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Assessing the Relationship Between Electricity Generation Mix and Indirect Carbon Cost Compensation under the EU ETS (Phase IV, 2021-2024): A Comparative Analysis of Germany, France, Spain and Poland

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Abstract

This study examines how electricity generation mixes influence indirect carbon cost compensation under the EU Emissions Trading System throughout 2021-2024. It is a comparative analysis of Germany, Poland, Spain, and France, focusing on differences in electricity generation sources, compensation levels and their evolution over time. The analysis investigates the relationship between electricity generation mixes and indirect carbon cost compensation, assessing how differences in the carbon intensity of electricity systems are reflected in compensation levels and how these relationships evolve over the study period.

Keywords: EU Emissions Trading System (EU ETS), indirect carbon costs, electricity generation mix, compensation, EU climate policy

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Chapter 1: Introduction

1.1: Background and research problem

Climate change has become a major component of European policy, leading the European Union (EU) to adopt, amongst other tools, market-based instruments to reduce greenhouse gas (GHG) emissions and to limit the economic costs of decarbonisation. One of the most important instruments of this policy framework is the European Union Emissions Trading System (EU ETS). The EU ETS sets a cap on emissions and creates a market price for GHG allowances (European Commission, 2026). The system applies to electricity and heat generation, industrial production, maritime transport and aviation, and covers around 40% of the EU's total GHG emissions. By putting a price on carbon, the EU ETS aims to provide an economic incentive to firms to reduce their emissions and invest in lower-carbon technologies (SWD(2025) 388 final).

The fourth trading phase of the EU ETS started in 2021, and will cover the period 2021-2030. This phase constitutes part of the EU's broader effort to strengthen its climate policy and increase the pace of emissions reductions (European Parliament & Council of the European Union, 2003, 2025 update). In parallel, the EU ETS has become an increasingly important source of public revenue. These revenues are distributed between Member States and EU-level funds to support climate action, energy transformation, and the transition towards a low-carbon economy (European Commission, 2026).

In electricity markets, the cost of EU ETS allowances can be incorporated into electricity prices by electricity producers and then passed on to electricity consumers, including households and energy-intensive industries (Arlia and Hutchinson, 2026). The costs are commonly referred to as indirect carbon costs. They can be particularly significant for electricity-intensive industries which may therefore be exposed to a risk of carbon leakage, or "the transfer of CO_2 emissions from one country to another when, due to strict climate policy, companies relocate their production to countries with weaker emission constraints" (European Commission, 2025a, para. 1). As a consequence, "this can contribute to an increase in global greenhouse gas emissions" (Ibid). As it will be discussed further in this study, the EU framework consequently allows Member States to provide State aid to certain sectors to compensate for part of these indirect costs (C/2020/6400 final). However, according to Carbon Market Watch (2025), such compensation may reduce the incentive for companies to decarbonise their production processes or increase their use of renewable energy sources.

The relationship between the EU ETS and electricity prices makes the electricity generation mix particularly relevant to the study of indirect carbon costs. Electricity generated from coal, oil, and natural gas has a higher carbon intensity than electricity generated from renewable or nuclear sources (COWI, 2023). As a consequence, countries with different electricity-generation structures may experience different degrees of exposure to carbon cost transmission through electricity prices, and therefore different degrees of exposure to a risk of carbon leakage. In turn, the need for compensation may vary between Member States.

This issue appears particularly relevant during Phase IV because Member States have experienced significant differences in both their electricity generation structures and the revenues generated through the EU ETS. These differences make it possible to analyse whether the structure of national electricity generation is associated with variations in the relative importance of indirect carbon cost compensation.

1.2: Research question and objectives

This thesis aims to answer the following research question:

> How does the electricity generation mix influence carbon cost compensation under the EU ETS during Phase VI (2021-2024)?

To answer this question, the study pursues three objectives. First it examines the evolution of electricity generation sources in Germany, France, Spain, and Poland between 2021 and 2024. Second, it analyses the evolution of EU ETS auction revenues and indirect carbon cost compensation in the four cases over the same period. Third, it compares the two dimensions in order to assess whether differences and changes in electricity generation structures are associated with differences and changes in the relative importance of compensation expenditure.

1.3: Research design and methodology

This thesis uses a comparative and longitudinal research design to investigate the relationship between national electricity generation structures and indirect carbon cost compensation under the EU ETS. The empirical analysis concentrates on four EU Member States: Germany, France, Spain, and Poland. The four countries were selected for two reasons. First, they represent very different electricity generation structures. Second, they are the four countries that generated the most ETS revenues throughout the period. Italy generated more revenues than France, and therefore would have replaced the latter in the analysis but the country reported only a very limited share of its ETS revenue spending (Helak et al., 2025), making it impossible to assess the relationship between the aforementioned two dimensions.

The study covers the period 2021-2024, which correspond to the first four years of Phase IV of the EU ETS. This period is particularly relevant because it coincides with major developments in both European electricity markets and the carbon market. It includes the sharp increase in energy prices and important fluctuations in EUA prices, while the electricity generation mix also continued to evolve across the four cases. 2024 is the last year of study because data were not yet available for the following years. Using annual observations makes it possible to consider not only differences between countries, but also how these variations develop over time.

Three main categories of data are brought together in the empirical analysis: electricity-generation data, ETS auction revenues and indirect carbon cost compensation. The main indicators used to compare the four countries are therefore the electricity mix and the share of ETS auction revenues allocated to indirect carbon cost compensation. Expressing compensation as a share of revenues provides a common basis for comparison between countries with substantially different levels of revenues. The relationship between the electricity mixes and compensation is subsequently examined through cross-country comparison and graphical analysis. These include comparisons across countries and over time, as well as a scatterplot combining the fossil share of electricity generation with the compensation share for the 16 country-year observations.

This research design entails some limitations. The analysis is restricted to four cases and a four-year period, meaning that the findings should not be interpreted as representative of all EU Member States or as establishing a general causal relationship. Moreover, the fossil share provides only an approximate measure of electricity carbon intensity, since different fossil fuels have different emissions profiles. These limitations are taken into consideration when interpreting the empirical findings and are discussed further in the conclusion.

1.4: Hypotheses

This thesis advances three hypotheses:

H1: Countries with more carbon-intensive electricity generation allocate a higher share of ETS auction revenues to indirect carbon cost compensation.

H2: Changes in the electricity generation mix over time are associated with changes in the share of ETS auction revenues allocated to indirect carbon-cost compensation, following the same trend over time.

H3: Countries with similar electricity generation structures can exhibit substantially different levels of indirect carbon-cost compensation relative to their ETS auction revenues.

These hypotheses are examined through a comparative analysis of annual observations rather than country-level averages. By doing so, this approach makes it possible to capture changes between 2021 and 2024 and to identify differences in the evolution of electricity generation and compensation over time.

1.5: Structure of the thesis

The structure of the study is organised as follows. Chapter 2 presents the EU ETS and the framework governing indirect carbon cost compensation. Chapter 3 develops the theoretical framework linking electricity generation structure, carbon intensity and indirect carbon costs. Chapter 4 examines the evolution of electricity generation mixes and EU ETS auction revenues in Germany, France, Spain, and Poland. Chapter 5 examines the evolution of indirect carbon cost compensation and more importantly, 5.3 brings the data from Chapter 4 and 5 together to assess the relationships identified in the hypotheses. Finally, Chapter 6 concludes the thesis by presenting the main findings, assessing the hypotheses, discussing the limitations of the study and identifying potential avenues for further research.

Chapter 2: EU ETS and indirect carbon cost compensation

2.1: Evolution of the EU ETS

Established in 2005, the EU ETS was the first international carbon market of its kind and is still a central instrument of EU climate policy. The system is currently under its fourth trading phase, covering the period from 2021 to 2030.

As part of the European Green Deal, the European Commission presented the Fit for 55 package on 14 July 2021. This comprehensive package introduced a set of legislative proposal aimed at aligning EU climate and energy policies with the objective of achieving climate neutrality by 2050. It also sought to translate into concrete policy measures the EU's commitment to reducing net greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels (COM/2021/550 final). Among various measures, the proposals included important revisions of the EU ETS, the Effort Sharing Regulation, and legislation covering transport and land use. Taken together, these reforms were meant to strengthen the EU's existing climate policy framework and establish the regulatory conditions necessary to meet its long-term climate objectives (European Commission, 2025).

The Kyoto Protocol

The origins of the EU ETS can be traced back to the adoption of the Kyoto Protocol in 1997, which introduced legally binding greenhouse gas emission reduction commitments for 37 industrialised countries (United Framework Convention on Climate Change, n.d.). The establishment of these targets created a need for effective policy mechanisms capable of supporting their achievement.

In March 2000, the European Commission took a substantial step towards establishing such a mechanism by publishing a Green Paper outlining initial options for the design and operation of an EU-wide emission trading scheme. The document provided the basis for consultations with stakeholders, whose contributions subsequently influenced the development and structure of the system (COM/2000/0087 final).

The legal framework for the EU ETS was established through the adoption of the EU ETS Directive in 2003, while the trading system officially became operational in 2005 (Directive 2003/87/EC). During its initial phase, the overall quantity of emission allowances was determined at the national level through National Allocation Plans (NAPs), which specified the number of allowances allocated to installations within each Member State (European Commission, 2025b).

Phase 1 (2005-2007)

The first phase of the EU ETS, covering the period from 2005 to 2007, was designed as a three-year pilot period based on a learning by doing approach. Its main purpose was to introduce the foundations of the system and identify potential shortcomings before the EU ETS became an important instrument for meeting the EU's Kyoto Protocol commitments during the subsequent phase (European Commission, 2025c).

