Dipartimento di Impresa e Management

LM-77 Management

Analysis of Market Dynamics in Emissions Trading Systems: Prices and Volatility

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Index

1. Introduction

Climate change is regarded as one of the most intricate and pressing global challenges in the present socio-political context. The repercussions of climate change and global warming have been substantiated through a myriad of international studies and reports, thereby validating their existence. The proliferation of extreme phenomena, in conjunction with the escalating pressure on natural resources, is causing profound modifications to the environment, which may lead to deleterious consequences for the planet's ecological, political, economic, and social balance.

To provide further substantiation for the aforementioned statements, the document entitled “Climate and Catastrophe Insight (2025)” [1] prepared by the consulting firm AON will be cited. As indicated in Figure 1 of the report, economic losses amounting to $368 billion were incurred in 2024 due to occurrences of extreme natural events.

Figure1: Key statistics on economic and insured losses, natural disasters, and global climate records in 2024

Figure 1: Source: Aon (2025), Climate and Catastrophe Insight, p. 3.

A critical component of this transformation is the mitigation of greenhouse gas (GHG) emissions. It is evident that rising average global temperatures, which are directly linked to increased GHG emissions, contribute to global warming and, consequently, the intensification of extreme weather phenomena. The underlying causes of this

[1] **Aon. (2025).** *Climate and Catastrophe Insight*. Aon. Retrieved from https://www.aon.com/en/insights/reports/climate-and-catastrophe-report

phenomenon are thoroughly delineated in the 2023 Intergovernmental Panel on Climate Change (IPCC) report, titled “Climate and Catastrophe Insight”[2]. This seminal report unequivocally states that the predominant cause of global warming is attributable to anthropogenic activity, thereby establishing a definitive link between human influence and climatic shifts on a global scale. The aforementioned report states the following: “*Human activities, principally through emissions of greenhouse gases, have unequivocally caused global warming, with global surface temperature reaching 1.1°C above 1850-1900 in 2011-2020. Global greenhouse gas emissions have continued to increase, with unequal historical and ongoing contributions arising from unsustainable energy use, land use and land-use change, lifestyles and patterns of consumption and production across regions, between and within countries, and among individuals*” (IPCC, 2023).

In the 2023 IPCC report, the organization asserts that rising global temperatures represent one of numerous greenhouse gas-induced consequences. In the absence of further adaptation, it is evident that this phenomenon will exert an even greater impact on natural and socioeconomic systems.

As illustrated in Figure 2, several potential scenarios are presented, emphasizing particular critical factors.

[2] **Intergovernmental Panel on Climate Change (IPCC). (2023).** *AR6 Synthesis Report: Climate Change 2023*. IPCC. Retrieved from https://www.ipcc.ch/report/sixth-assessment-report-cycle/

