0.0000267)	(0.0000272)	(0.0000267)
Time trend	0.00271***	0.00254***	0.00252***	0.00206**	0.00164*	0.00148
	(0.000845)	(0.000822)	(0.000834)	(0.000864)	(0.000975)	(0.000933)
ETS-Exposure Approx. 2-year response			0.000352**			0.000208**
			(0.000163)			(0.000102)
ETS-Exposure Approx. 3-year response				0.000488**		0.000256
				(0.000217)		(0.000160)
ETS-Exposure Approx. 4-year response					0.000440*	0.0000821
					(0.000253)	(0.000112)
Constant	-6.114***	-5.722***	-5.657***	-4.908***	-4.341***	-3.994***
	(1.443)	(1.371)	(1.392)	(1.432)	(1.575)	(1.507)
Observations	2,457	2,403	2,384	2,256	2,121	2,110
R-squared	0.152	0.152	0.162	0.164	0.151	0.171
Number of country_sector_id	148	145	146	146	146	144
Country-sector FEs	YES	YES	YES	YES	YES	YES
Time trend	YES	YES	YES	YES	YES	YES
Controls	YES	YES	YES	YES	YES	YES
Clustered SEs	YES	YES	YES	YES	YES	YES

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 6. Sequential inclusion of control variable

VARIABLES	(1) Trend only	(2) + GDP	(3) + Electricity price	(4) + Gas price
ETS-Exposure Approx. 1-year response	0.000231*	0.000209*	0.000209*	0.000216*
	(0.000121)	(0.000121)	(0.000116)	(0.000125)
ln(GDP)		0.0463	0.0468	0.0605
		(0.0323)	(0.0326)	(0.0428)
Electricity price			0.000126	0.000110
			(0.000684)	(0.000692)
Gas price				0.00000790
				(0.0000250)
Time trend	0.00363***	0.00298***	0.00296***	0.00271***
	(0.000585)	(0.000653)	(0.000674)	(0.000845)
Constant	-7.215***	-6.474***	-6.438***	-6.114***
	(1.179)	(1.180)	(1.229)	(1.443)
Observations	3,078	2,945	2,800	2,457
R-squared	0.161	0.163	0.158	0.152
Number of country_sector_id	175	168	167	148
Country-sector FEs	YES	YES	YES	YES
Time trend	YES	YES	YES	YES
GDP	NO	YES	YES	YES
Electricity price	NO	NO	YES	YES
Gas price	NO	NO	NO	YES

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 7. Extended dynamic specifications

VARIABLES	(1) Lags 1-5
ETS-Exposure Approx. 1-year response	0.0000939
	(0.000140)
ETS-Exposure Approx. 2-year response	0.000492
	(0.000302)
ETS-Exposure Approx. 3-year response	-0.000137
	(0.000110)
ETS-Exposure Approx. 4-year response	-0.000181
	(0.0000896)
ETS-Exposure Approx. 5-year response	0.00000530
	(0.000134)
Electricity price	0.000236
	(0.000659)
ln(GDP)	0.0682
	(0.0441)
Gas price	0.0000148
	(0.0000249
Time trend	0.00263**
	(0.00104)
Constant	-6.067***
	(1.858)
Observations	1,874
Number of country_sector_id	144
R-squared	0.168
Country-sector FEs	YES
Time trend	YES
Controls	YES
Clustered SEs	YES

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 8. Non negative

VARIABLES	(1) Nonnegative	(2) Lag 1	(3) Lag 2	(4) Lag 3
ETS-Exposure Approx. 1-year response-nn	0.00126***			
	(0.000288)			
Electricity price	-0.0000214	-0.000153	-0.0000768	-0.00000952
	(0.000669)	(0.000660)	(0.000658)	(0.000672)
ln(GDP)	0.0348	0.0421	0.0641	0.0851*
	(0.0406)	(0.0402)	(0.0416)	(0.0466)
Gas price	-0.0000223	-0.0000264	-0.0000130	0.00000120
	(2.64e-05)	(0.0000271)	(0.0000271)	(0.0000260)
Time trend	0.00199***	0.00181**	0.00148*	0.00113
	(0.000736)	(0.000741)	(0.000792)	(0.000877)
ETS-Exposure Approx. 2-year response-nn		0.00147***		
		(0.000287)		
ETS-Exposure Approx. 3-year response-nn			0.00172***	
			(0.000320)	
ETS-Exposure Approx. 4-year response-nn				0.00266***
				(0.000517)
Constant	-4.363***	-4.082***	-3.684***	-3.251**
	(1.288)	(1.289)	(1.357)	(1.435)
Observations	2,457	2,439	2,309	2,173
R-squared	0.193	0.208	0.200	0.191
Number of country_sector_id	148	150	150	150
Country-sector FEs	YES	YES	YES	YES
Time trend	YES	YES	YES	YES
Controls	YES	YES	YES	YES
Clustered SEs	YES	YES	YES	YES

