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Effectiveness of Carbon Pricing Policies in the EU

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Abstrakt

Die CO_2-Bepreisung ist ein zentrales Instrument der europäischen Klimapolitik, ihre Auswirkungen auf strukturelle Veränderungen in der Stromerzeugung sind jedoch weiterhin eine offene empirische Frage. Diese Masterarbeit untersucht, wie das Europäische Emissionshandelssystem (EU ETS) die Zusammensetzung der Stromproduktion in europäischen Ländern im Zeitraum von 1990 bis 2023 beeinflusst hat. Mithilfe eines Difference-in-Differences-Ansatzes werden zunächst Basiseffekte der Teilnahme am EU ETS sowie die Plausibilität der Parallel-Trends-Annahme analysiert. Anschließend wird die empirische Strategie erweitert, indem Heterogenität in der vorbestehenden CO_2-Intensität der Stromerzeugung genutzt wird, um unterschiedliche Exposition gegenüber einem gemeinsamen CO_2-Preissignal zu untersuchen. Durch die Einbeziehung aktualisierter Daten, die auch Phase IV des EU ETS abdecken, und die Betonung länderspezifischer Unterschiede in den Ausgangsstrukturen der Stromsysteme leistet die Arbeit einen Beitrag zum Verständnis, wie CO_2-Bepreisung mit nationalen Energiestrukturen interagiert und Anpassungsprozesse im Rahmen der europäischen Energiewende beeinflusst.

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1. Introduction

Climate change represents one of the most significant economic and societal challenges of the twenty-first century. Rising concentrations of greenhouse gases in the atmosphere have led to sustained increases in global average temperatures, contributing to more frequent and severe extreme weather events, sea-level rise, and biodiversity loss. These developments pose substantial risks to economic activity, public health, and long-term welfare, motivating increasingly ambitious climate policy interventions across the world (IPCC, 2021).

Among the major sources of greenhouse gas emissions, the electricity sector plays a central role. Power generation accounts for a large share of global carbon dioxide emissions, primarily due to the continued reliance on fossil fuels such as coal, oil, and natural gas. At the same time, the electricity sector offers considerable potential for decarbonization, as low-carbon alternatives, including renewable energy sources and nuclear power, are already technologically feasible at scale. As a result, policies that influence electricity generation decisions are widely viewed as critical components of any credible climate mitigation strategy (IEA, 2023).

In response to the climate externality, economists have long advocated the use of market-based instruments that internalize the social cost of carbon emissions. By placing a price on emissions, such instruments aim to align private decision-making with social objectives, encouraging emissions reductions where they can be achieved at lowest cost (Pigou, 1920; Stavins, 2008). Carbon pricing can take various institutional forms, most notably carbon taxes and emissions trading systems, both of which have been implemented in a growing number of jurisdictions over the past two decades (World Bank, 2023).

Within this broader policy landscape, the European Union Emissions Trading System (EU ETS) occupies a particularly prominent position. Introduced in 2005, the EU ETS represents the world's first large-scale, multinational cap-and-trade system and remains the cornerstone of European climate policy. The system covers energy-intensive sectors, most importantly electricity and heat generation, and imposes a binding cap on total emissions while allowing firms to trade emission allowances. By design, this framework is intended to achieve emissions reductions in a cost-effective manner by equalizing marginal abatement costs across regulated entities (Montgomery, 1972; European Commission, 2016).

Although the primary objective of the EU ETS is to reduce aggregate emissions, its effects may extend beyond emissions outcomes alone. In the electricity sector, carbon pricing directly affects the relative costs of different generation technologies. Carbon-intensive fuels, such as coal and lignite, become more expensive relative to lower-emission alternatives, such as natural gas, renewable energy, and nuclear power. As a result, carbon pricing has the potential to influence electricity dispatch decisions in the short run and investment decisions in the longer run, thereby altering the composition of electricity generation (Aghion et al., 2016; Bayer & Aklin, 2020).

Understanding whether carbon pricing induces such structural changes is of substantial policy relevance. Emissions reductions achieved through efficiency improvements or fuel switching within the fossil fuel category may differ in their long-term implications from reductions driven by a sustained expansion of low-carbon generation capacity. From a policy perspective, shifts in the energy mix are often viewed as more durable and politically salient indicators of progress toward decarbonization than short-run emissions responses alone (Acemoglu et al., 2012).

A growing empirical literature has examined the performance of the EU ETS along several dimensions, including emissions reductions, firm-level behavior, innovation, and economic efficiency. Early studies documented limited effects during the initial phases of the system, largely due to over-allocation of allowances and weak price signals (Ellerman & Buchner, 2008). More recent work, however, finds stronger evidence of emissions abatement and improved effectiveness following successive reforms and rising allowance prices (Bayer & Aklin, 2020; Dechezleprêtre et al., 2018).

Despite these advances, comparatively less attention has been devoted to the impact of the EU ETS on the composition of electricity generation itself. While some studies suggest that carbon pricing has contributed to fuel switching away from coal toward natural gas, evidence on broader shifts toward renewable energy remains mixed. This gap in the literature is notable, given the central role of the electricity sector in long-term decarbonization strategies and the EU's parallel use of renewable energy support policies (Aghion et al., 2016).

Recent work by Perdiguero and Sanz (2025) makes an important contribution by explicitly analyzing the effects of the EU ETS on the energy mix of European countries. Using a Difference-in-Differences framework combined with modern estimators designed to address staggered treatment adoption, they find that the EU ETS has increased the share of renewable electricity generation and reduced reliance on fossil fuels, particularly in later phases of the system. Their results suggest that carbon pricing can play a meaningful role in shaping electricity generation choices, complementing other climate and energy policies.

This thesis builds on and extends this line of research in two key respects. First, it re-examines the core empirical approach of Perdiguero and Sanz (2025) using updated data and an extended sample. Replication plays a crucial role in empirical economics, particularly in policy-relevant settings, by assessing the robustness and reproducibility of existing results. Second, the thesis introduces an extension that exploits heterogeneity in countries' exposure to a common carbon price. While all EU ETS countries face the same allowance price, they differ substantially in their baseline carbon intensity and electricity generation structure. This heterogeneity provides an additional source of variation that can be used to study differential responses to carbon pricing.

Methodologically, the analysis combines traditional two-way fixed effects Difference-in-Differences models with the multi-period estimator proposed by Callaway and Sant'Anna (2021), which explicitly accounts for treatment effect heterogeneity and staggered adoption. In addition, an exposure-based specification is employed that interacts the EU ETS allowance price with pre-treatment measures of carbon intensity. This approach allows for a more nuanced assessment of how carbon pricing affects electricity generation outcomes across countries with different initial conditions.

The empirical analysis focuses on electricity generation by source: fossil fuels, renewable energy, and nuclear power, as well as on carbon intensity measures of electricity production. The results provide evidence consistent with reductions in fossil-fuel-based electricity generation and increases in renewable energy shares in response to higher carbon prices, although the magnitude and statistical significance of these effects vary across specifications and phases of the EU ETS. Effects on nuclear generation are limited and difficult to identify due to structural constraints and limited variation. The exposure-based analysis further indicates that countries with more carbon-intensive electricity systems tend to respond more strongly to increases in the carbon price.

The remainder of the thesis is structured as follows. Section 2 reviews the relevant literature on carbon pricing, emissions trading systems, and electricity generation outcomes. Section 3 provides an overview of the institutional design and evolution of the European Union Emissions Trading System (EU ETS). Section 4 describes the data sources, variable construction, and sample selection. Section 5 presents exploratory descriptive evidence and assesses the plausibility of the parallel trends assumption underlying the Difference-in-Differences framework. Section 6 reports baseline empirical results using two-way fixed effects Difference-in-Differences methods and extends the analysis using the Callaway–Sant'Anna estimator. Section 7 introduces an exposure-based identification strategy that exploits heterogeneity in baseline carbon intensity and examines heterogeneous responses to changes in the EU ETS allowance price. Section 8 concludes.

2. Literature Review

2.1. Carbon pricing and the case for emissions trading

A central insight in environmental economics is that climate change constitutes a negative externality, implying that private production and consumption decisions generate social costs not reflected in market prices. Market-based instruments, such as emissions taxes and cap-and-trade systems, aim to internalize this externality by attaching an explicit cost to greenhouse gas emissions. In principle, pricing emissions can achieve a given environmental target at lower cost than prescriptive regulation by allowing abatement to occur where it is cheapest, and by equalizing marginal abatement costs across regulated entities (Pigou, 1920; Montgomery, 1972; Stavins, 2008; Aldy & Stavins, 2012). Within the family of market-based instruments, cap-and-trade systems provide quantity certainty via an emissions cap, while leaving the carbon price to be determined by market trading among regulated actors.