During this initial period, almost all emission allowances were allocated free of charge to participating installations, while the financial penalty for failing to comply with the scheme's requirements was set at €40 per tonne of CO_2. The system applied exclusively to CO_2 emissions form electricity generation and energy-intensive industrial sectors (Anderson, 2026).

Phase 1 played an important role in establishing the basic functioning of the EU carbon market. Indeed, it introduced a market price for carbon, enabled the trading of emission allowances across Member States, and created the necessary institutional and technical infrastructure for the monitoring, reporting and verification of emissions. However, the first phase was affected by significant uncertainties regarding the actual level of emissions. Since reliable and comprehensive emissions data were not yet available, national caps were largely established using estimates. As a consequence, the number of allowances allocated exceeded actual emissions, leading to an important oversupply in the market. As demand was therefore considerably lower than supply, allowances prices decline sharply and ultimately reached zero in 2007 (European Commission, 2025c). This outcome was also linked to the fact that allowances from phase 1 could not be carried forward, or banked across the phase boundary (Dechezleprêtre et al., 2023).

Phase 2 (2008-2012)

During phase 2, the EU ETS continued to operate through NAPs, although the overall emissions cap was tightened compared with the first phase. The cap was established using verified emissions data collected during phase 1, which allowed national authorities to base allowance allocations on more reliable information (European Commission, 2025c).

Despite this tightening, approximately 90% of allowances continued to be allocated free of charge, while the first allowance auctions were introduced (Ibid). Phase 2 also permitted companies to use international carbon offsets for compliance, resulting in the introduction of more than one billion international credits into the EU carbon market by 2012 (European Commission, 2025d).

However, several factors contributed to a significant structural oversupply of allowances. The combination of a generous emissions cap, the availability of international credits, and the economic downturn following the 2008 financial crisis led to an enormous oversupply that placed downward pressure on EUA prices (Emissions Trading Extra, 2022).

Phase 3 (2013-2020)

The third phase introduced major reforms. The allocation system was revised, with auctioning becoming the principal method for distributing EUAs. Particularly, the electricity sector generally ceased to receive allowances free of charge, although limited free allocations remained available in certain Member States to support the modernisation of their power sectors (European Commission, 2026a).

Another substantial change was the introduction of a single EU-wide emissions cap. This created a more harmonised framework for emissions trading across the EU and straightened the market-based nature of the system. The use of international carbon credits was also more restricted (Ibid).

Moreover, to address the persistent structural imbalance between the supply and demand for allowances, the Market Stability Reserve (MSR) was established in 2015. The mechanism began withdrawing surplus allowances from the market in 2018, progressively reducing the excess supply. By responding more dynamically to the accumulated allowance surplus, it helped restore confidence in the carbon market and contributed to the recovery of EUA prices after several years of persistently low prices (Dimitrova, 2025).

Phase 4 (2021-2030)

The fourth (current) phase of the EU ETS represents a further strengthening of the EU's carbon pricing framework. Under the revised system, the EU has increased its ambition by setting a target of reducing greenhouse gas (GHG) emissions by 62% compared with 2005 levels (COM(2025) 668 final).

The scope of the EU ETS currently encompasses electricity and heat generation, as well as a broad range of energy-intensive industrial activities. The system also applies to aviation, covering flights within the EU and the European Economic Area (EEA), as well as flights departing from the EU to Switzerland and the United Kingdom. In addition, maritime transport has been incorporated into the system, with surrender obligations being introduced progressively between 2024 and 2026 (Publications Office of the European Union, 2025).

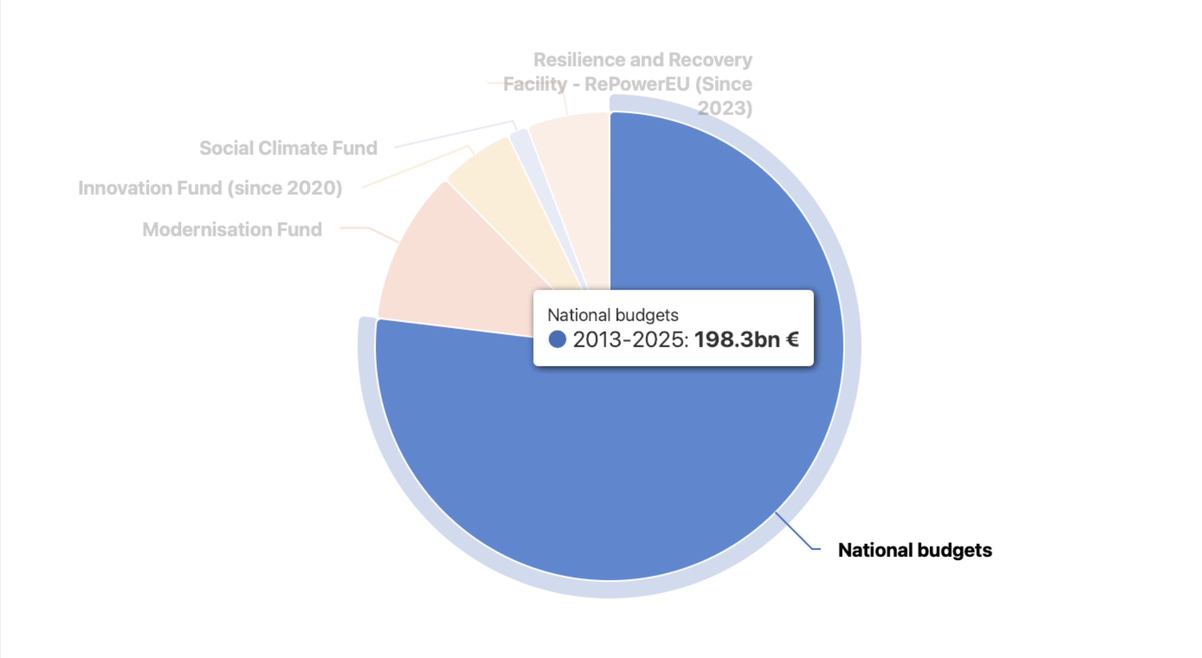
2.2: Generation of revenues and use

As aforementioned, under phase 4, a significant share of emission allowances under the EU ETS is allocated through auctioning. The revenues generated from these auctions are primarily allocated to EU Member States participating in the system. The remaining auction revenues are channelled towards several EU-level funding instruments designed to support the transition towards a low-carbon economy. These include the Innovation Fund and the Modernisation Fund, which finance projects related to clean technology, decarbonisation and the modernisation of energy systems. In addition, resources contribute to the Recovery and Resilience Facility (FFF), which supports investments aimed at strengthening the energy transition and improving energy security across Member States (European Commission, 2026b).

The substantial increase in carbon prices since 2017 has contributed to a corresponding rise in the revenues generated through the auctioning of allowances. Member States' ETS auction revenues increased from approximately €5 billion in 2017 to €24 billion in 2024. However, this represented a 27% decrease compared with 2023, when auction revenues reached around €33 billion. Despite this decline, ETS revenues remain an important source of funding for climate-related investments and the broader transition towards a low-carbon economy (European Environment Agency, n.d.).

On a longer period, from 2013 to the end of 2025, EU ETS auctions have generated over €258 billion in revenue. On the same period, €198.3 billion have been distributed to Member States (see figure 1).

Figure 1: *ETS revenues distributed to Member States, 2013-2025 (€ billion)*



Source: European Commission (2026b), *What are ETS revenues used for?*.

Between the first four years of Phase IV, total auction revenues reached around €152.65 billion. 74% of this amount, which corresponds to approximately €112.4 billion, was allocated directly to the national budgets of EU Member States (Marcu et al., 2026).

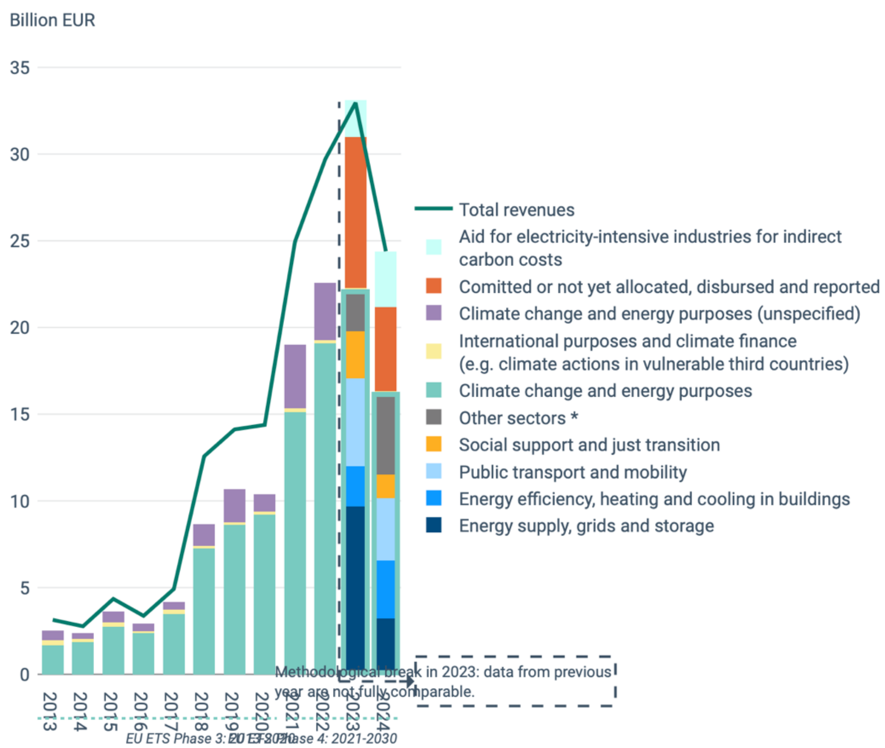
Prior to June 2023, Member States were encouraged to allocate at least 50% of their auction revenues towards climate- and energy-related objectives (Ibid). The eligible areas for spending revenues cover a broad range of measures aimed at supporting decarbonisation and the transition to a climate neutral-neutral economy. These expenditures can include industrial decarbonisation, the transformation of energy systems, and the development and deployment of clean technologies. Moreover, Member States can also use the revenues to finance climate change adaptation measures and initiatives aimed at reducing emissions from the transport sector. Finally, ETS revenues may support just transition measures, helping regions, workers and communities manage the economic and social consequences associated with the transition towards a low-carbon economy (European Environment Agency, n.d.).