Figure 2: Future climate change without additional adaptation

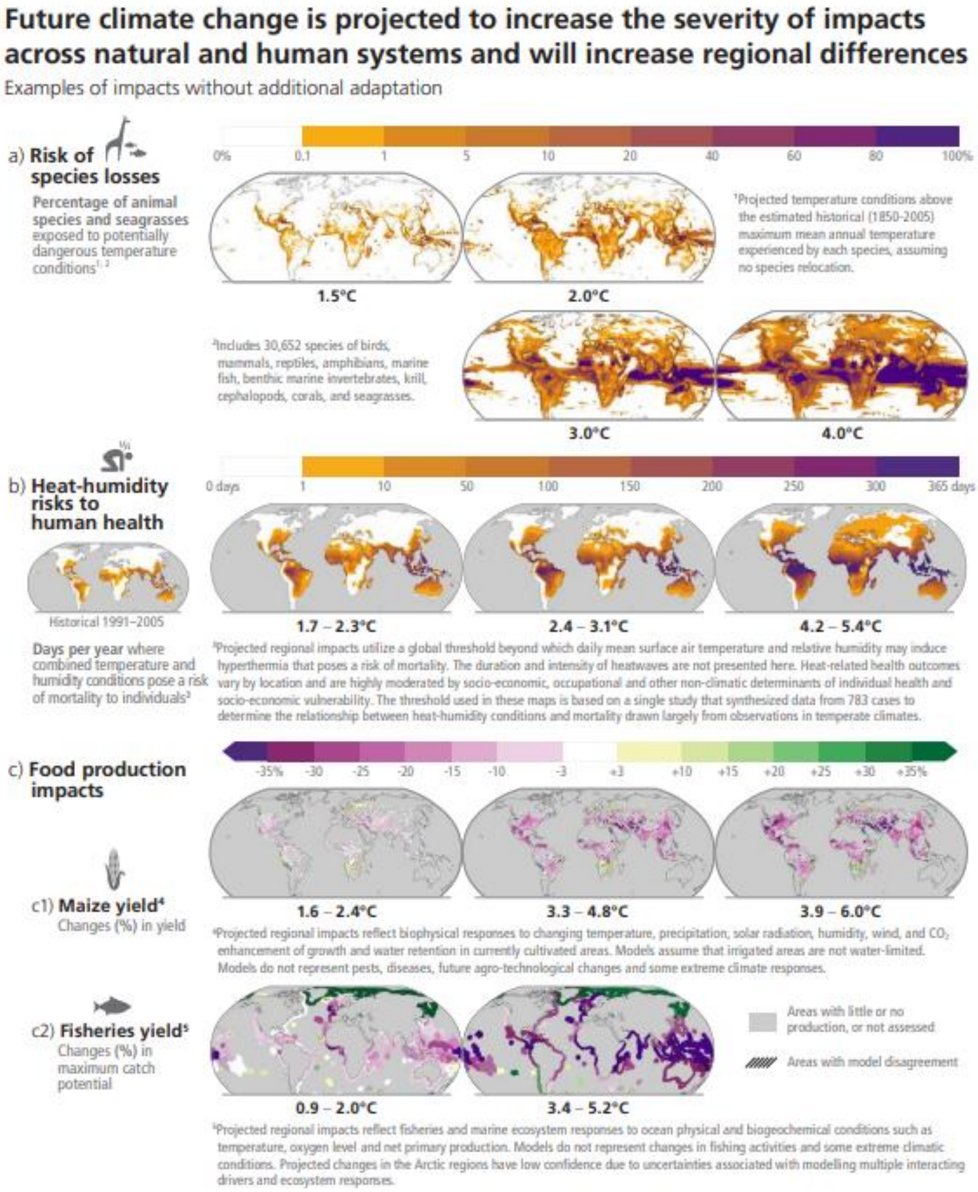

Figure 2: Source: IPCC AR6 Synthesis Report, 2023, p.9.

These findings underscore the multifaceted nature of climate change, demonstrating its role not only as a risk factor for environmental degradation but also as a catalyst for broader socio-economic challenges. Consequently, the implementation of effective strategies to mitigate the effects of such emissions on Earth's ecosystems is essential.

One of the tools at our disposal for addressing this issue is the Emission Trading System (ETS) market. According to the definition established by ICAP, an ETSs is characterized as follows: "*is a market-based instrument that can be used to reduce greenhouse gas (GHG) emissions*"[3].

1.1 What are ETS Markets?

Emission Trading Systems (ETS) are a form of market-based environmental policy instrument designed to reduce greenhouse gas (GHG) emissions cost-effectively.

The fundamental principle underlying the operation of an emissions trading system, or ETS, has been designated as "cap-and-trade"[4]. Government authorities in the respective states where market activity is taking place have established a limit on emissions. This limit is collectively referred to as a "*cap*"[5]. The cap is equivalent to the maximum number of allowances that can be issued within a specified time frame within the system. Each allowance confers the right to emit one ton of $MtCO_2e$ (carbon dioxide equivalent)[6,7]. Companies within these markets will also have the power to proceed to buy or sell their allowances, based on specific "trade" needs.

The implementation of this regulatory framework enables the establishment of an economic value for emissions, thereby transforming pollution into a commodifiable resource. The adoption of these markets has been demonstrated to have a positive influence on companies, encouraging them to improve their practices and invest in more sustainable technological solutions with the ultimate goal of gaining economic benefits from the sale of their allowances.