The EU ETS is often used in the literature as a leading case for evaluating whether emissions trading systems deliver emissions reductions, induce technology adoption and innovation, and promote structural change. A recurring theme is that the effectiveness of an ETS depends on institutional design and credibility, including allowance allocation, banking rules, and measures to address surplus allowances and price collapses (Ellerman et al., 2010; Bayer & Aklin, 2020). This design sensitivity makes the EU ETS a valuable setting for empirical work because it includes multiple phases with distinct institutional features and substantial price variation over time.

2.2. Evidence on emissions reductions from the EU ETS

A large empirical literature examines whether the EU ETS reduced emissions among regulated sectors and firms. Early work focused on Phase I, where over-allocation and weak price signals raised concerns about limited abatement incentives. Using the 2005–2006 emissions data, Ellerman and Buchner (2008) discuss whether observed outcomes reflect genuine abatement versus over-allocation. Ellerman et al. (2010) similarly evaluate the pilot phase and provide evidence consistent with emissions reductions relative to plausible counterfactual paths. Subsequent research has expanded the analysis to later phases and alternative empirical strategies, with evidence suggesting that stronger institutional design and higher allowance prices are associated with more pronounced emissions reductions (Bayer & Aklin, 2020; Dechezleprêtre et al., 2018).

More recent contributions provide evidence that the EU ETS reduced CO_2 emissions despite periods of low allowance prices. Bayer and Aklin (2020), for example, estimate statistically significant emissions reductions and argue that the system was effective even when prices were relatively modest, highlighting the role of credibility and expectations. A related strand of work examines firm-level responses and finds that regulated firms reduced emissions and adjusted production processes, often through improvements in carbon intensity and technology choices rather than large-scale output contractions (Dechezleprêtre et al., 2018; Martin et al., 2016). This line of evidence suggests that the EU ETS can generate real abatement, although magnitudes and channels may differ by sector and time period.

2.3. Firm behavior, competitiveness, and leakage-related design

Beyond emissions outcomes, the literature has investigated whether emissions trading harms competitiveness or induces carbon leakage, and how allowance allocation affects firm behavior. In the EU context, free allocation was initially motivated in part by leakage concerns and political feasibility. Empirical work often concludes that leakage effects were limited in early phases, though results depend on the sector and identification strategy, and the policy debate has remained active (Ellerman et al., 2010; Dechezleprêtre et al., 2018; Martin et al., 2016).

Related contributions examine pass-through of carbon costs into electricity prices and output prices, with the power sector frequently highlighted as a key channel through which carbon pricing can affect the broader economy due to the central role of electricity as an intermediate input (Sijm et al., 2006; Fabra & Reguant, 2014).

This literature is relevant for energy mix outcomes because competitiveness and pass-through shape the strength of the carbon price signal faced by power producers and industrial consumers. If carbon costs are passed through to electricity prices, electricity producers face incentives to shift dispatch away from carbon-intensive technologies, while electricity consumers may adjust demand. Conversely, if policy design weakens effective pass-through or dilutes incentives (e.g., through excess allowance supply), compositional effects on electricity generation may be more muted (Ellerman et al., 2010; Bayer & Aklin, 2020).

2.4. Innovation and low-carbon technological change

A prominent hypothesis in climate policy research is that carbon pricing can stimulate low-carbon innovation by increasing the relative returns to clean technologies. Empirical evidence on this channel is mixed and sensitive to institutional design and time horizons. Calel and Dechezleprêtre (2016) provide evidence that the EU ETS increased low-carbon patenting among regulated firms, suggesting that carbon pricing can influence innovation incentives.

At the same time, several studies emphasize that early phases of the EU ETS, characterized by low and volatile allowance prices and generous free allocation, may have been insufficient to generate strong investment or innovation responses, particularly for capital-intensive technologies (Ellerman et al., 2010; Aghion et al., 2016). This distinction is important for interpreting energy mix outcomes, as innovation and investment responses typically unfold over long time horizons, while short-run adjustments may instead reflect changes in dispatch or fuel switching within existing capacity.

2.5. From emissions to the energy mix: why electricity is different

While a substantial literature documents emissions impacts of carbon pricing, fewer studies explicitly examine how such policies affect the *composition* of energy use and electricity generation. This distinction matters because emissions reductions can arise through multiple channels, including fuel switching within fossil generation, efficiency improvements, changes in output, or expansion of low-carbon technologies. From a policy perspective, compositional changes in the electricity mix are often viewed as more structural and potentially more persistent than short-run efficiency gains alone (Bayer & Aklin, 2020).

The electricity sector is a particularly relevant setting for studying compositional effects of carbon pricing for several reasons. First, electricity generation technologies differ sharply in carbon intensity, making carbon prices a potentially powerful determinant of relative costs. Second, electricity dispatch is largely governed by marginal cost considerations and system constraints, allowing price signals to translate into operational changes even in the absence of immediate investment. Third, electricity systems are shaped by country-specific infrastructure and legacy generation portfolios, implying that identical carbon prices may generate heterogeneous responses across countries depending on baseline carbon intensity and fuel availability (Ellerman et al., 2010; Perdiguero & Sanz, 2025).

2.6. Positioning of this thesis within the literature

Taken together, the literature provides substantial evidence that emissions trading systems can reduce emissions, with the EU ETS serving as the most prominent case study. However, the mechanisms through which these reductions occur, particularly whether they involve durable changes in the composition of electricity generation, remain an area where additional empirical evidence is valuable. Building on Perdiguero and Sanz (2025), this thesis revisits their empirical framework and extends the analysis in two dimensions: by incorporating more recent data covering Phase IV of the EU ETS and by exploiting heterogeneity in baseline carbon intensity to study differential exposure to a common carbon price. In doing so, it sheds light on how electricity-sector adjustment varies across countries with different initial conditions.

3. The European Union Emissions Trading System (EU ETS)

The European Union Emissions Trading System (EU ETS) is the European Union's central market-based instrument for reducing greenhouse gas emissions and constitutes the cornerstone of EU climate policy. It was launched in 2005 and represents the first large-scale, multinational emissions trading system in the world (European Commission, 2016). Cap-and-trade systems such as the EU ETS are designed to reduce emissions in a cost-effective manner by placing a price on carbon emissions and allowing regulated entities to trade emission allowances within a capped framework (Stavins, 2008).

The economic rationale behind the EU ETS is rooted in the Pigouvian framework, which argues that pricing negative externalities leads to socially efficient outcomes by aligning private incentives with social costs (Pigou, 1920; Stavins, 2008). By assigning a monetary cost to emitting carbon dioxide, the EU ETS incentivizes firms to reduce emissions where abatement costs are lowest and encourages investment in cleaner production technologies (Aldy & Stavins, 2012). In contrast to command-and-control regulation, emissions trading systems allow for flexibility in compliance, thereby reducing aggregate compliance costs while achieving a given environmental target (Montgomery, 1972).

3.1. Cap-and-trade mechanism and price formation

The EU ETS operates under a cap-and-trade mechanism. A fixed cap is set on the total amount of greenhouse gas emissions that can be emitted by installations covered by the system. Within this cap, firms receive or purchase emission allowances, each of which grants the right to emit one tonne of CO_2 (European Commission, 2016). At the end of each compliance period, firms are required to surrender allowances equal to their verified emissions, with penalties imposed for non-compliance (European Commission, 2016).

Allowances are tradable, meaning firms with low abatement costs can reduce emissions and sell excess allowances, while firms facing higher abatement costs can purchase allowances instead of undertaking costly emission reductions (Stavins, 2008). This trading mechanism ensures that emission reductions occur where they are cheapest, equalizing marginal abatement costs across firms and sectors (Montgomery, 1972). The market price of allowances thus reflects the marginal cost of emissions abatement within the system and serves as the central economic signal of the EU ETS (Aldy & Stavins, 2012).