In the revised EU ETS Directive adopted in 2023, the Member States are now obligated to spend 100% of auctioning revenues on climate- and energy-related activities, except for any revenue spent in aid for indirect carbon costs, as it will be discussed further (European Parliament & Council of the European Union, 2023, Directive (EU) 2023/959). EU ETS revenues may also be spent outside the EU, with Member States using them to support developing countries (on climate mitigation, adaptation, capacity-building or knowledge transfer) (European Environment Agency, 2026).

Over the past decade, Member States have mostly used ETS auction revenues to finance climate and energy measures within their own territories. The share of ETS revenues devoted to international initiatives has remained relatively limited. Since 2018, annual spending at the international level has generally remained between €100 million and €200 million, with these funds primarily supporting developing countries through multilateral funds and international institutions (Ibid).

Overall, Member States have reported a substantial level of commitment to climate- and energy-related expenditure. Between 2013 and 2022, around 75% of ETS auction revenues were reported as either committed or spent on climate and energy purposes across the EU-27 (European Environment Agency, n.d.). See Figure 2 for Member State auctioning revenues and reported usage between 2013 and 2024.

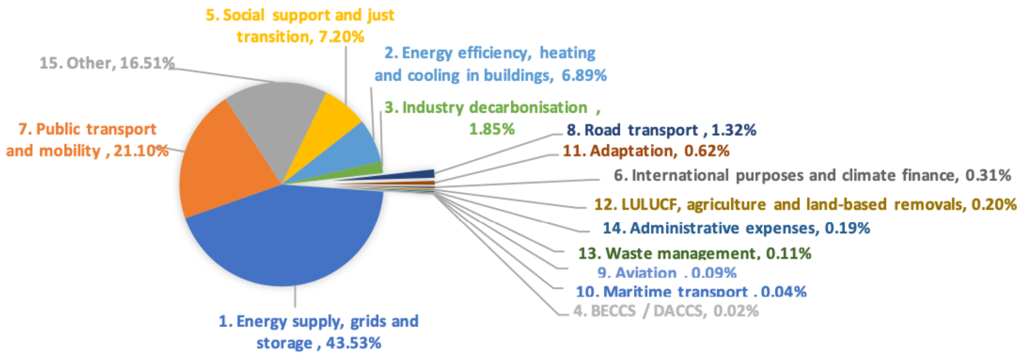
Figure 2: *Member State auction revenues and reported usage, 2013-2024, scope EU-27 (€ billion)*



Source: European Environmental Agency (n.d.). *Use of auctioning revenues generated under the EU Emissions Trading System*.

In 2023, EU ETS auctions generated total revenues of approximately €43.6 billion. Of this amount, around €33 billion was transferred directly to EU Member States. Approximately €30.9 billion was allocated to climate action and the transformation of energy systems (European Commission, 2026). Almost half of EU ETS reported revenue (43%) was disbursed on “Energy supply, grids and storage”, followed by “Public transport and mobility” (21%), “others” (16%), and “Social support and just transition” (7%) (Marcu et al., 2025).

Figure 3: *EU ETS reported MS auction revenues EU 27 per category (2024 reporting, 2023 data) (%)*



Source: Marcu et al., 2025. *2025 State of the EU ETS report.*

The remaining €2.1 billion was used to compensate electricity-intensive industries for indirect carbon costs.

In 2024, auctions generated around €38.8 billion revenues, of which €24.4 billion was allocated to Member States (EEA, 2025). Of this amount, approximately €21.2 billion was subject to the requirement to support climate action and the energy transition under Article 10(3) of Directive 2003/87/EC. The remaining €3.2 billion was reported as having been spent for electricity-intensive industries for indirect carbon costs, under Article 10a(6) (European Commission, 2026b). This will be discussed further in the next section.

2.3: Framework for compensation for indirect carbon costs

Articles 10a(6) and 10b of the Directive 2003/87/EC sets out two types of State aid: “Aid to compensate for increases in electricity prices resulting from the inclusion of the costs of greenhouse gas emissions due to the EU ETS (commonly referred to as “indirect emission costs”)” and “Aid involved in the optional transitional free allocation for the modernisation of the energy sector” (European Commission, Guidelines on certain State aid measures in the context of the system for greenhouse gas emission allowance trading post-2021, para.12 and 13, 2020/C317/04). We will focus only on the indirect emission costs in this thesis.

When power plants pass on the cost of EUAs on to electricity consumers, it may increase energy costs for electricity-intensive industries. To mitigate the resulting competitiveness pressures, Member States can provide state aid to certain energy-intensive industries affected by these indirect carbon costs. At present, approximately half of EU Member States operate such compensation schemes to support their domestic industries. To ensure that measures are applied consistently across the EU and do not create significant distortions within the internal market, the European Commission established the EU ETS State Aid Guidelines. The guidelines were revised in 2020 to cover the 2021-2030 period (European Commission, 2025e).

The guidelines states:

"Under Article 10a(6) of Directive 2003/87/EC, Member States should adopt financial measures in favour of sectors or subsectors which are exposed to a genuine risk of carbon leakage due to significant indirect costs that are actually incurred from greenhouse gas emission costs passed on in electricity prices, provided that such financial measures are in accordance with State aid rules, and in particular do not cause undue distortions of competition in the internal market." (European Commission, Guidelines on certain State aid measures in the context of the system for greenhouse gas emission allowance trading post-2021, para. 12, 2020/C317/04).

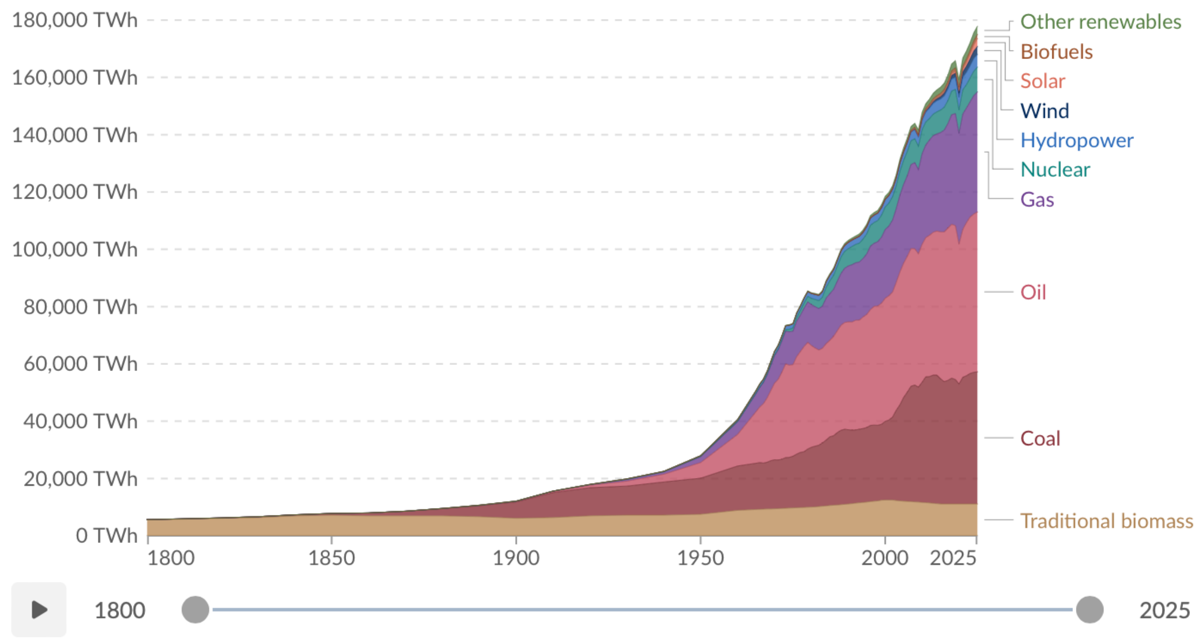
Member States that provide this type of state aid are subject to transparency and reporting obligations. Each year, they must disclose the amount of compensation granted, both at the sectoral level and in aggregate. In addition, to prevent an excessive proportion of ETS revenues from being redirected towards compensation for indirect costs, Member States are expected to limit such expenditure to 25% of their auction revenues. Where this threshold is exceeded, the State concerned must provide the European Commission with a report explaining the reasons for the higher level of expenditure (European Commission, 2025).

Chapter 3: Theoretical framework

3.1: Energy mix versus electricity mix

The energy mix describes the combination and relative share of different energy sources used to satisfy energy demand within a particular country or geographical area. It encompasses fossil fuels, such as oil, natural gas and coal, alongside renewable energy sources, including biomass, hydropower, wind and solar power, as well as other forms of energy such as nuclear power. These sources can be used for a range of purposes, including electricity generation, as it will be discussed further, transportation, and the heating and cooling of residential and industrial buildings (Planete Energies, 2023). Figure 4 shows the global primary energy use by source.