A substantial diversification of Emission Trading System (ETS) markets has been observed on a global scale and at various levels of governance, including regional, national, and sub-national levels, with notable participation from a diverse range of sectors, such as energy, transport, industry, among others. Notwithstanding the discrete attributes inherent within the various systems in operation, a uniform objective is evident:

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[3] **International Carbon Action Partnership (ICAP). (2023).** *Emissions Trading Systems: Introduction and overview* (ICAP Brief No. 1). https://icapcarbonaction.com/system/files/document/icap_briefs-en-brief-1.pdf
[4] **Oxford University Press. (n.d.).** *Cap and trade*. Retrieved from https://www.oxfordlearnersdictionaries.com/definition/english/cap-and-trade
[5] **International Carbon Action Partnership (ICAP). (2023).** *Emissions Trading Systems: 7 reasons for emissions trading* (ICAP Brief No. 2). https://icapcarbonaction.com/system/files/document/icap_briefs-en-brief-2.pdf
[6] **European Commission. (n.d.).** *EU ETS emissions cap*. Climate Action - European Commission. Retrieved, from https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/eu-ets-emissions-cap_en
[7] CO_2eq is the unit of measurement for the impact of different greenhouse gases (GHGs) on global warming in terms of the amount of CO2 calculated on the basis of the Global Warming Potential index. **zeroCO2. (n.d.).** *CO_2 equivalent: What it is and how it is calculated*. Retrieved from https://zeroco2.eco/en/magazine/environment/co2-equivalent/

the mitigation of greenhouse gas emissions through the implementation of cap-and-trade mechanisms.

As illustrated in Figure 3, there is a global prevalence of markets, as well as a considerable number that are still in the developmental phase or are in the planning stage.

Figure 3: Emissions trading worldwide, the current state of play

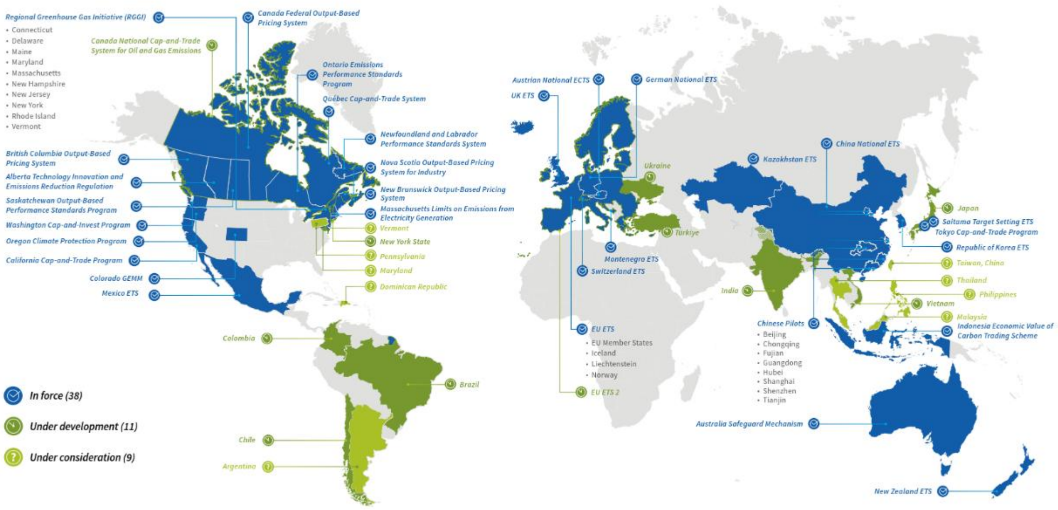

Figure 3: Source: ICAP, 2025.[8]

1.2How does ETS Markets Works?

As previously mentioned, Emission Trading System (ETS) markets are based on the principle of cap-and-trade. In accordance with the regulatory framework governing these specific marketplaces, companies are obligated to relinquish their allowances, equivalent in quantity to their documented emissions. This disposition aligns with the stipulated compliance period that governs their operational domain.