3.2. Sectoral and geographic coverage

The EU ETS covers emissions from energy-intensive sectors where emissions can be reliably monitored, reported, and verified. These sectors include electricity and heat generation, oil refineries, steel, cement, chemicals, glass, pulp and paper, and commercial aviation (European Commission, 2016). The electricity sector plays a particularly important role, as it accounts for a large share of emissions covered by the system and exhibits relatively high potential for fuel switching and technological substitution (Perdiguero & Sanz, 2025).

Geographically, the EU ETS applies to all EU Member States as well as Iceland, Liechtenstein, and Norway, forming a unified carbon market across the European Economic Area (European Commission, 2016). In total, the system regulates approximately 45% of total EU greenhouse gas emissions and includes around 11,000 installations, making it one of the most comprehensive carbon pricing schemes globally (European Commission, 2016).

The broad coverage of the EU ETS implies that its effects extend beyond emissions reductions alone and can influence production decisions, energy input choices, and long-run investment patterns across participating countries (Bayer & Aklin, 2020). This is particularly relevant for the electricity sector, where generation technologies with different carbon intensities directly compete within integrated electricity markets.

3.3. Allowance allocation: auctioning and free allocation

A key design feature of the EU ETS is the method of allowance allocation. In the early phases of the system, a substantial share of allowances was allocated for free, primarily to address competitiveness concerns and to facilitate political acceptance of the policy (Ellerman et al., 2010). Over time, the system has progressively shifted toward auctioning as the default allocation method, especially for electricity generation (European Commission, 2016).

Auctioning is generally considered the most efficient allocation mechanism, as it ensures that firms fully internalize the cost of emissions and avoids windfall profits associated with free allocation (Aldy & Stavins, 2012). Revenues generated from auctions can also be used to finance climate-related investments, energy efficiency measures, or to mitigate distributional impacts (European Commission, 2016).

Despite this shift, free allocation remains an important component of the EU ETS for sectors deemed to be at significant risk of carbon leakage. Carbon leakage refers to the relocation of production to jurisdictions with weaker climate policies, potentially undermining the environmental effectiveness of the system (Aldy & Stavins, 2012). Free allocation in the EU ETS is benchmark-based, meaning that more efficient installations receive relatively more allowances, thereby preserving incentives for efficiency improvements even in sectors receiving free permits (European Commission, 2016).

3.4. Evolution of the EU ETS across trading phases

The EU ETS has undergone several reforms since its inception, reflecting policy learning and responses to observed market outcomes. These reforms are typically structured into distinct trading phases, each characterized by different design features and levels of stringency.

Phase I (2005–2007) is commonly described as a "learning-by-doing" phase. Allowance caps were largely based on national allocation plans, which led to an over-allocation of permits and a collapse of allowance prices toward the end of the phase (Ellerman & Buchner, 2008).

Phase II (2008–2012) introduced tighter caps and coincided with the first commitment period of the Kyoto Protocol. However, the global financial crisis substantially reduced economic activity and emissions, leading to a persistent surplus of allowances and continued price weakness (Bel & Joseph, 2015). This experience highlighted the sensitivity of emissions trading systems to macroeconomic conditions.

Phase III (2013–2020) marked a major reform of the EU ETS. An EU-wide cap replaced national caps, auctioning became the default allocation method, and the cap was set to decline annually by 1.74% (European Commission, 2016). Nevertheless, the legacy surplus of allowances continued to depress prices until further interventions were introduced.

To address structural imbalances, the EU introduced the Market Stability Reserve (MSR), which began operating in 2019. The MSR automatically adjusts the supply of allowances in response to market conditions, enhancing the resilience of the system to economic shocks and improving the credibility of the carbon price signal (European Commission, 2016; Bayer & Aklin, 2020).

Phase IV (2021–2030) further strengthens the EU ETS by increasing the annual linear reduction factor of the emissions cap to 2.2 percent, reflecting a higher level of ambition consistent with the EU's long-term climate objectives (European Union, 2018). Although the full effects of Phase IV lie beyond the time horizon of some empirical analyses, the increased stringency of the system may influence expectations and long-term investment decisions in the power sector.

3.5. EU ETS, electricity generation, and energy mix adjustment

Although the primary objective of the EU ETS is emissions reduction, the system can indirectly affect the composition of electricity generation. By increasing the relative cost of carbon-intensive fuels, such as coal and lignite, the EU ETS alters dispatch decisions and encourages fuel switching toward less carbon-intensive options, including natural gas and renewable energy sources (Ellerman et al., 2010; Perdiguero & Sanz, 2025).

Empirical evidence suggests that the EU ETS has contributed to a reduction in fossil fuel use and an increase in renewable electricity generation, particularly in later phases when allowance prices increased substantially (Bayer & Aklin, 2020; Perdiguero & Sanz, 2025). These effects are expected to be heterogeneous across countries, depending on baseline energy mixes, carbon intensity, and the availability of alternative generation technologies.

Importantly, the EU ETS operates alongside other EU climate and energy policies, most notably renewable energy directives that mandate minimum shares of renewables in final energy consumption. These overlapping policies complicate causal attribution and motivate empirical strategies that explicitly account for concurrent policy interventions (Perdiguero & Sanz, 2025).

3.6. Implications for empirical identification

Two institutional characteristics of the EU ETS are particularly relevant for the empirical analysis conducted in this thesis. First, the system imposes a common carbon price across participating countries (European Commission, 2016). However, countries differ substantially in their exposure to this price due to variation in energy structure and baseline carbon intensity. Differences in electricity generation portfolios across countries are emphasized in prior work (Perdiguero & Sanz, 2025). Second, the stringency of the system evolves over time, implying that responses to carbon pricing may differ across phases as the allowance price signal strengthens.

These features motivate empirical approaches that exploit heterogeneity in exposure to carbon pricing rather than relying solely on binary treatment indicators, and they provide a strong institutional foundation for analyzing how carbon pricing influences both energy mix and carbon intensity outcomes in the electricity sector.

4. Data

This section describes the data sources, variable construction, country coverage, and sample structure used in the empirical analysis. The focus is on electricity generation by source, carbon intensity of electricity production, and carbon pricing indicators, which together allow an assessment of how carbon pricing policies relate to changes in the energy mix and emissions intensity of the power sector.

4.1. Country coverage and treatment definition

The empirical analysis is conducted at the country–year level and focuses on European countries subject to the EU Emissions Trading System (EU ETS), complemented by a small group of non-EU ETS countries used as a control group.

The treated group consists of:

- All European Union Member States, and
- Norway and Iceland, which participate in the EU ETS through the European Economic Area (EEA) agreement.

These countries are fully integrated into the EU ETS and face the common carbon allowance price determined in the EU-wide market (European Commission, 2016).

The control group consists of:

- Serbia,
- Turkey,
- North Macedonia, and
- Albania.

According to official EU ETS scope and participation lists published by the European Commission, none of the control countries participated in the EU Emissions Trading System during the sample period considered in this study (European Commission, 2016).

These non-EU ETS countries are closely connected to the European electricity system through cross-border trade and regulatory alignment. In particular, several Western Balkan countries are members of the Energy Community, which aims to integrate their electricity markets with the EU internal energy market by adopting EU energy acquis and market rules (Energy Community Secretariat, 2023). Turkey is also physically interconnected with the European electricity network through European Network of Transmission System Operators for Electricity (ENTSO-E), allowing for electricity trade and transmission coordination with EU Member States (ENTSO-E, 2023).

4.2. Electricity generation by source

Electricity generation data are obtained from Eurostat's energy balances, specifically the dataset on gross electricity production by type of, which provides harmonized annual data across European countries (Eurostat, 2024).

Electricity generation chosen for this analysis is disaggregated into the following categories:

- Fossil fuels
- Nuclear energy, and
- Renewable energy sources

Using these data, three key outcome variables are constructed:

1. The share of renewable electricity generation,
2. The share of fossil-fuel-based electricity generation, and
3. The share of nuclear electricity generation.

Each share is computed as the ratio of electricity generated from a given source to total gross electricity generation in a given country and year. Focusing on shares rather than absolute levels allows for comparability across countries with different electricity system sizes and isolates changes in the composition of electricity production rather than changes driven purely by demand growth or contraction (Perdiguero & Sanz, 2025).

The electricity generation data cover the period 1990–2023 and form the backbone of both the exploratory analysis and the regression-based results.