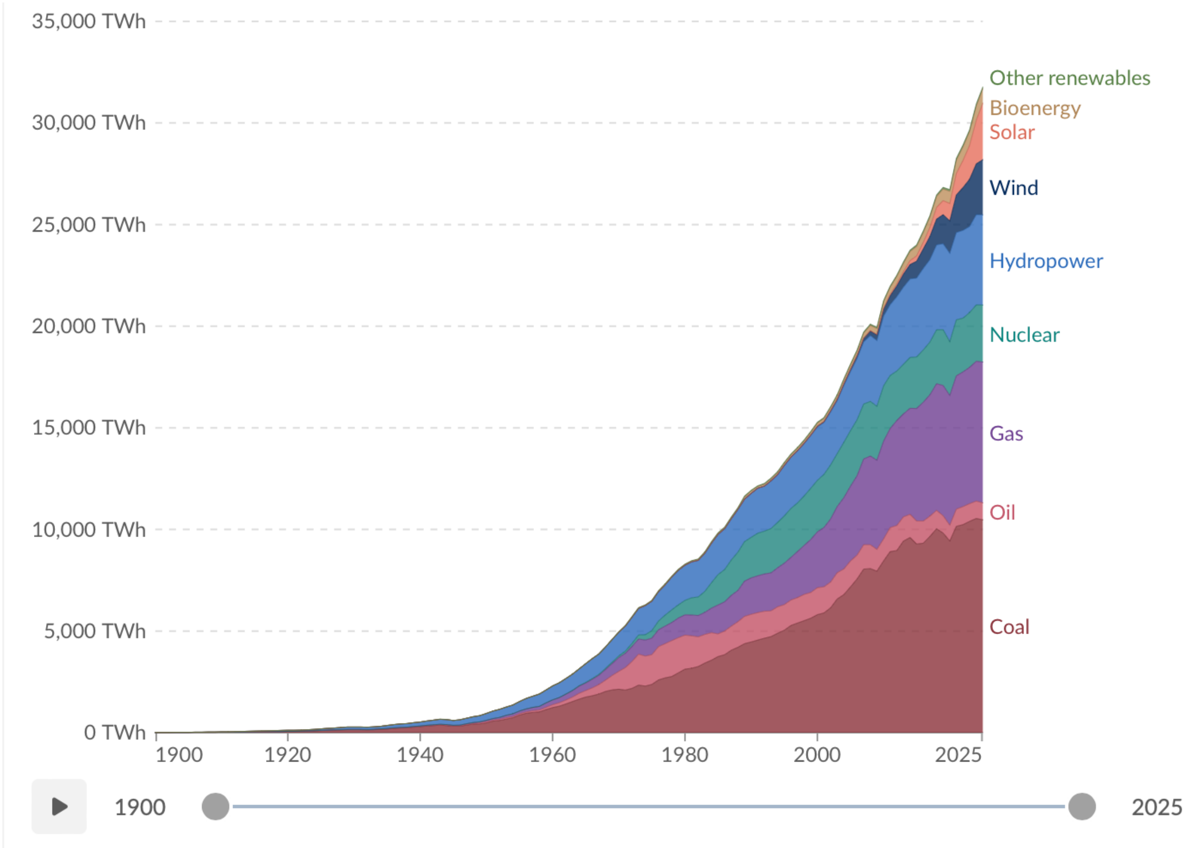
Figure 4: *Global primary energy use by source, 1800-2025 (TWh)*



Source: Ritchie and Rosado, 2026. *Energy mix*. Our world in Data.

The energy mix is to be distinguished from the power generation mix, or electricity mix, which refers specifically to the combination of energy sources used to produce electricity. While the energy mix encompasses all major forms of energy consumption, the power generation mix focuses exclusively on the sources used for electricity production (Planete energies, 2023). Figure 5 shows worldwide electricity generation by source 1900-2025.

Figure 5: *Electricity generation by source, world, 1900-2025 (TWh)*



Source: Ritchie et al., 2026. *Electricity mix*. Our world in Data.

3.2: Energy mix in the EU

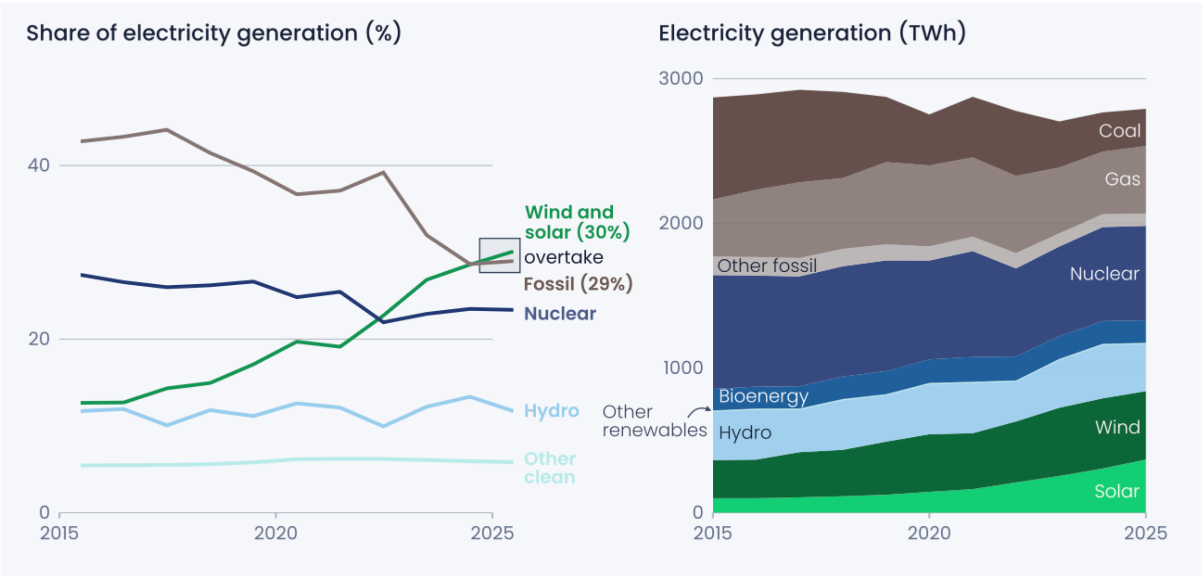
The energy available within the EU is supplied through a combination of energy produced from within and energy imported from countries outside the EU. In 2024, domestic production accounted for approximately 42% of the EU's energy supply, while the remaining 57% was obtained through imports from non-EU countries (European Commission, Directorate-General for Energy, 2026).

In 2024, the EU's overall energy mix was composed primarily of five main energy sources. Crude oil and petroleum products represented the largest share, accounting for 38% of the energy mix, followed by natural gas at 21%. Renewable energy sources accounted for approximately 20%, while nuclear energy represented 12%. Solid fossil fuels made up the remaining 10% (Eurostat, 2026).

3.3: Electricity mix in the EU

Energy production within the EU relies on a diverse range of sources, including solid fossil fuels, natural gas, crude oil, nuclear energy and renewable sources such as hydropower, wind and solar energy. However, the relative importance of these sources varies considerably across Member States. In 2024, renewable energy accounted for 48% of total energy produced within the EU, making it the largest source of domestic energy production. Nuclear energy represented the second-largest source, contributing 28%, followed by solid fuels at 15%, natural gas at 5%, and crude oil at 3% (Eurostat, 2026). Figure 6 shows the evolution of the share of electricity generation in the EU for the period 2015-2025.

Figure 6: *Share of electricity generation, EU, 2015-2015 (%)*



Source: Ember, 2026. *European electricity review 2026.*

3.4: EU ETS price transmission

EU ETS carbon costs are primarily transmitted through electricity prices. Electricity and centralised heat generation represented the largest share of ETS1 emissions in 2024, accounting for approximately 50% of total emissions, although this proportion has been declining rapidly. The power sector is the largest purchaser of auctioned EU ETS allowances and the main price transmission channel is the wholesale electricity price (European Commission, DG ECFIN, 2025).

When a fossil-fuel power plant is the marginal producer, that is, the installation determining the market price, the cost of purchasing emission allowances is generally incorporated into the price of electricity. Empirical research supports a substantial degree of carbon cost pass-through. Bail and Okullo (2023), for instance, find evidence of full pass-through of carbon prices into wholesale electricity prices in Belgium, Germany, Italy, the Netherlands, Scandinavia and the United Kingdom between 2009 and 2018. Dagoumas and Polemeis (2020) identify an almost complete pass-through in Greece. Similarly, Fabra and Reguant (2013) presented an empirical assessment of the introduction of emissions regulation in the Spanish electricity market. Overall, they found that the power companies appeared to have responded strongly to changes in emissions allowance prices. As a result, the costs associated with emissions regulation were almost entirely passed through to electricity prices. The impact is generally greater when coal is the marginal fuel than when natural gas is used, due to coal's higher carbon intensity.

The direct ETS1 costs for fossil-fuel-intensive industries is partly offset by free allocation of allowances. In 2024, industrial processes accounted for 38% of ETS1 emissions, primarily from energy-intensive industries. The free allowances provided to these industries and to district heating have generally been broadly aligned with their emissions, helping to limit their direct carbon costs. However, the extent to which ETS1 costs are passed through to the prices of basic materials varies considerably across countries and sectors. Neuhoff and Ritz (2019) find that complete cost pass-through occurs only in a limited number of cases (European Commission, DG ECFIN, 2025).

Chapter 4: Electricity mix and EU ETS revenue in the four cases

4.1: A recent history of the cases' electricity mixes

In 2019, France established a legal objective of achieving net-zero emissions by 2050, followed in 2020 by an updated energy transition framework, including a new National Low-Carbon Strategy and a ten-year energy plan. Despite these measures, progress has been slower than expected and implementation remains challenging. France has historically benefited from relatively low-carbon electricity generation, largely due to the dominant role of nuclear power (International Energy Agency, 2021).

Indeed, France has the highest share of nuclear power generation among IEA countries, with nuclear accounting for approximately 67% of electricity generation in 2020. Combined with significant contributions from hydropower and other renewable sources, this resulted in around 80% of France's electricity production being carbon-free. However, the planned retirement of ageing nuclear reactors and the government's previous objective of reducing nuclear power's share to 50% by 2035 created challenges for the country's electricity supply. Replacing this capacity with variable renewable sources also raised concerns regarding the reliability and security of electricity supply (IEA, 2022, June 30).