The allocation of allowances across various markets is governed by two primary mechanisms.

1) *Free allocation*: In sectors most vulnerable to competition from other sectors or from foreign players, this is especially crucial in order to prevent a phenomenon

[8] **International Carbon Action Partnership (ICAP). (2025).** *ETS map: Emissions Trading Systems worldwide*. Retrieved from https://icapcarbonaction.com/en/ets

known in academia as "Carbon Leakage”[9]. Free allocation can be executed through two distinct methodologies:

1.1) *Grandparenting*: The allocation of permits to companies is contingent upon their historical or previous emissions. While this process appears straightforward, its efficacy in reducing emissions is questionable. A concurrent decrease in the baseline level of emissions would be required to observe a net reduction, which this approach may not achieve. Therefore, a reduction in emissions would not be advantageous for companies. This is because the reduction would result in a decrease in the allowances allocated to companies.

1.2) *Benchmarking*: Companies receive allowances based on a set of performance indicators, commonly referred to as "benchmarks." These terms refer to the emissions intensity of a particular product or sector within the context of the operations of the specific company.

2) *Auction*: Companies will be required to purchase the shares, and the price of the shares will be determined in the usual market way[10].

The implementation of these methodologies exhibits considerable variation across different global markets. Nonetheless, it is widely accepted that, in nascent market contexts, auctions are employed, albeit to a limited extent. However, as the market matures, this tendency to intensify is observed to occur in later stages.

As illustrated in Figure 4, the global distribution of emission allowances through ETS markets in 2023 showcases the current state of these markets.

[9] Carbon leakage refers to the situation that may occur if, for reasons of costs related to climate policies, businesses were to transfer production to other countries with laxer emission constraints. This could lead to an increase in their total emissions. **European Commission, (n.d.).** Retrieved from: https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/free-allocation/carbon-leakage_en

[10] **International Carbon Action Partnership (ICAP). (2023).** *Emissions Trading Systems: how emissions allowances are distributed* (ICAP Brief No. 5). https://icapcarbonaction.com/system/files/document/icap_briefs-en-brief-5.pdf

Figure 4: How allowances are distributed across ETS markets

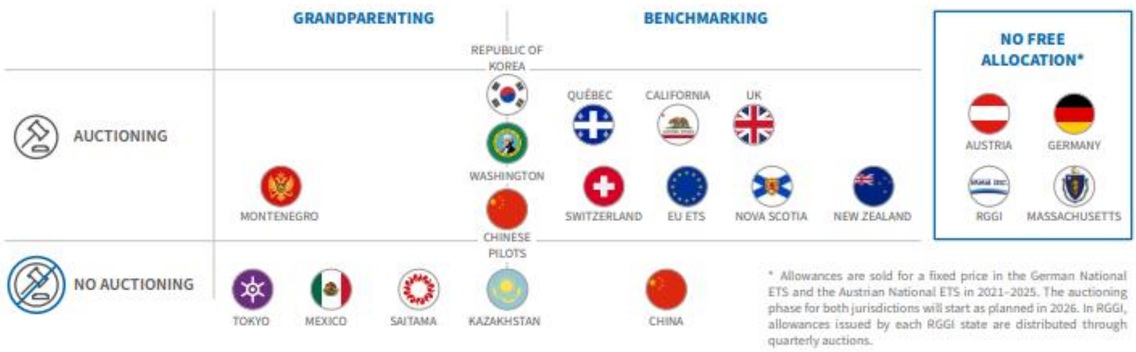

Figure 4: Source: ICAP Brief #5, 2023, p.2[11]

Furthermore, each ETS possesses the capacity to exercise a certain degree of flexibility in its decision-making processes. This flexibility can be divided into four main thematic areas:

1) Banking and Borrowing
2) Length of compliance period
3) Use of Offset credits
4) Use of revenues

Banking and Borrowing

The term "banking" refers to the market practice of allowing companies to retain a portion of allowances received or purchased during the year for use in a future period. Firms that adopt this strategy will experience a reduction in emissions in the short term and will be able to plan with greater efficacy for the future by maintaining a reserve of permits (allowances) for any potential future excess emissions. However, it should be noted that this dynamic may ultimately contribute to elevated emission levels during the subsequent phases of the market's evolution.