4.3. Carbon intensity of electricity generation

Carbon intensity of electricity generation is measured as CO_2 emissions per unit of electricity produced (gCO_2/kWh). The data are obtained from EMBER, an independent energy and climate data provider that compiles electricity-sector emissions intensity indicators using a combination of sources, including Eurostat, national energy exchanges, IPCC emission factors, UNECE data, and country-specific energy statistics (EMBER, 2024).

Carbon intensity data are available from 2000 onward. To construct a pre-treatment measure of structural carbon exposure, the country-specific average carbon intensity over the period 2000–2004 is calculated and used as a baseline indicator in the subsequent empirical analysis. This baseline measure captures cross-country differences in the carbon intensity of electricity generation prior to the implementation of the EU ETS.

4.4. Carbon allowance prices

Historical EU ETS allowance price data are obtained from official European Environment Agency and European Commission publications, which report annual average prices for EU Allowances (EUAs) traded in the EU ETS market (European Environment Agency, 2024).

The allowance price reflects the marginal cost of emitting one tonne of CO_2 within the EU ETS and is the key policy variable through which carbon pricing affects firm behavior (European Commission, 2016). In the empirical analysis, the allowance price is used in interaction with country-specific measures of exposure, such as baseline carbon intensity, to capture heterogeneous responses to a common carbon price signal.

4.5. Sample structure and summary

The empirical analysis relies on multiple purpose-built datasets, each constructed as a balanced country–year panel tailored to a specific part of the analysis. The baseline Difference-in-Differences and Callaway–Sant'Anna estimations are conducted using a balanced panel covering the full period from 1990 onward, restricted to countries for which electricity generation data by source are jointly available.

The exposure-based analysis exploiting heterogeneous responses to the EU ETS allowance price is based on a separate balanced panel beginning in 2000, reflecting the earliest availability of carbon intensity data. This panel is restricted to EU ETS countries for which carbon intensity and allowance price data are jointly available.

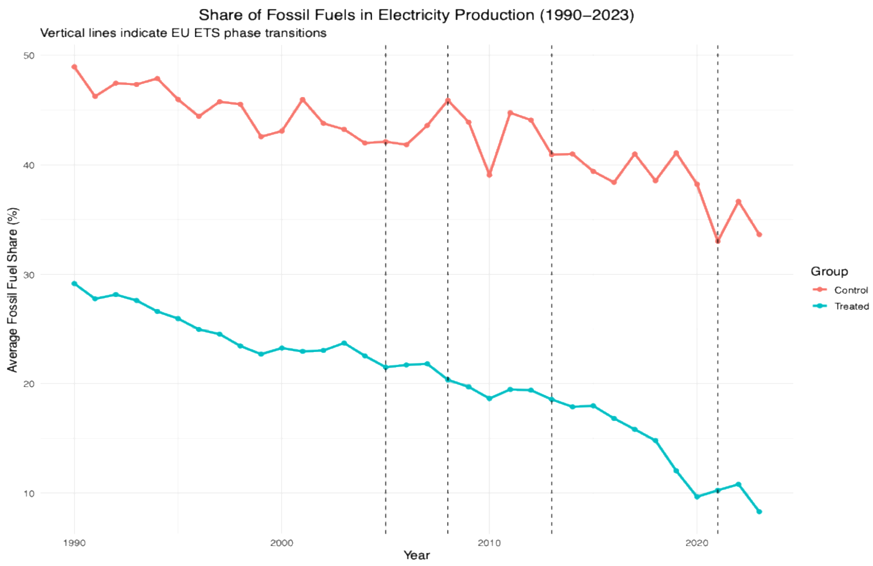
The use of specification-specific balanced panels ensures internal consistency within each empirical exercise while allowing the analysis to utilize the longest possible time horizon where data permit.

5. Exploratory Analysis and Parallel Trends Assessment

A central identifying assumption of the Difference-in-Differences (DiD) framework is that, in the absence of treatment, the outcome variables for treated and control groups would have evolved along parallel trends over time (Angrist & Pischke, 2009; Callaway & Sant'Anna, 2021). In this context, the assumption implies that, prior to the introduction of the EU Emissions Trading System (EU ETS), trends in electricity generation shares would have evolved similarly in EU ETS countries and in the selected non-EU ETS control countries.

Given the central role of this assumption, this section presents both graphical and statistical evidence on pre-treatment trends for the three main outcome variables: the share of fossil fuels, the share of renewable energy, and the share of nuclear energy in electricity production.

5.1. Graphical evidence of pre-treatment trends

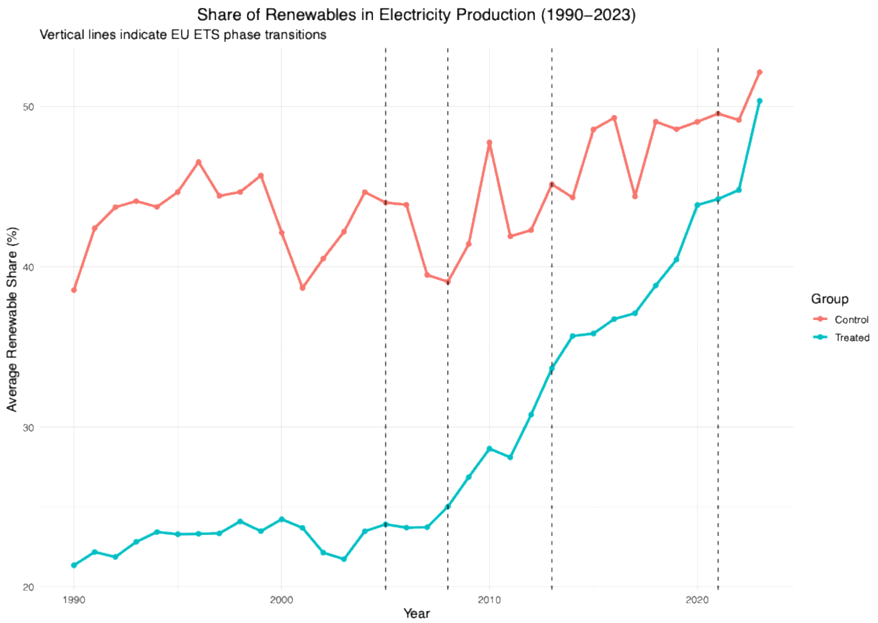


Source: Own elaboration

Figure 1: Share of Fossil Fuels in Electricity productions (1990-2023), treated vs control, with EU ETS phase markers)

Figure 1 presents the evolution of the average fossil fuel share in electricity production for EU ETS (treated) countries and non-EU ETS (control) countries over the period 1990–2023. Prior to the introduction of the EU ETS in 2005, the treated and control groups exhibit broadly similar trends in fossil fuel shares, with both groups displaying gradual changes over time. While levels differ across groups, the pre-treatment trajectories appear relatively parallel, providing preliminary graphical support for the parallel trends assumption underlying the Difference-in-Differences framework.

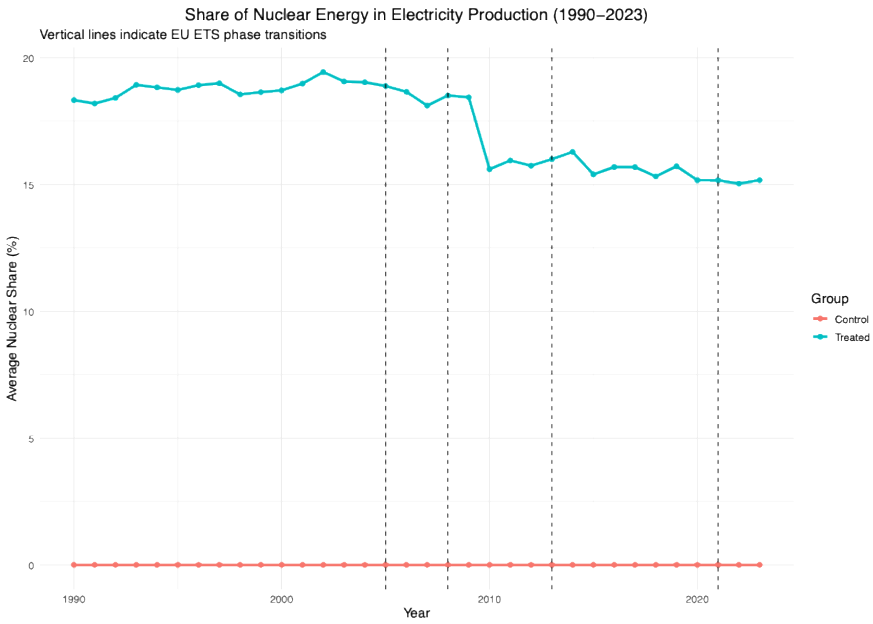
Following the introduction of the EU ETS, fossil fuel shares decline in both groups, although the magnitude and timing of these changes vary across phases. Vertical lines indicate the transition between EU ETS trading phases.