Poland's energy policy is centred on decarbonising the energy system through the expansion of renewable energy, the development of nuclear power, the electrification of transport and improvements in energy efficiency. A key priority is reducing the country's dependence on coal, particularly in electricity generation. Poland's has made significant progress in its energy transition, particularly through the rapid expansion of distributed solar PV and the development of offshore wind projects. Nevertheless, Poland's energy and electricity mixes remain heavily dependant on fossil fuels, meaning substantial efforts are still required to expand renewable energy, reduce energy consumption and cut greenhouse gas emissions (IEA, 2022, May 12).

Since 2015, Spain has addressed its long-standing electricity and gas tariff deficits and completed the closure of its coal mines. These developments have enabled the government to place climate change and the energy transition at the centre of national energy policy, while increasingly aligning its objectives with those of the European Union. Spain's current energy and climate framework is guided by the objective of achieving climate neutrality by 2050, alongside targets for 100% renewable electricity generation and 97% renewable energy across the overall energy mix (IEA, 2021, May 26).

To this end, Spain's main policy framework for the energy and climate transition during the current decade is its National Energy and Climate Plan (NECP) 2021-2030. The plan establishes a range of measures across sectors. By 2030, Spain aims to achieve a 23% reduction in greenhouse gas emissions compared with 1990 levels, a 42% share of renewables in final energy consumption, a 39.5% improvement in energy efficiency, and a 74% share of renewables in electricity generation. To reach these targets, the NECP promotes the expansion of renewable electricity and renewable gases, transport electrification and modal shifts, building renovation and renewable heating, as well as energy efficiency and fuel switching industry and agriculture (Ministry for the Ecological Transition and the Demographic Challenge, 2024).

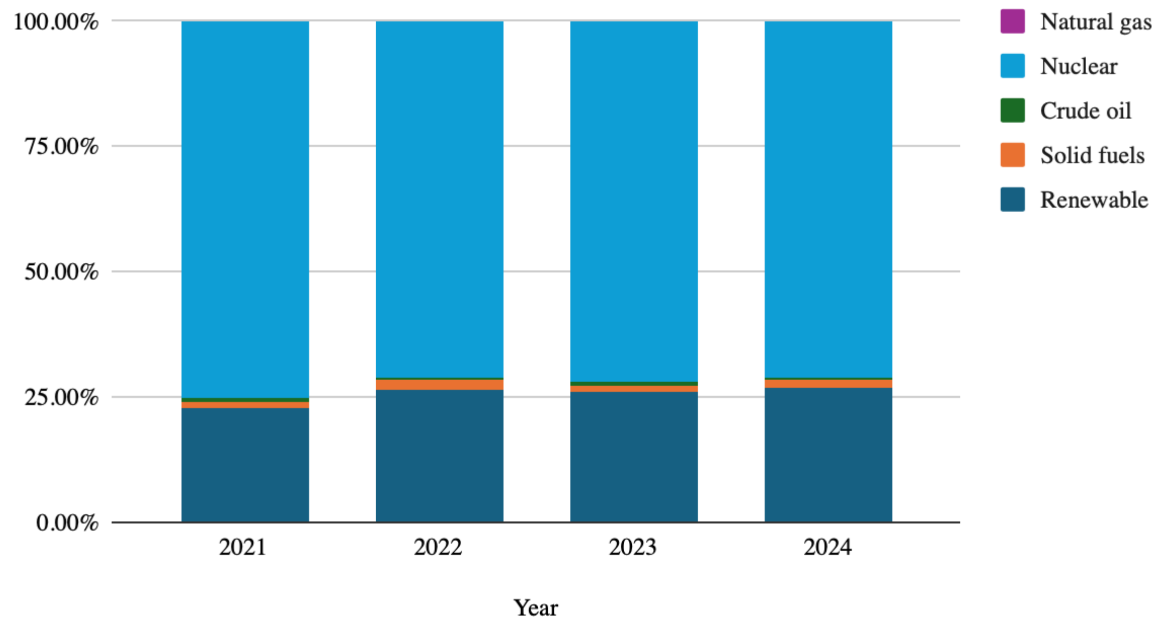
Germany has made substantial progress in its energy transition (Energiewende) in recent years, with the country moving away from both fossil fuels and nuclear power towards a renewables-based energy system. Renewable electricity generation has expanded significantly over the past decade, while nuclear power generation was fully phased out in 2023. Germany has also reduced its historically strong dependence on Russian energy imports, particularly oil and natural gas (IEA, 2025, April 7).

Consistent with the EU's broader energy and climate objectives, the government's "Easter Package" further strengthened the country's commitment to accelerating the deployment of renewable energy, making it a central element of Germany's energy strategy. Indeed, at the centre of Germany's Easter Package is the recognition that renewable energy serves an overriding public interest and contributes to energy security. The government aims for almost all electricity generation to come from renewable sources by 2035. To achieve this objective, the package provides for the development of additional sites for solar photovoltaics, greater participation of municipalities in onshore wind and solar projects, and the expansion of low-wind sites. It also seeks to create a more favourable regulatory framework for the deployment of rooftop solar installations (Federal Ministry for Economic Affairs and Climate Action, 2022).

These differences between the four countries provide substantial variation in electricity carbon intensity, which is central to the analysis of indirect carbon costs developed in the following sections.

4.2: Electricity generation by source, 2021-2024

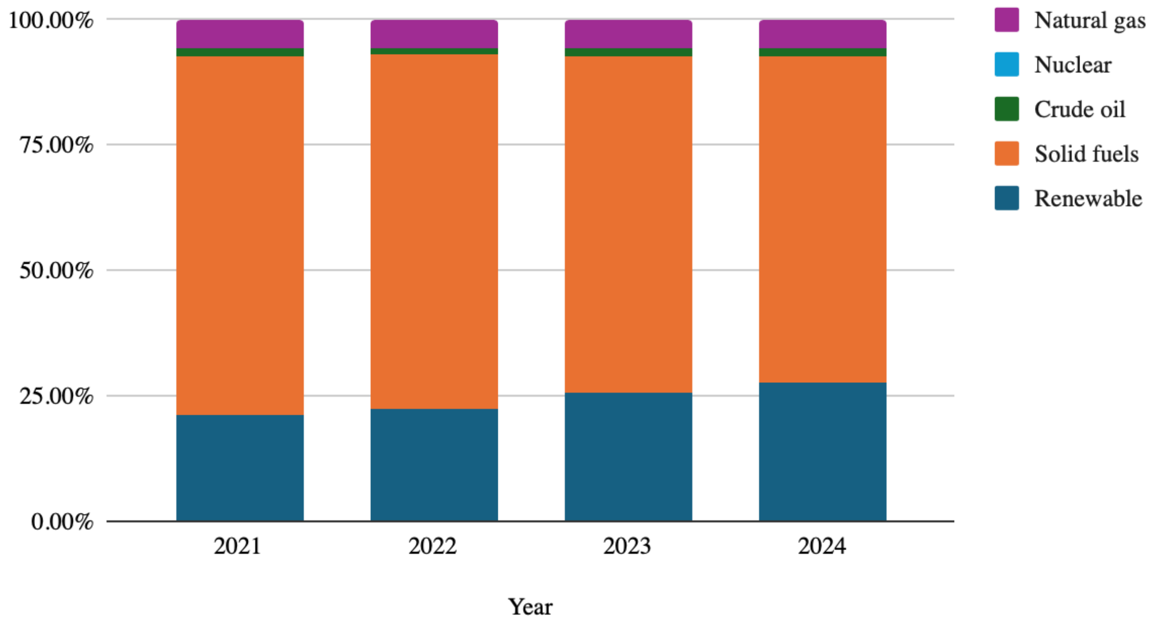
Figure 7: *Evolution of France's electricity generation mix, 2021-2024 (%)*



Source: adapted from data by Eurostat (2023, 2024, 2025, 2026). The complete raw data table broken down by source year is provided in Appendix A.

France's electricity generation mix remained strongly dominated by nuclear power throughout phase 4 of the EU ETS. Indeed, nuclear generation accounted for roughly 71-75% of electricity generation, while renewables represented around one-quarter of the mix. Fossil fuels played only a marginal role, with solid fuels and crude oil accounting for very small shares and natural gas being absent (Eurostat, 2023, 2024, 2025, 2026).