The term 'borrowing' is employed to denote the anti-banking practice, that is to say, the capacity of commercial enterprises operating within the market to obtain emission allowances that they will be certain to receive for free in the future. This methodological

[11] **International Carbon Action Partnership (ICAP). (2023).** *Emissions Trading Systems: how emissions allowances are distributed* (ICAP Brief No. 5). https://icapcarbonaction.com/system/files/document/icap_briefs-en-brief-5.pdf

approach confers a number of significant advantages upon companies, particularly in the context of formulating a regulatory compliance strategy. Nevertheless, this approach may result in delays in the attainment of the emission reduction target by the ETS market. [12]

Figure 5 illustrates the decisions made by markets in this area (2023).

Figure 5: Which way ETS Markets allows banking and borrowing

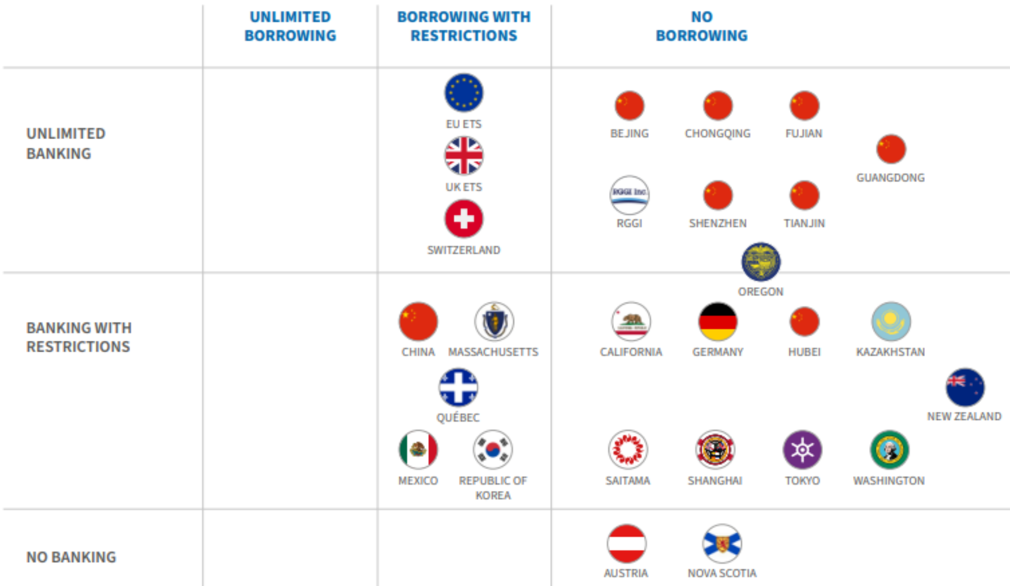

Figure 5: Source: ICAP Brief #8, 2023, p.2

Length of compliance period

The term "Compliance Period" refers to the time frame during which companies are obligated to meet their emission reduction obligations. This is distinct from the trading period or phase, which refers to specific time periods during which certain rules are implemented in the Energy Trading System (ETS) market. A given trading period could encompass multiple compliance periods, thus demonstrating a high degree of adaptability within a broader regulatory framework.

In light of this consideration, the periodicity of compliance may be subject to variation in accordance with prevailing market regulations. On average, the duration of such a period range from one to three years. A longer time frame may permit companies to fulfil the

[12] **International Carbon Action Partnership (ICAP). (2023).** *Banking and Borrowing (Brief #8)*. Retrieved from https://icapcarbonaction.com/system/files/document/icap_briefs-en-brief-8.pdf

established benchmarks over a more protracted period. However, it is important to consider the possibility that this could result in a concurrent increase in the time required to achieve established market targets.[13]

Use of Offset Credits

The term "Offset Credits" refers to: "*voluntary initiatives undertaken by companies and individuals to support environmentally-sustainable projects and reduce GHG emissions*." (Dalrada Energy)[14]. Typically, these projects are initiated as a part of broader emission reduction or elimination initiatives, which are subsequently certified through credit mechanisms, thereby ensuring their environmental integrity. The primary concern with these credits pertains to their propensity to increase the limit (cap) imposed within the market. Additionally, the valuation process is not always executed with absolute precision. Due to these problems to maintain quality standards, these devices are often restricted in terms of type, source, and quantity.