Source: Own elaboration

Figure 2: Share of Renewables in Electricity productions (1990-2023), treated vs control, with EU ETS phase markers)

Figure 2 presents the evolution of renewable energy shares in electricity production for treated and control countries over the period 1990–2023. Prior to 2005, renewable shares in the two groups follow broadly similar trajectories, with the control group exhibiting higher average levels and slightly more volatility but no huge divergence in pre-treatment trends. After 2005, renewable shares increase in both groups; however, treated countries experience a stronger rise, gradually reducing the gap relative to the control group over time.



Source: Own elaboration

Figure 3: Share of Nuclear Energy in Electricity productions (1990-2023), treated vs control, with EU ETS phase markers)

Figure 3 presents the evolution of nuclear energy shares in electricity production for treated and control countries over the period 1990–2023. Unlike fossil fuels and renewables, nuclear generation is observed only in the treated group, while the control group exhibits virtually no nuclear output throughout the sample period. As a result, cross-group comparisons of pre-treatment trends are inherently limited.

Within the treated group, nuclear shares fluctuate moderately over time but do not exhibit sharp changes around the introduction of the EU ETS in 2005. The absence of nuclear generation in the control group constrains the applicability of the standard parallel trends assessment for this outcome and limits the informativeness of a treated-versus-control Difference-in-Differences comparison.

While graphical inspection may suggest differences in pre-treatment levels or slopes, such visual deviations do not necessarily imply violations of the parallel trends assumption once fixed effects and common time shocks are accounted for, particularly in small samples (Roth et al., 2023).

5.2. Statistical tests of parallel trends

Table 1

Parallel trends regression results for nuclear, renewable, and fossil fuel shares

	Fossil Share	Renewables Share	Nuclear Share
Pre-trend interaction (yearxtreated)	-0.078	0.077	0.052
	(0.850)	(0.926)	(0.734)
Number of Observation	495	495	495

*p<0.1, **p<0.05, ***p<0.01

Source: Own elaboration

To formally test for differential pre-treatment trends, Table 1 reports regression-based parallel trends tests for fossil fuel, renewable, and nuclear electricity shares using only pre-treatment observations. The reported coefficients correspond to the interaction between a linear time trend and the treatment indicator, capturing whether treated countries exhibit statistically different trends prior to the introduction of the EU ETS.

Across all three outcome variables, the estimated pre-trend interaction coefficients are statistically insignificant, indicating no evidence of differential trends between treated and control countries before treatment.

From an econometric perspective, these results imply that the null hypothesis of parallel trends cannot be rejected for any of the three outcomes. However, failure to reject the null of parallel trends should not be interpreted as evidence of equivalence of trends, particularly in settings with a small and structurally distinct control group, where statistical power may be limited (Roth et al., 2023).

5.3. Implications for identification strategy

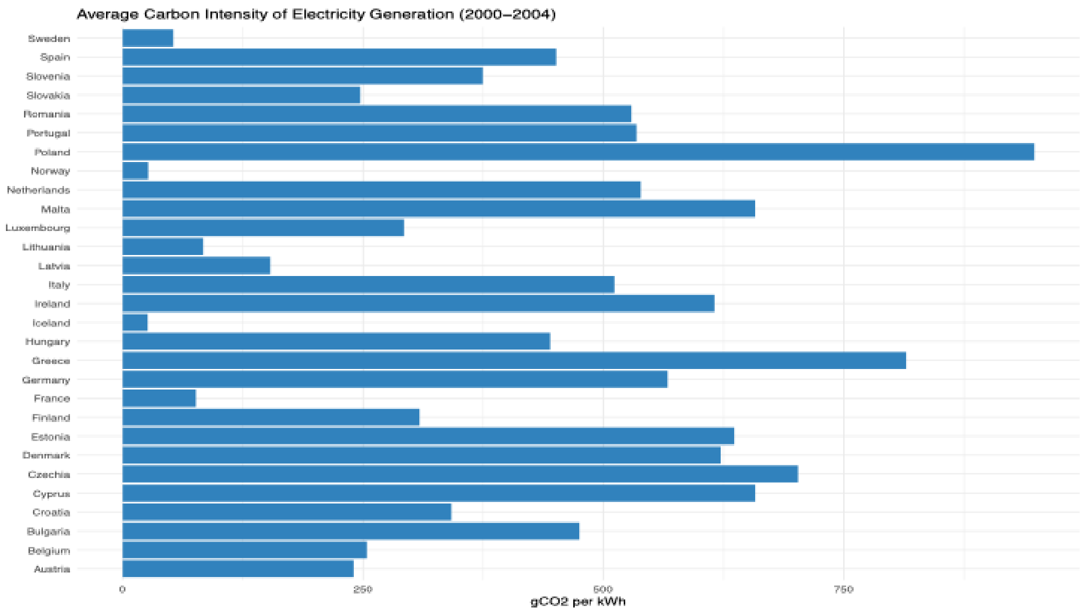
Interpretation of both graphical and statistical evidence must account for the small and structurally distinct control group, which motivates the complementary identification strategy based on heterogeneous exposure to a common carbon price developed in Section 7.

Overall, the graphical inspection and regression-based pre-trend tests provide no evidence of differential pre-treatment trends across outcomes. Although level differences are present, particularly for renewable and fossil fuel shares, these appear relatively stable prior to 2005 and do not suggest sharply diverging trajectories. Taken together, the parallel trends assumption underlying the baseline Difference-in-Differences framework appears plausible for an initial analysis.

5.4 Baseline Carbon Intensity

Figure 4 presents the average carbon intensity of electricity generation across EU ETS countries during the pre-ETS period (2000–2004). The figure reveals substantial cross-country variation in baseline carbon intensity, with some countries exhibiting highly carbon-intensive electricity systems while others display comparatively low emissions per unit of electricity generated.

This dispersion reflects differences in generation technologies and pre-existing energy mixes prior to the introduction of the EU ETS. The marked heterogeneity in baseline carbon intensity provides a useful descriptive foundation for the exposure-based analysis developed in Section 7.



Source: Own elaboration

Figure 4: Average carbon intensity of electricity generation (2000-2004)

6. Main Findings

6.1. Baseline Difference-in-Differences Results: Two-Way Fixed Effects

This subsection presents the baseline empirical results obtained from a two-way fixed effects (TWFE) Difference-in-Differences (DiD) specification. While the TWFE Difference-in-Differences estimator provides a useful benchmark, its estimates should be interpreted with caution in settings where treatment effects may vary across groups and over time (Callaway & Sant'Anna, 2021). The aim is to assess how the introduction and evolution of the European Union Emissions Trading System (EU ETS) are associated with changes in the composition of electricity generation across fossil fuels, renewable energy, and nuclear energy.

Empirical specification

The baseline regression model is specified as follows:

$$
\begin{aligned}
Y_{it} = {} & \beta_0 + \beta_j \text{Phase1}_{it} + \beta_k \text{Phase2}_{it} + \beta_l \text{Phase3}_{it} + \beta_m \text{Phase4}_{it} \\
& + \gamma_0(\text{Treated}_i \times \text{Phase1}_{it}) + \gamma_p(\text{Treated}_i \times \text{Phase2}_{it}) \\
& + \gamma_q(\text{Treated}_i \times \text{Phase3}_{it}) + \gamma_r(\text{Treated}_i \times \text{Phase4}_{it}) + \beta_n \text{EUDir}_{it} + \theta_i \\
& + \delta_t + \varepsilon_{it}
\end{aligned}
$$

The dependent variable Y_{it} represents the share of electricity generation from a given source: fossil fuels, renewable energy or nuclear energy in country i and year t. Separate regressions are estimated for each outcome.

The indicator Treated_i takes the value one for countries participating in the EU ETS (EU Member States, Norway, and Iceland) and zero for non-EU ETS control countries (Serbia, Turkey, North Macedonia, and Albania). The variables Phase1_{it} to Phase4_{it} are dummy variables corresponding to the four phases of EU ETS implementation. The interaction terms between Treated_i and each phase dummy capture the differential change in electricity generation shares in EU ETS countries relative to control countries during each phase, compared to the pre-treatment period.