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 9. Positive only

VARIABLES	(1) (1) Positive only	(2) (2) Lag 1	(3) (3) Lag 2	(4) (4) Lag 3
ETS-Exposure Approx. 1-year response-Positive only	0.00113***			
	(0.000238)			
Electricity price	0.0000115	0.0000763	0.0000740	0.0000841
	(0.000707)	(0.000726)	(0.000710)	(0.000698)
ln(GDP)	-0.0257	-0.0193	-0.00457	-0.00880
	(0.0550)	(0.0573)	(0.0578)	(0.0585)
Gas price	-0.0000887	-0.0000826	-0.0000446	0.00000317
	(0.0000873)	(0.0000882)	(0.0000799)	(0.0000717)
Time trend	0.00431***	0.00458***	0.00464***	0.00578***
	(0.00147)	(0.00157)	(0.00162)	(0.00173)
ETS-Exposure Approx. 2-year response-Positive only		0.000945***		
		(0.000221)		
ETS-Exposure Approx. 3-year response-Positive only			0.000899***	
			(0.000258)	
ETS-Exposure Approx. 4-year response-Positive only				0.000651**
				(0.000304)
Constant	-8.268***	-8.906***	-9.204***	-11.44***
	(2.499)	(2.666)	(2.797)	(3.016)
Observations	1,223	1,220	1,192	1,145
R-squared	0.326	0.320	0.298	0.269
Number of country_sector_id	137	138	137	136
Country-sector FEs	YES	YES	YES	YES
Time trend	YES	YES	YES	YES
Controls	YES	YES	YES	YES
Clustered SEs	YES	YES	YES	YES

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 10. Separate estimations before and after the Phase III reforms

	(1) Pre-2013	(2) Post-2013
ETS-Exposure Approx. 1-year	-0.000184	0.000137
	(0.000134)	(0.000130)
Electricity price	-0.003310	0.000386
	(0.004484)	(0.000742)
ln(GDP)	-0.105059	0.026841
	(0.078348)	(0.039411)
Gas price	-0.000029*	0.000004
	(0.000017)	(0.000056)
Time trend	0.003795***	0.003724***
	(0.000905)	(0.001166)
Country-sector FEs	YES	YES
Observations	763	1,694
R-squared	0.081360	0.127276

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 11. Descriptive statistics excluding small countries

	Obs	Mean	SD	Median	Min	Max
RES	2942	0.095	0.174	0.004	0.000	0.954
Exposure	2942	-0.913	26.436	-0.013	-1396.000	1.000
Exposure,nn	2942	0.147	0.250	0.000	0.000	1.000
Exposure,ihs	2942	-0.101	0.632	-0.013	-7.935	0.881
ETS Exposure	2942	-0.305	23.688	-0.083	-521.231	84.875
ETS Exposure-nn	2942	5.025	12.140	0.000	0.000	84.875
Emissions	2942	19697.627	89918.784	2783.228	0.001	1341993.667
Allocated allowances	2942	14075.957	64274.938	2398.852	0.000	1306655.701
Electricity price	2674	1.066	4.211	0.207	0.079	50.005
Gas price	2410	88.469	231.818	22.607	9.224	1476.159
ln(GDP)	2809	12.420	1.325	12.403	9.574	14.945
Observations	2942					

Table 12. Mean-difference tests before and after 2013

Variable	Pre-2013 Mean	Post-2013 Mean	Difference (Pre−Post)	t-statistic
Renewable share	0.074	0.110	-0.037***	-5.40
Exposure (IHS)	-0.287	0.014	-0.301***	-12.92
Verified emissions	22,656	16,875	5,781*	1.74
Allocated allowances	23,618	8,110	15,508***	6.56
Obs	1068	2010		

(N = 3,078). *** p<0.01, ** p<0.05, * p<0.10.

Table 13. Sector harmonization between Eurostat and EU ETS classifications

Data ETS sectors	Eurostat data sector code
Combustion: electricity and heat generation	(TI_EHG_E)
Refineries:	(NRG_PR_E, TI_RPI_E)
Iron and steel:	(FC_IND_IS_E, TI_CO_E)
Other metals:	(FC_IND_NFM_E)
Non-metallic minerals:	(FC_IND_NMM_E)
Chemicals:	(FC_IND_CPC_E)
Pulp and paper:	(FC_IND_PPP_E)

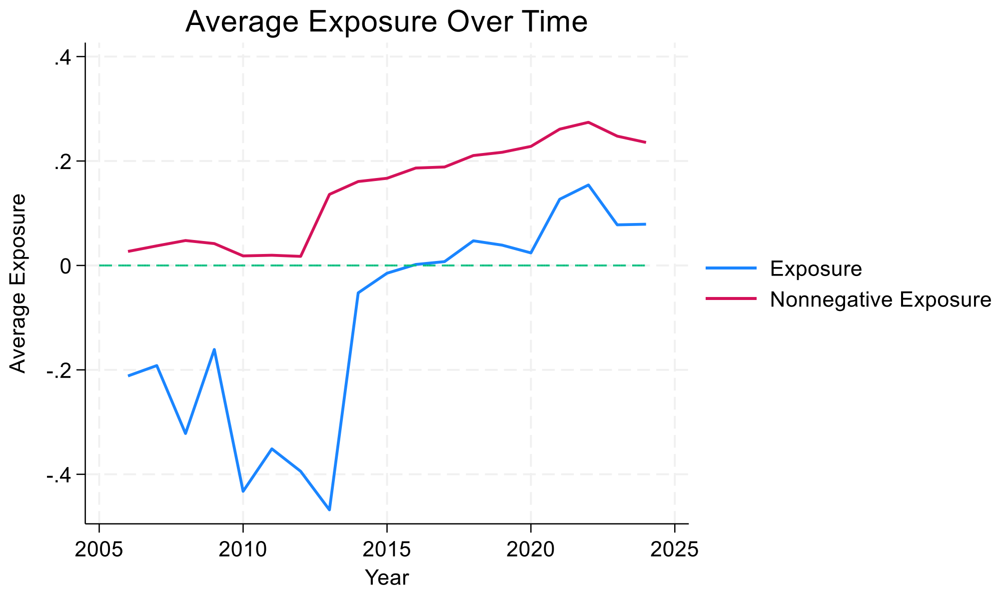

Figure 3.Average exposure for nn and with negative values

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