In 2023, the situation regarding the use of offset credits was outlined as highlighted in Figure 6[15].

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[13] **International Carbon Action Partnership (ICAP). (2023).** *Emissions Trading Systems: banking and borrowing* (ICAP Brief No. 8). https://icapcarbonaction.com/system/files/document/icap_briefs-en-brief-8.pdf
[14] **Dalrada Energy. (n.d.).** *Explaining carbon credits and offsets*. Retrieved, from https://dalradaenergy.com/explaining-carbon-credits-and-offsets/
[15] **International Carbon Action Partnership (ICAP). (2023).** *Emissions Trading Systems: offset credits in emissions trading* (ICAP Brief No. 7). https://icapcarbonaction.com/system/files/document/icap_briefs-en-brief-7.pdf

Figure 6: Offset programs around the world.

Figure 6: Source: ICAP Brief #7, 2023, p.2

Use of Revenues

As previously stated, a proportion of the permits available in the market are distributed through an auction process. As indicated by the latest data, since 2008, auctions of this type have contributed to revenues that have amounted to a sum of 224 billion in the year 2022. Consequently, governments can utilize these revenues in a variety of ways. The following are the most common types:

- Financial assistance to disadvantaged groups: "*Governments can support low-income households or vulnerable communities to counter rising energy costs and to facilitate the transition to a low-carbon economy*" (ICAP Brief #6, 2023)
- Fund climate actions: "*Governments can invest in adaptation, renewable or other low-carbon technologies, energy efficiency, clean transport infrastructure, waste management, and forestry*" (ICAP Brief #6, 2023)
- Contribution to the public budget: "Governments can use ETS auction revenues to reduce taxes, finance other policy priorities, or to reduce budget deficits." (ICAP Brief #6, 2023)[16]

[16] **International Carbon Action Partnership (ICAP). (2023).** *Use of Revenues from Emissions Trading (Brief #6)*. Retrieved from https://icapcarbonaction.com/system/files/document/icap_briefs-en-brief-6.pdf

1.3Price and Volatility in the ETS Markets

In the specific context of the ETS markets under analysis, the price of allowances exerts a substantial influence in directing corporate investment decisions toward low-emission technologies. Consequently, it is imperative for policymakers to consider this aspect when formulating strategies to enhance market efficiency and promote continuous progress.

Additionally, the volatility patterns inherent within these markets must be taken into account. Such volatility has the potential to generate uncertainty and undermine the efficacy of the system in its entirety, resulting in diminished accuracy of market signals and, consequently, a perception of limited stability.

Given the evidence presented, a comprehensive understanding of the dynamics influencing these aspects is essential for evaluating the functionality and efficiency of Emission Trading System (ETS) markets.

In recent years, the academic community has proposed a multitude of analyses concerning the determinants of price and volatility in ETS (Emissions Trading System) markets, with a particular focus on the EU-ETS (European Union Emissions Trading System). A body of research, including studies undertaken by Alberola, Chevallier and Chèze (2009)[17], Chevallier (2011)[18], Creti et al. (2012)[19], Lutz et al. (2013)[20] e Li et al. (2021)[21], has demonstrated how macroeconomic, energy, and climate variables significantly influence the system under investigation. However, such studies frequently exhibit recurrent limitations.