The variable EUDir_{it} is a dummy that equals one for EU countries during the period 2010–2020, corresponding to the implementation of EU renewable energy directives. Country fixed effects (θ_i) control for time-invariant country characteristics, while year fixed effects (δ_t) absorb common shocks affecting all countries. Standard errors (ε_{it}) are clustered at the country level to account for serial correlation within countries over time.

The coefficients of interest are $\gamma_0, \gamma_p, \gamma_q$, and γ_r, which represent the DiD estimates for each EU ETS phase.

Table 2
Difference-in-differences

	Fossil Share	Renewables Share	Nuclear Share
Dnd_phase1	-0.006	0.015	-0.002
	(0.022)	(0.036)	(0.007)
Dnd_phase2	-0.019	0.045	-0.005
	(0.031)	(0.042)	(0.009)
Dnd_phase3	-0.009	0.088**	-0.007
	(0.065)	(0.041)	(0.010)
Dnd_phase4	-0.044	0.163***	-0.037
	(0.098)	(0.040)	(0.030)
EuDir	-0.032	0.018	-0.024
	(0.033)	(0.022)	(0.023)
Controlling by year	YES	YES	YES
Controlling by country	YES	YES	YES
Controlling by time	YES	YES	YES
No Obs.	1122	1122	1122

*$P<0.1$ **$P<0.05$, ***$P<0.01$

Source: Own elaboration

Fossil fuel share

The estimated coefficients for fossil fuel shares are negative across all EU ETS phases, suggesting a relative decline in the fossil-fuel share of electricity generation in EU ETS countries compared to control countries. The magnitude of the estimates increases over time, from −0.006 in Phase 1 (−0.6 percentage points) to −0.044 in Phase 4 (−4.4 percentage points).

However, none of these coefficients are statistically significant at conventional levels. As such, the baseline TWFE specification does not provide statistically robust evidence of a reduction in fossil fuel generation shares attributable to the EU ETS. While the pattern of coefficients is directionally consistent with theoretical expectations, the absence of statistical significance implies that these results should be interpreted cautiously.

Renewable energy share

The results for renewable energy shares exhibit a markedly different pattern. The estimated coefficients are positive in all phases and increase over time. In Phase 1, the estimated increase in renewable share is 0.015 (1.5 percentage points) and statistically insignificant. In Phase 2, the magnitude rises to 0.045 (4.5 percentage points) but remains statistically insignificant.

A statistically significant effect emerges in Phase 3, where the renewable share increases by approximately 0.088 (8.8 percentage points) in EU ETS countries relative to control countries. This effect is significant at conventional levels. In Phase 4, the estimated increase reaches 0.163 (16.3 percentage points) and is statistically significant at the 1% level.

Economically, these magnitudes are substantial. An increase of over 16 percentage points in the renewable share represents a large compositional shift in the electricity mix. The strengthening of estimated effects across phases is consistent with the increasing stringency and credibility of the EU ETS over time. Importantly, because the dependent variable is expressed as a share of total electricity generation, these estimates reflect compositional adjustments within the electricity mix rather than absolute increases in renewable output.

Nuclear energy share

For nuclear energy, the estimated coefficients are negative across all phases, ranging from −0.002 to −0.037, but none are statistically significant. The estimated magnitudes are relatively small compared to those observed for renewable shares.

These findings should be interpreted in light of structural features of nuclear generation. Nuclear electricity production is largely determined by long-term investment decisions and national energy policies, including phase-out programs in some EU countries. Moreover, the control countries in the sample do not operate nuclear power plants, limiting cross-group variation and constraining the interpretability of the DiD estimates for this outcome.

Accordingly, the baseline TWFE results do not provide statistically robust evidence of a systematic relationship between the EU ETS and nuclear electricity generation. The absence of statistical significance likely reflects limited identifying variation rather than definitive evidence of no effect.

6.2. Difference-in-Differences with Multiple Time Periods: Callaway–Sant'Anna Estimator

While the two-way fixed effects (TWFE) Difference-in-Differences estimator provides a useful benchmark, recent econometric literature highlights that its interpretation can be challenging in settings with staggered treatment adoption and heterogeneous treatment effects (Callaway & Sant'Anna, 2021). In such contexts, TWFE estimates may combine treatment effects across cohorts and time periods in ways that obscure underlying heterogeneity.

To address these concerns, this subsection applies the Difference-in-Differences estimator proposed by Callaway and Sant'Anna (2021), which explicitly accounts for staggered treatment timing and allows treatment effects to vary across cohorts and over time by constructing group-time average treatment effects on the treated (ATT). Treated cohorts are defined by the timing of EU ETS participation across different phases, while non-EU ETS countries serve as the control group.

The Callaway–Sant'Anna framework produces both dynamic event-study estimates and aggregate ATT estimates. The dynamic specification traces treatment effects relative to the year of treatment, while the aggregate ATT summarizes the average post-treatment effect across treated units. These estimates serve as a robustness check to the TWFE results by relaxing the homogeneity assumptions embedded in the standard fixed-effects framework.

In the present application, the aggregate ATT estimates are statistically insignificant across electricity generation outcomes. The dynamic event-study estimates similarly do not reveal statistically significant post-treatment effects, nor do they indicate systematic violations of pre-treatment trends. For brevity, the full set of aggregate estimates and event-study figures is reported in Appendix B.

Given the absence of robust aggregate effects in the binary-treatment framework and the relatively small external control group, the analysis proceeds by exploiting continuous heterogeneity in exposure to a common carbon price. This exposure-based approach, developed in Section 7, provides a complementary perspective on how carbon pricing influences electricity generation outcomes across countries with different baseline carbon intensities.

7. Extension: Exploiting Heterogeneous Exposure to the EU ETS

The analyses presented in Section 6 rely on binary treatment indicators that distinguish EU ETS countries from non-EU ETS control countries. While informative, this approach faces limitations due to the small and structurally different control group and the presence of heterogeneous treatment effects across countries (Callaway & Sant'Anna, 2021). This section therefore adopts an alternative identification strategy that exploits heterogeneous exposure to a common carbon price within the EU ETS.

7.1. Motivation and identification strategy

The EU ETS operates through a single, common carbon allowance price faced by all participating countries. However, countries differ substantially in their baseline exposure to this price, depending on their initial carbon intensity of electricity generation. Countries with more carbon-intensive electricity sectors are expected to be more strongly affected by changes in the EU ETS allowance price than countries with cleaner generation mixes (Bayer & Aklin, 2020).

By exploiting this within-system heterogeneity, the exposure-based approach reduces reliance on external control groups and mitigates concerns related to weak parallel trends between treated and control countries. Rather than comparing treated and untreated countries, this strategy identifies effects from differential exposure to a common policy.

The identifying assumption underlying this approach is that, conditional on country and year fixed effects, EU-wide variation in the allowance price is plausibly exogenous to idiosyncratic country-specific shocks affecting electricity generation outcomes, and that baseline carbon intensity captures pre-determined structural exposure to the carbon price.

This reasoning is consistent with standard panel identification arguments used in empirical analyses of carbon pricing mechanisms (Bayer & Aklin, 2020).

7.2. Empirical specification

The exposure-based specification is given by:

$$Share_{it} = \alpha_i + \gamma_t + \beta(CarbonIntensity_i \times ETSPrice_t) + \varepsilon_{it},$$

where $Share_{it}$ denotes the share of electricity generation from a given source (fossil fuels, renewable energy, or nuclear energy) in country i and year t. The term $CarbonIntensity_i$ represents baseline carbon intensity of electricity generation, measured prior to the introduction of the EU ETS, and is constructed as the country-specific average over the pre-treatment period. $ETSPrice_t$ denotes the EU ETS allowance price in year t.

Country fixed effects (α_i) control for time-invariant differences across countries, including structural features of electricity systems, while year fixed effects (γ_t) absorb common shocks affecting all countries in a given year, including EU-wide policy changes, macroeconomic conditions, and aggregate energy market developments.

The interaction term $CarbonIntensity_i \times ETSPrice_t$ captures heterogeneous exposure to the common carbon price. Because baseline carbon intensity is time-invariant and predetermined, it serves as a proxy for structural exposure to carbon pricing. The coefficient of interest, β, measures how the marginal effect of the EU ETS allowance price on electricity generation shares varies with baseline carbon intensity.