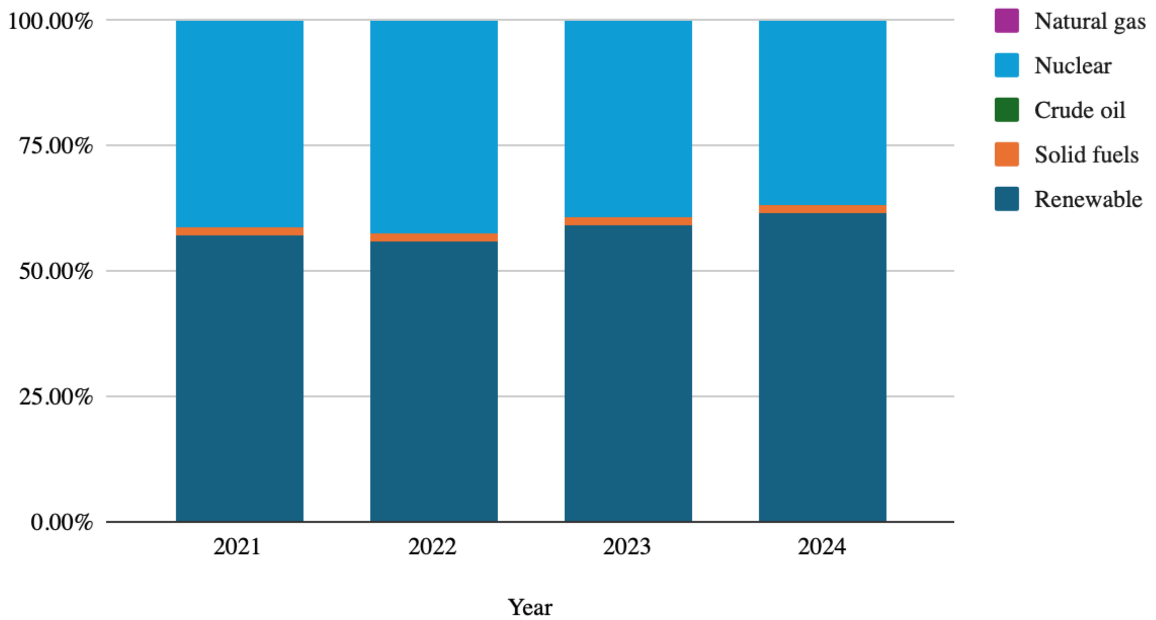
Figure 8: *Evolution of Poland's electricity generation mix, 2021-2024 (%)*



Source: adapted from data by Eurostat (2023, 2024, 2025, 2026). The complete raw data table broken down by source year is provided in Appendix B.

Poland remained heavily dependent on solid fuels throughout the period, even if their share declined gradually from 71.6% in 2021 to 65% in 2024. Renewable generation increased from 21.2% to 27.6%, showing a gradual diversification of the electricity mix, while natural gas remained relatively stable at around 6%. Unlike Germany, France, and Spain, Poland had no nuclear generation during the period. The country continued to rely predominantly on solid fuels, which make it the most carbon-intensive electricity mix among the four cases (Eurostat, 2023, 2024, 2025, 2026).

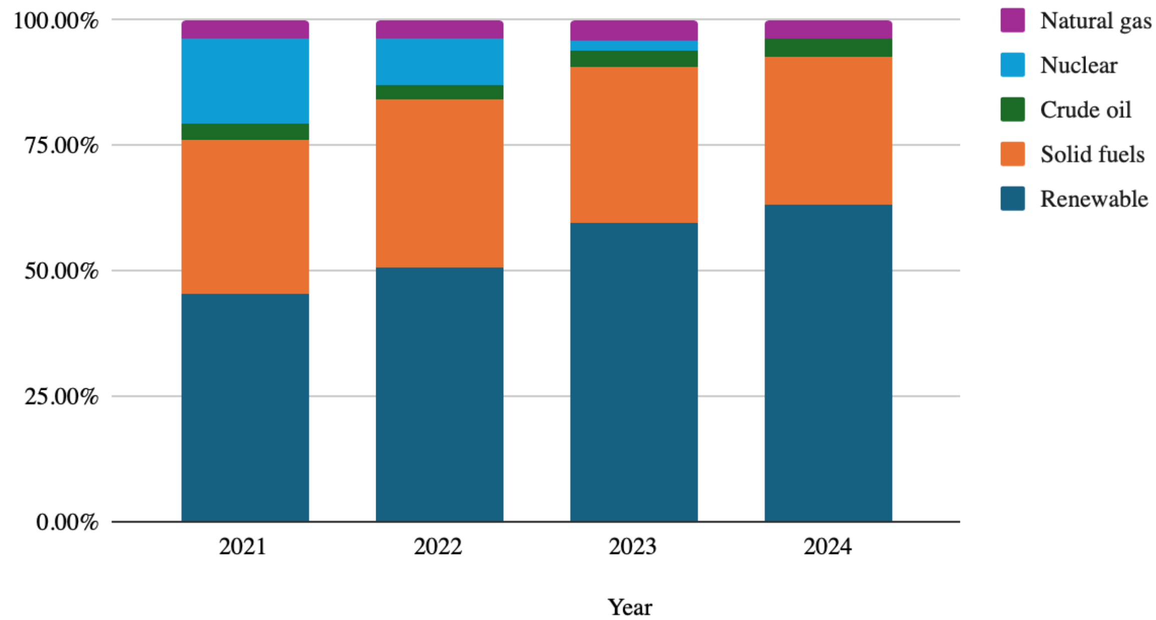
Figure 9: *Evolution of Spain's electricity generation mix, 2021-2024 (%)*



Source: adapted from data by Eurostat (2023, 2024, 2025, 2026). The complete raw data table broken down by source year is provided in Appendix C.

Spain's electricity mix was characterised by a high and increasing share of renewable generation. Renewables represented more than half of electricity generation throughout the period and reached over 60% in 2024. This increase was accompanied by a gradual decline in the contribution of nuclear power, although it remained substantial between 41.3% in 2021 and 36.8% in 2024. Fossil fuels played a negligible role in the electricity mix, with crude oil and natural gas generating respectively 0% or 0.1%, and solid fuels around 1.5% (Eurostat, 2023, 2024, 2025, 2026).

Figure 10: *Evolution of Germany's electricity generation mix, 2021-2024 (%)*



Source: adapted from data by Eurostat (2023, 2024, 2025, 2026). The complete raw data tables broken down by source year is provided in Appendix D.

Germany experienced a clear shift towards renewable electricity generation between 2021 and 2024. Indeed, the share of renewables increased substantially over the period, while nuclear power was progressively phased out and reached zero in 2024. At the same time, solid fuels remained an important component of the electricity mix, accounting for around one-third of generation (Eurostat, 2023, 2024, 2025, 2026).

4.3: EU ETS auction revenues

We will see in this subsection the variation and evolution of the revenues generated through the auctioning of EUAs across Germany, France, Spain, and Poland for the period 2021-2024. It is to be noted that numbers refer to revenues from the auctioning of general EUAs and exclude aviation allowances.

Germany has consistently had the highest auction revenues among the four cases, reflecting its large industrial base. The country's revenues increased from approximately €5.3 billion in 2021 (COM(2023) 654 final) to €6.8 billion in 2022 (COM(2024) 538 final, before reaching a peak of around €7.6 billion in 2023 (SWD(2024) 264 final). In 2024, the amount declined to around €5.5 billion (SWD(2025) 388 final). Despite this decline, Germany remained the country generating the largest auction revenues among the four cases throughout the period.

Poland and Spain occupied an intermediate position. Poland's revenues amounted to around €5.0 billion in 2021 (COM(2023) 654 final) and 2022 (COM(2024) 538 final). In 2023, they increased to approximately €5.4 billion (SWD(2024) 264 final), before declining to around €3.8 billion in 2024 (SWD(2025) 388 final).

Spain generated lower auction revenues than Poland during the period. They increased form around €2.5 billion in 2021 (COM(2023) 654 final) to €3.2 billion in 2022 (COM(2024) 538 final). A year later, they reached approximately €3.5 billion (SWD(2024) 264 final) and subsequently declined to around €2.6 billion in 2024 (SWD(2025) 388 final).

France recorded the lowest auction revenues among the four cases throughout the period. Its revenues increased from around €1.4 billion in 2021 (COM(2023) 654 final) to €1.8 billion in 2022 (COM(2024) 538 final). In 2023, they reached approximately €2.1 billion (SWD(2024) 264 final), before dropping to around €1.5 billion in 2024 (SWD(2025) 388 final).

Overall, the four countries followed a similar pattern over the period, with auction revenues increasing between 2021 and 2023, before declining in 2024. The initial increase to 2023 can be explained by a period of high EUAs prices, which in turn increased the value of allowances sold at auction. Indeed, in 2021 and 2022, EUAs prices increased sharply. The average price doubled in 2021compared with the previous year, reaching €54.15/t CO_2-eq. This upward trend continued in 2022, when the average price rose to €80.18/t CO_2-eq, with a peak of €97.51/t CO_2-eq, representing a historical high at the time. In 2023, the average EUA price remained relatively high at €83.60/t CO_2-eq. However, prices declined in 2024, with the annual average falling to €64.76/t CO_2-eq (Nissen et al., 2025).

As we saw, the amount of revenues generated varied significantly between the four countries. Throughout the period, Germany generated the highest revenues, followed by Poland, Spain, and France. See Table 1 for the exact numbers.

Table 1: *EU ETS auction revenues, 2021-2024 (€ million)*

Country	2021	2022	2023	2024
Germany	5 270.9	6 772.4	7 582.5	5 528.7
Poland	4 966.4	4 966.4	5 406.7	3 843.2
Spain	2 452.4	3 186.8	3 514.0	2 575.4
France	1 445.9	1 834.7	2 060.1	1 533.8

Source: COM(2023) 654 final, COM(2024) 538 final, SWD(2024) 264 final, SWD(2025) 388 final.

Chapter 5: Indirect carbon costs compensation

5.1: Absolute amount of compensation for indirect carbon costs

We will see in this subsection the absolute amount of compensation for the four cases throughout the period 2021-2024.

Table 2: *Absolute amount of compensation for indirect carbon costs, 2021-2014 (€ million)*

Country		2021	2022	2023	2024
Germany		806	1 643,70	2 395	323,7
Poland		167,6	372,7	614,6	614,7
Spain		244	228,8	282,8	244
France		300,2	604,2	908,8	833,8

Source: COM(2023) 654 final, COM(2024) 538 final, COM(2025) 735 final, EEA (2025) *Use of auctioning revenues generated under the EU Emissions Trading System*.

The four cases show significant differences in the amount of compensation for indirect carbon costs disbursed during the period covered. Germany recorded the highest level of compensation during the three first years. It increased from €806 million in 2021 to €1.64 billion in 2022, before a peak of around €2.4 billion in 2023. However, in 2024, indirect carbon cost compensation dropped to €323.7 million. Thus, Germany's compensation expenditure increased by almost threefold between 2021 and 2023 before falling importantly in the final year.