Thus, the impact of a price change depends on a country's pre-treatment carbon intensity. For example, in the fossil share regression, a negative value of β implies that increases in the carbon price are associated with larger reductions in fossil generation shares in countries with higher baseline carbon intensity.

Identification relies on the assumption that, conditional on country and year fixed effects, EU-wide variation in the allowance price is not systematically correlated with unobserved country-specific shocks affecting electricity generation outcomes. Since baseline carbon intensity is measured prior to the introduction of the EU ETS, it cannot respond to contemporaneous changes in the carbon price, mitigating concerns about reverse causality.

7.3. Heterogeneous Effects of Carbon Pricing on Electricity Generation Shares

This subsection presents the results of the exposure-based specification that interacts the EU ETS allowance price with baseline carbon intensity. The objective is to assess whether countries with more carbon-intensive electricity systems prior to the introduction of the EU ETS respond more strongly to changes in the carbon price in terms of their electricity generation mix.

Table 3

Effect of ETS Price x CO2 Intensity on fossil fuels share

	Coef.	Std.Err.	t-test	p-value
ETS price x emission intensity	-3.35e-06	9.09e-07	-3.68156	0.00098

Source: Own elaboration

Table 3 reports the estimated effect of the interaction between the EU ETS allowance price and baseline CO_2 intensity on the share of fossil-fuel-based electricity generation. The estimated coefficient is negative and highly statistically significant ($p < 0.001$).

Economically, this result indicates that countries with higher baseline carbon intensity experience a larger reduction in fossil fuel shares as the EU ETS allowance price increases. The negative sign is consistent with the central mechanism of carbon pricing: higher carbon prices disproportionately increase the marginal cost of fossil-based generation in electricity systems that are initially more carbon intensive.

The estimated coefficient is -3.35×10^{-6}. To illustrate the magnitude, consider a country with a baseline carbon intensity of 500 gCO_2/kWh. A €1 increase in the EU ETS allowance price implies a change in the fossil fuel share of -0.001675, corresponding to a 0.17 percentage point reduction in the fossil fuel share. While the effect of a €1 increase is modest, EU ETS allowance prices have increased by several tens of euros over the sample period, implying economically meaningful reductions in fossil generation shares.

Table 4
Effect of ETS Price x CO2 Intensity on renewables share

	Coef.	Std.Err.	t-test	p-value
ETS price x emission intensity	1.54e-06	1.21e-06	1.27137	0.21406

Source: Own elaboration

Table 4 presents the corresponding results for renewable electricity generation. The estimated coefficient on the interaction term is positive, indicating that higher allowance prices are associated with larger increases in renewable shares in more carbon-intensive countries. However, the coefficient is not statistically significant at conventional levels.

This suggests that while carbon pricing may contribute to renewable expansion, the effect is not estimated with sufficient precision in this specification. Renewable deployment is often shaped by complementary policies, investment cycles, permitting constraints, and grid infrastructure, which may weaken or delay the measurable response to carbon price signals in a reduced-form framework.

Table 5
Effect of ETS Price x CO2 Intensity on nuclear share

	Coef.	Std.Err.	t-test	p-value
ETS price x emission intensity	1.12e-06	6.11e-07	1.82812	0.078205

Source: Own elaboration

Table 5 reports the results for nuclear electricity generation. The estimated coefficient is positive and statistically significant at the 10% level. This implies that, in countries with higher baseline carbon intensity, increases in the EU ETS allowance price are associated with a relative increase in the nuclear share of electricity generation.

The magnitude of the coefficient is small, and the weaker statistical significance suggests that the effect should be interpreted cautiously. Nuclear capacity is largely determined by long-term policy and investment decisions, limiting short-run responsiveness to price signals. The observed association likely reflects adjustments in the utilization of existing nuclear capacity relative to fossil generation, rather than new investment responses over the sample period.

8. Conclusion

This thesis examined whether the European Union Emissions Trading System (EU ETS) has influenced the composition of electricity generation in participating countries, with particular attention to fossil fuels, renewable energy, and nuclear power. Building on and extending the framework of Perdiguero and Sanz (2025), the analysis combined a replication of established Difference-in-Differences results with an exposure-based extension exploiting heterogeneity in baseline carbon intensity across EU ETS countries.

The baseline Difference-in-Differences results provide limited evidence of uniform effects of the EU ETS on electricity generation outcomes across countries. Although point estimates for fossil fuel and renewable shares are generally consistent with theoretical expectations, they are not consistently statistically significant across specifications. Within the country-level framework employed in this thesis, the results do not support strong causal claims that participation in the EU ETS alone generated systematic and homogeneous shifts in the electricity mix across all treated countries.

In contrast, the exposure-based analysis yields more informative results. By interacting the common EU ETS allowance price with pre-treatment measures of carbon intensity, the extension exploits differential exposure to carbon pricing within a shared policy environment. The results reveal a statistically significant and economically meaningful reduction in fossil-fuel-based electricity generation in countries with higher baseline carbon intensity when allowance prices increase. This finding indicates that carbon pricing induces stronger behavioral responses in electricity systems where the carbon price signal is more binding, consistent with the mechanism of fuel switching and cost reallocation predicted by economic theory.

Importantly, these findings do not imply that carbon pricing uniformly transforms national electricity systems or immediately triggers large-scale structural change. Rather, the evidence points to heterogeneous responses: electricity systems that are initially more carbon-intensive adjust more strongly to increases in the allowance price, primarily through reductions in fossil fuel generation shares. Effects on renewable electricity generation are estimated imprecisely, and no robust evidence emerges for systematic responses of nuclear generation, reflecting both the rigidity of nuclear capacity and identification constraints inherent in cross-country data.

Taken together, the findings underscore that the impact of the EU ETS depends critically on initial conditions. While the system does not appear to generate uniform effects across all participating countries, it exerts stronger pressure where exposure to carbon pricing is greatest. This heterogeneity helps reconcile mixed evidence in the literature and aligns with existing research emphasizing that carbon pricing effects are shaped by sectoral structure, institutional design, and pre-existing energy portfolios (Ellerman et al., 2010; Bayer & Aklin, 2020).

Several limitations merit consideration. First, causal interpretation remains constrained by the observational nature of the data and the coexistence of multiple climate and energy policies, including renewable support schemes and national regulatory interventions. Second, the analysis focuses on short- to medium-run adjustments in electricity generation shares and does not directly capture long-term investment dynamics or technological change. Third, the use of aggregate country-level data may mask important within-country heterogeneity across firms and generation technologies.

Despite these limitations, the results contribute to the literature on carbon pricing by demonstrating that increases in EU ETS allowance prices are associated with meaningful reductions in fossil fuel use in more carbon-intensive electricity systems. This suggests that carbon pricing can serve as an effective mechanism for inducing emissions-relevant adjustments where exposure is high, although complementary policies may be necessary to ensure broader and more uniform transitions toward low-carbon electricity generation.

Future research could build on this analysis by incorporating plant-level data, explicitly modeling investment decisions, or examining interactions between carbon pricing and renewable energy support policies. Such extensions would deepen understanding of the long-run structural effects of emissions trading systems and further inform the design of effective climate policy.

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Appendix A

This appendix reports descriptive statistics for electricity generation shares in the final pre-treatment year, 2004. Reporting pre-treatment descriptive statistics allows for a transparent comparison of initial conditions between EU ETS countries and control countries prior to the introduction of the EU Emissions Trading System.

Table A1
Descriptive statistics in 2004.

Variable	Mean	Std. Dev.	Minimum	Maximum
Fossil Fuels Share	0.248921	0.2528934	0	0.9154242
Renewables Share	0.2604718	0.2940979	0	0.9995362
Nuclear Share	0.1672434	0.2440833	0	0.7835426

Source: Own elaboration

Table A2
Descriptive statistics by groups in 2004.

Variable	EU ETS Countries	Control Countries
Fossil Fuels Share	0.2253377 (0.2317460)	0.4198997 (0.3695602)
Renewables Share	0.2347977 (0.2824625)	0.4466090 (0.3540752)
Nuclear Share	0.1903115 (0.2520728)	0 (0)

Source: Own elaboration

Appendix B

This appendix reports additional results obtained using the Callaway–Sant'Anna (2021) Difference-in-Differences estimator. The Callaway–Sant'Anna approach allows for treatment effect heterogeneity across cohorts and over time and serves as a robustness check to the baseline two-way fixed effects estimates presented in the main text. Aggregate average treatment effects and dynamic event-study estimates are reported for completeness.