Poland recorded a gradual increase in compensation, from €167.6 million in 2021 to €372. 7 million in 2022, followed by a further increase to €614.6 million in 2023 and €614.7 million in the last year. Poland did not experience a reduction in compensation in 2024, unlike Germany.

France experienced the second largest increase in compensation among the four cases. The amount rose from €300.2 million in 2021 to €604.2 million in 2022. In 2023, it increased even further to €908.8 million. The last year of the period, compensation decreased moderately to €833.8 million, but represented the largest amount paid this year among the four countries. Thus, the French trajectory is characterised by a strong increase between 2021 and 2023, followed by a limited decline in 2024.

Spain presents a more stable pattern. Compensation decreased slightly from €244 million the first year to €228.8 million in 2022, and €282.8 million in 2023. In 2024, the amount paid for indirect carbon costs returned to €244 million. Overall, Spain's compensation remained within a relatively narrow range during the period.

Overall, the evolution of indirect carbon cost compensation presents significant variation between the cases. While Germany recorded the largest absolute payments during the three first year, France and Poland also experienced important increases during the period, with France recording the largest payment in 2024. Spain's compensation remained comparatively stable. The following section compares compensation expenditure with the revenues generated through auctioning and examines whether the relative importance of compensation varies across the four cases.

<u>5.2: Compensation as a share of ETS revenues</u>

To account for differences across the four Member States, indirect carbon cost compensation will be here expressed as a share of national ETS auction revenues. For 2021-2023, the share is based on COM(2023) 654 final, COM(2024) 538 final, and COM(2025) 737 final. The share for 2024 is calculated by dividing the amount of indirect carbon cost compensation paid this year by the corresponding revenue generated from the auctioning of EUAs, and multiplying the result by 100:

Compensation share (%) = (Indirect carbon cost compensation / ETS auction revenue) x 100.

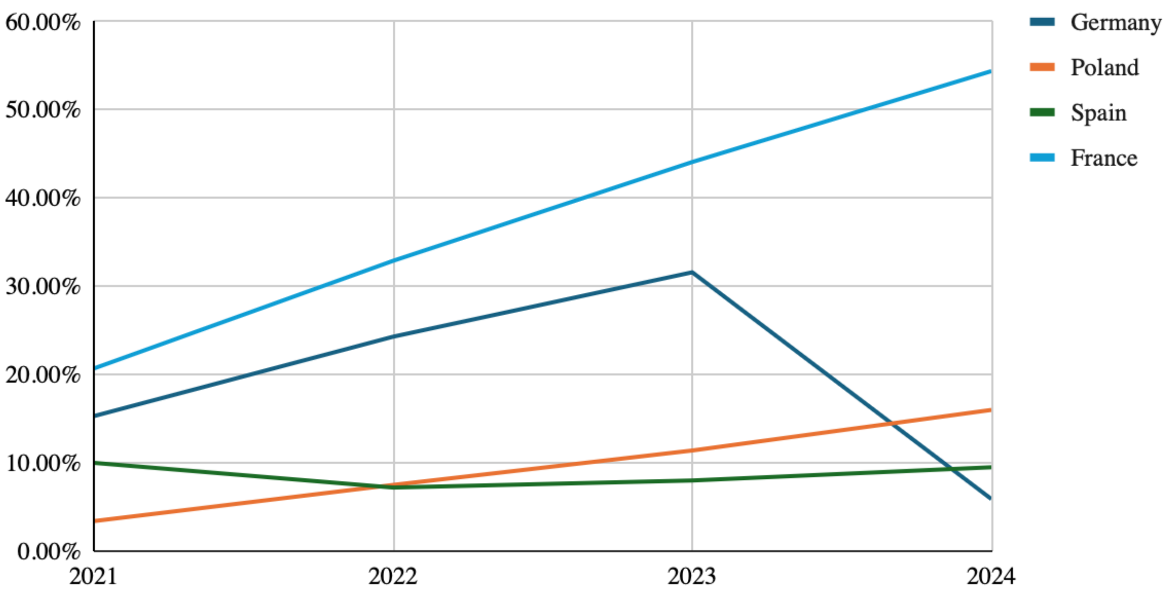
This measure makes it therefore possible to compare the relative importance of compensation expenditure across cases, independently of the aforementioned differences in the absolute amount of compensation.

Table 3: *Indirect carbon cost compensation as a share of ETS auction revenues, 2021-2024 (%)*

Country		2021	2022	2023	2024
Germany		15,30%	24,30%	31,60%	5,90%
Poland		3,40%	7,50%	11,40%	16%
Spain		10,00%	7,20%	8,00%	9,50%
France		20,70%	32,90%	44,10%	54,40%

Source: for 2024, the share was calculated based on data from EEA (2025). *Use of auctioning revenues generated under the EU Emissions Trading System*.

Figure 11: *Indirect carbon cost compensation as a share of ETS auction revenues, 2021-2024 (%)*



Source: adapted from the data provided in Table 3.

The results present significant differences in the size and the evolution of compensation relative to ETS revenues across the four cases. Germany experienced a strong increase between 2021 and 2023, with the compensation share rising from 15,3% in 2021 to 24,3% in 2022 and 31,6% in 2023. However, this upward trend was sharply reversed in 2024, when the share dropped to only 5,9%. Therefore, compensation represented a highly variable proportion of Germany's ETS revenues over the period.

Poland followed a more gradual and steadier upward trend. Its compensation share increased from 3,4% in 2021 to 7,5% in 2022, and further in 2023 with 11,4% and 16% in 2024. Thus, Poland consistently recorded a lower compensation share than Germany, except for the last year of the period covered. However, the steady increase is noteworthy and contrasts with the sharp decline observed in Germany in 2024.

France presents a particularly notable trajectory. Indeed, its compensation share increased from 20,7% in 2021 to 32,9% in 2022, before reaching 44,1% in 2023 and 54,4% in 2024. France therefore displayed the highest ratio of compensation compared to its revenues among the four cases in the four years of the period.

Spain displayed a relatively more stable trend among the four cases. Its compensation share decreased from 10% the first year to 7,2% in 2022, before a slight increase to 8% in 2023 and

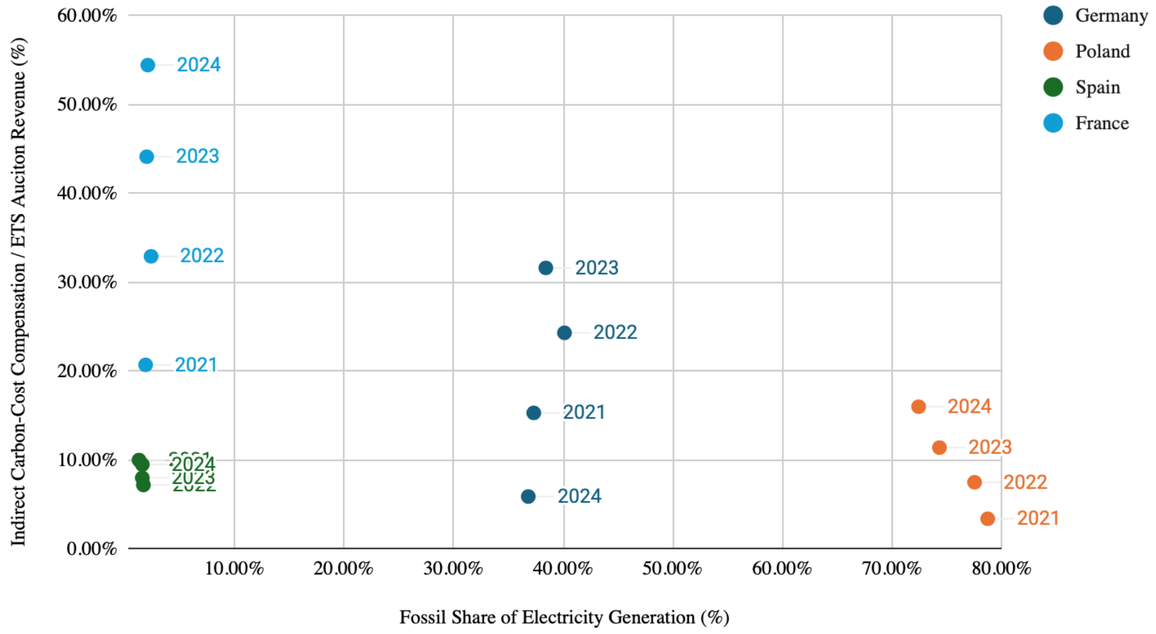
9,5% in 2024. Thus, the ratio remained close to 10% throughout the period, with much less variation than observed in Germany, Poland, or France.

Overall, the results provide an initial indication than the relationship between electricity generation and compensation is more complex than a simple linear relationship between fossil electricity and compensation. The four cases reveal very distinct patterns: a highly volatile trajectory in Germany, a gradual increase in Poland, a significant share of compensation coupled with a sustained increase in France, and relative stability in Spain. These findings provide an important basis for analysing between electricity generation and compensation in the following section.

5.3: Relationship between electricity mix and compensation for indirect carbon costs

The four cases showed important variations in both electricity generation sources and indirect carbon cost compensation. This section brings these two dimensions together and assess whether differences in the electricity mix are reflected in the relative importance of indirect carbon cost compensation. To make the analysis easier to compare, electricity generation sources are grouped into two categories: low-carbon generation, including renewable and nuclear energy, and fossil-based generation, including solid fuels, natural gas, and oil. The fossil share is used as a simplified indicator of the carbon intensity of the electricity systems. Then, this share is compared with the share of ETS auction revenues paid for indirect carbon cost compensation.