Appendix B1 - Aggregate ATT estimates (tables)

Tables B1–B3 report aggregate average treatment effect (ATT) estimates for fossil fuel, renewable, and nuclear electricity generation shares using the Callaway–Sant'Anna estimator. Across outcomes, the estimated effects are not statistically significant.

Table B1

Regression results for fossil fuels share (Callaway and Sant'Anna).

	Coef.	Std.Err.	t-test	p-value
ATT	-0.0472	0.1398	-0.3375	0.7357

Source: Own elaboration

Table B2

Regression results for renewables share (Callaway and Sant'Anna).

	Coef.	Std.Err.	t-test	p-value
ATT	0.0956	0.138	0.6929	0.4884

Source: Own elaboration

Table B3

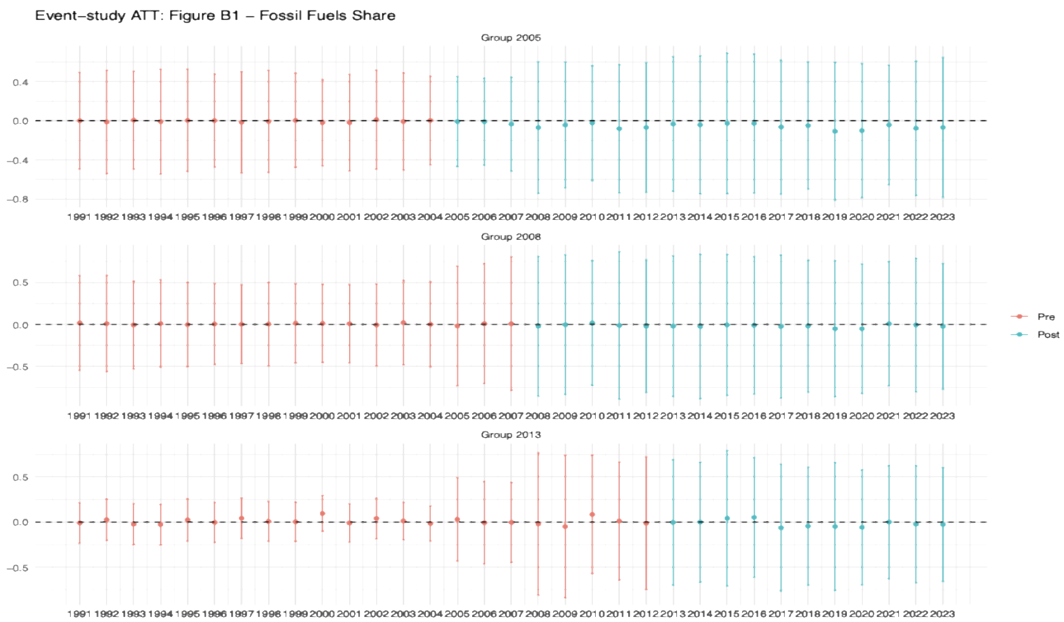
Regression results for nuclear share (Callaway and Sant'Anna).

	Coef.	Std.Err.	t-test	p-value
ATT	-0.0266	0.0436	-0.6108	0.5413

Source: Own elaboration

Appendix B2 - Dynamic event-study estimates (figures)

Figures B1–B3 display dynamic event-study estimates by treatment cohort. The estimated pre-treatment coefficients do not indicate systematic violations of parallel trends, while post-treatment coefficients remain imprecisely estimated and statistically insignificant across outcomes.



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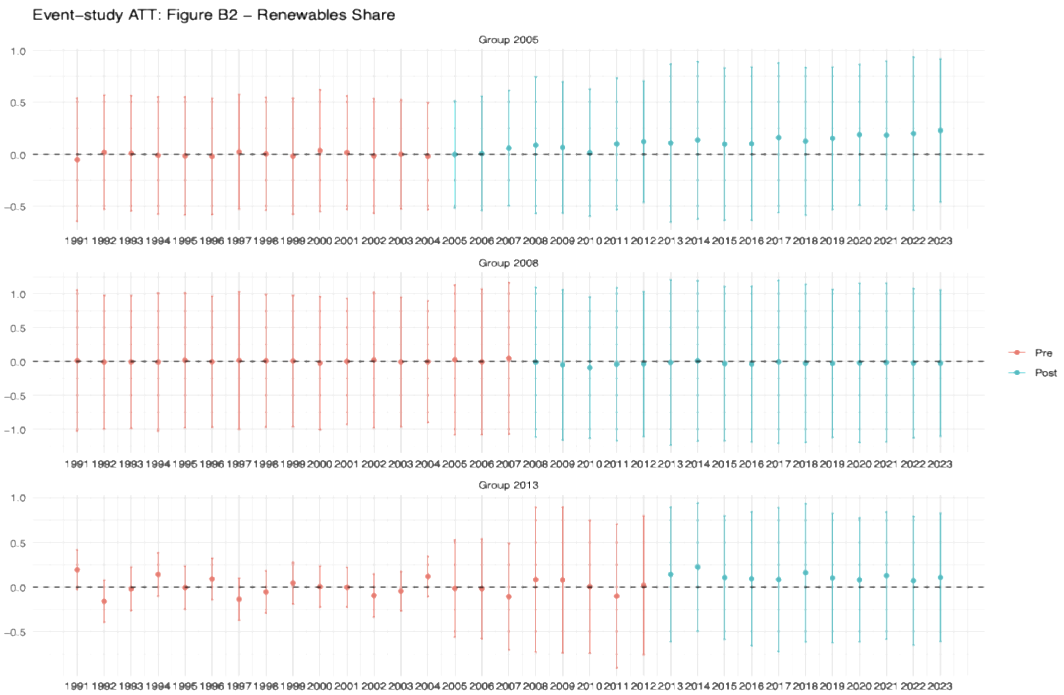

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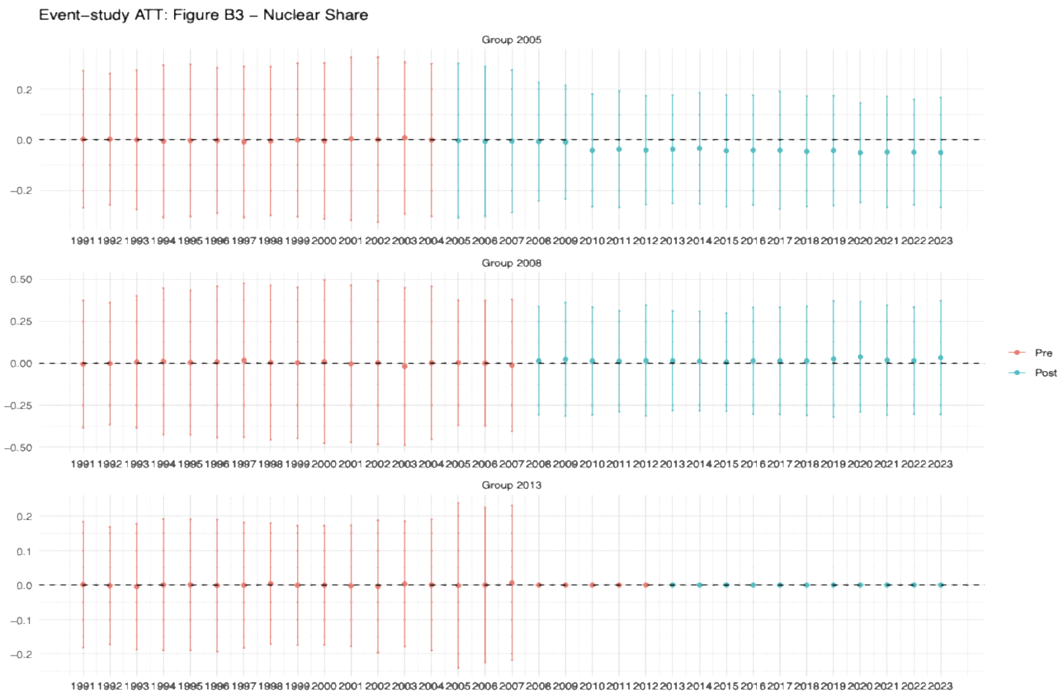

Source: Own elaboration