Figure 12: *Relationship between fossil share of electricity generation and indirect carbon cost compensation as a share of ETS revenues, 2021-2024 (%)*



Source: for the electricity mix, adapted from data by Eurostat (2023, 2024, 2025, 2026). For the compensation as a share of ETS revenues, adapted from COM(2023) 654 final, COM(2024) 538 final, COM(2025) 737 final, and EEA (2025). *Use of auctioning revenues generated under the EU Emissions Trading System*. The complete raw data table is provided in Appendix E.

The results do not indicate a simple positive link between the fossil intensity of electricity generation and the relative importance of compensation for indirect carbon cost. Poland provides the clearest example. The fossil intensity of its electricity generation was by far the most important throughout the period, representing more than two-third of total generation. However, its compensation share remained relatively low, with an increase from 3,4% in 2021 to 16% in 2024. This suggests that a highly carbon-intensive electricity generation system does not necessarily result in a high proportion of ETS revenues being disbursed to indirect carbon cost compensation.

France constitutes an opposite case. Its fossil share was extremely low throughout the period, reflecting that low-carbon sources were predominant for its electricity generation. Nevertheless, the country had the highest compensation shares among the four cases from 2021 onwards. The ratio went up from 20,7% in 2021 to 32,9% in 2022, 44,1% in 2023 and 54,4% in 2024.

Spain displays the most stable pattern. Its fossil share remained low during the period, between 1,3% and 1,7%, while its compensation share varied within a narrow range between 7,2% and 10%. The Spanish case appears to be consistent with the coexistence of a predominantly low-carbon electricity system and a moderate compensation for indirect carbon cost. However, Spain's limited variation in both indicators make it hard to provide any type of relationship between changes in electricity generation and compensation.

The graph shows that the German's compensation trajectory was highly volatile. Its fossil share remained within a narrow range, between 36,8% and 40,1%, while its compensation share rose from 14,3% in 2021 to 24,3% in 2022 and 31,6% in 2023. A sharp change occurred in 2024, with the compensation share falling to only 5,9%. The German case therefore shows that changes in the relative importance of compensation cannot be directly inferred from changes in the fossil share of electricity generation. Indeed, the substantial increase in compensation between 2021 and 2023 did not come with an equivalent increase in fossil electricity generation.

Chapter 6: Conclusions

This thesis has examined the interaction between electricity mix and the share of ETS revenues allocated to indirect carbon cost compensation, in an attempt of addressing the following research question:

How does the electricity mix influence indirect carbon cost compensation under the EU ETS during phase IV (2021-2024)?

In order to answer this question, my hypotheses were the following:

H1: Countries with more carbon-intensive electricity generation allocate a higher share of ETS auction revenues to indirect carbon cost compensation.

H2: Changes in the electricity generation mix over time are associated with changes in the share of ETS auction revenues allocated to indirect carbon cost compensation (change a bit).

H3: Countries with similar electricity generation structures can display different levels of indirect carbon cost compensation relative to their ETS auction revenues.

6.1: Research findings

H1 is rejected from the empirical findings. Indeed, the comparison of Germany, Poland, Spain, and France does not show a clear positive relationship between the fossil share of electricity generation and the compensation for indirect carbon cost compared to ETS revenues. The sore contrast between Poland and France allows to reject this hypothesis. Poland, which had by far the most fossil-intensive electricity system throughout the period covered recorded relatively low compensation share, from 3,4% in 2021 to 16% in 2024. On the contrary, France recorded the highest compensation share each year, from 20,7% in 2021 to 54,4% in 2024, while the country had one of the lowest fossil shares, at around only 2%. Therefore, if a more carbon-intensive electricity mix may contribute to indirect carbon cost pressure, it appears that it does not translate automatically into a higher share of ETS revenues being allocated to compensation.

H2 is also rejected. The results show some temporal movement, but the relationship is inconsistent. Germany’s compensation share rose substantially between 2021 and 2023 despite the fossil share of its electricity mix remaining relatively consistent. Moreover, the important drop in its compensation share, from 31,6% in 2023 to only 5,9% in 2024, was not accompanied by a proportional fall in the fossil share of its electricity mix.

Poland experienced a gradual increase in its compensation share, while also showing a continuous reduction in its fossil electricity share. Spain's results revealed limited changes in both indicators, whereas France experienced a strong increase in compensation despite maintaining a predominantly low-carbon electricity generation system.

H3 receives stronger support from the comparative evidence. The pattern is clearly visible when comparing France and Spain. Indeed, both countries maintained very low fossil shares throughout the period, while their compensation shares followed different trajectories, with France's ratio rising from 20,7% in 2021 to 54,4% in 2024, and Spain's remaining stable below 10%. The contrast between these two cases demonstrates that similar broad electricity-generation structures can be accompanied by very different compensation outcomes.

Overall, the assessment of our three hypotheses suggests that the relationship between electricity generation and indirect carbon cost compensation is more complex than initially expected. It appears that the electricity mix is an important component of the mechanism through which EU ETS carbon costs can be transmitted to electricity consumers, but it cannot explain by itself the variation observed across Member States in compensation.

6.2: Limitations

Several limitations must be acknowledged. First, the scope of this study was limited to only four case studies. These countries were deliberately selected for two reasons: they represent very different electricity generation structures, and they generate the largest ETS auction revenues. However, the selection of four countries limits the generalisability of the patterns identified in this study.

A second limitation lies in the measurement of electricity carbon intensity. This thesis uses the fossil share of electricity generation as a simplified indicator for the carbon intensity of national electricity systems, which provides a useful basis for making the distinction between predominantly fossil-based from predominantly low-carbon electricity systems. However, it does not capture variation in the emissions intensity of individual generation sources. Indeed, coal, natural gas, and oil have different carbon intensities (American Geosciences Institute, n.d.), meaning that two countries with the same fossil share may have differences in their emissions per unit of electricity generated.

Third, the study does not examine the national factors that may explain differences in compensation between countries. Different industrial composition, national implementation of the EU State Aid framework, sectors eligible for compensation, and electricity consumption by energy-intensive industries, among other elements, may contribute to the divergent patterns identified in the empirical analysis.

6.3: Recommendations for further research

Future research could address these limitations by expanding the analysis to a larger number of EU Member States and extending the observation period as additional data for Phase IV become available. Future studies could also use direct measures of electricity carbon intensity, such as CO_2 emissions per kWH, and add indicators of sectoral exposure to indirect carbon costs and industrial electricity consumption. Another promising would be to analyse national compensation schemes and State Aid implementation, which may help explain the significant differences observed between countries with similar electricity-generation structures. These approaches would allow for a more comprehensive assessment of the factors determining indirect carbon cost compensation under the EU ETS.

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Appendix A

France’s electricity generation data table (2021-2024)

France	year	Renewable	Solid fuels	crude oil	nuclear	natural gas
	2021	22.8%	1.3%	0.6%	75.3%	0.0%
	2022	26.6%	1.7%	0.7%	70.9%	0.0%
	2023	26.0%	1.4%	0.6%	71.9%	0.0%
	2024	26.9%	1.5%	0.6%	71.0%	0.0%

Data retrieved from Eurostat (2023, 2024, 2025, 2026).

Appendix B

Poland’s electricity generation data table (2021-2024)

Poland	year	Renewable	Solid fuels	crude oil	nuclear	natural gas
	2021	21.2%	71.6%	1.5%	0.0%	5.6%
	2022	22.4%	70.5%	1.5%	0.0%	5.5%
	2023	25.7%	66.9%	1.6%	0.0%	5.8%
	2024	27.6%	65.0%	1.6%	0.0%	5.8%

Data retrieved from Eurostat (2023, 2024, 2025, 2026).

Appendix C

Spain’s electricity generation data table (2021-2024)

Spain	year	Renewable	Solid fuels	crude oil	nuclear	natural gas
	2021	57.3%	1.3%	0.0%	41.3%	0.0%
	2022	56.1%	1.6%	0.0%	42.2%	0.1%
	2023	59.3%	1.5%	0.0%	39.2%	0.1%
	2024	61.6%	1.5%	0.0%	36.8%	0.1%

Data retrieved from Eurostat (2023, 2024, 2025, 2026).

Appendix D

Germany's electricity generation data table (2021-2024)

Germany	Year	Renewable	Solid fuels	crude oil	nuclear	natural gas
	2021	45.6%	30.7%	2.9%	17.1%	3.7%
	2022	50.6%	33.5%	2.9%	9.2%	3.7%
	2023	59.4%	31.2%	3.3%	2.2%	3.9%
	2024	63.2%	29.5%	3.5%	0.0%	3.8%

Data retrieved from Eurostat (2023, 2024, 2025, 2026).

Appendix E

Relationship between electricity generation structures and indirect carbon cost compensation as a share of ETS revenues

Country	year	Fossil Share	compensation Share
Germany	2021	37,30%	15,30%
Germany	2022	40,10%	24,30%
Germany	2023	38,40%	31,60%
Germany	2024	36,80%	5,90%
Poland	2021	78,70%	3,40%
Poland	2022	77,50%	7,50%
Poland	2023	74,30%	11,40%
Poland	2024	72,40%	16%
Spain	2021	1,30%	10,00%
Spain	2022	1,70%	7,20%
Spain	2023	1,60%	8,00%
Spain	2024	1,60%	9,50%
France	2021	1,90%	20,70%
France	2022	2,40%	32,90%
France	2023	2,00%	44,10%
France	2024	2,10%	54,40%

For the electricity mix, data retrieved from Eurostat (2023, 2024, 2025, 2026). For the compensation as a share of ETS revenues, data retrived from COM(2023) 654 final, COM(2024) 538 final, COM(2025) 737 final for 2021, 2022, 2023. For 2024, calculated from data retrieved from EEA (2025). *Use of auctioning revenues generated under the EU Emissions Trading System*.