Firstly, the majority of studies have focused on examining a single market, predominantly the EU-ETS, thereby overlooking alternative geographic and regulatory contexts, such as the California (CA CaT) and Korean (K-ETS) systems. Secondly, there is a paucity of systematic comparative studies that directly compare different ETS markets and, consequently, their respective performances. Ultimately, the preponderance of extant

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[17] **Alberola, E., Chevallier, J., & Chèze, B. (2009).** Emissions compliances and carbon prices under the EU ETS: A country-specific analysis of industrial sectors. *Journal of Policy Modeling*, 31(3), 446–462. https://doi.org/10.1016/j.jpolmod.2008.12.004
[18] **Chevallier, J. (2011).** *Carbon price drivers: An updated literature review*. HAL. https://halshs.archives-ouvertes.fr/halshs-00586513
[19] **Creti A, Jouvet PA, Mignon V (2012)** Carbon price drivers: Phase I versus Phase II equilibrium? Energ Econ 34: 327–334. http://dx.doi.org/10.1016/j.eneco.2011.11.001
[20] **Lutz BJ, Pigorsch U, Rotfuss W (2013)** Nonlinearity in cap-and-trade systems: The EUA price and its fundamentals. Energ Econ 40: 222–232. https://doi.org/10.1016/j.eneco.2013.05.022
[21] **Li, P., Zhang, H., Yuan, Y., & Hao, A. (2021).** Time-Varying Impacts of Carbon Price Drivers in the EU ETS: A TVP-VAR Analysis. *Frontiers in Environmental Science*, 9, 651791. https://doi.org/10.3389/fenvs.2021.651791

research has relied on the implementation of linear econometric models. These models are found to have limitations in their ability to capture the entirety of the relationships present in complex markets, such as those observed in carbon trading. This deficit can lead to a loss of information, which is particularly salient in scenarios where nonlinear or complex relationships are in existence.

Moreover, the absence of integrated analysis regarding the factors influencing price and volatility constitutes a significant lacuna within the academic sphere. Despite the existence of a demonstrable correlation between the two phenomena, these studies are conducted independently. This limitation impedes the capacity to formulate a systemic analysis, thereby hindering the attainment of a comprehensive understanding of the phenomena observed in the markets under investigation.

The emergence of these gaps underscores the necessity for further investigation through targeted and systematic research, that allows to:

- Broaden the horizon of markets covered in previous research to include less explored markets such as CA CaT and K-ETS.
- Apply a uniform comparative methodology in order to highlight common traits and differences present among markets.
- Use heterogeneous econometric models that are not only able to capture possible relationships that are more complex than a classical linear model, but that ultimately provide a complete picture of all possible relationships present.
- Integrate the analysis of price with that of volatility in order to provide a deeper understanding of these two phenomena.

This thesis addresses the aforementioned research gap by making an original contribution from the perspectives of both theory and practical application.

1.4Research Objectives and Methodological Approach

In accordance with the preceding discussion, this study aims to examine the determinants of price and volatility in ETS markets. In order to achieve this objective, a comparative analysis of three representative systems will be conducted. The analysis will identify the key determinants that influence the dynamics of these markets.

- European Emission Trading System (EU-ETS) – Europe.
- California Cap-and-Trade (CA CaT) – California, USA.
- Korea Emission Trading System (K-ETS) – South Korea.

The central question to which this analysis is intended to contribute an answer is as follows:

What are the main determinants that influence the price and volatility of allowances in carbon trading markets and how do these differ in the EU-ETS, CA CaT and K-ETS systems?

The research will be developed on three distinct but interconnected objectives, from which the present study is structured.

1) Identify the determinants of price within the ETS markets considered.
2) Identify the determinants of volatility within the ETS markets considered.
3) Compare what emerged from the analyses in order to provide a complete picture of the similarities and differences that exist between them.

To this end, a quantitative approach was adopted, drawing upon an original dataset comprising monthly data from January 2014 to November 2024. The variables employed can be classified into three distinct categories:

- Macroeconomic variables.
- Energy variables.
- Climate Variables.

The implementation of this strategy entails the utilization of four distinct econometric models, meticulously selected based on their analytical capabilities and designed to address prior limitations.

- Ordinary Last Square (OLS): Simple linear regression model.

- Generalized Additive Model (GAM): Advance regression model for the non-linearity analysis.
- eXtreme Gradient Boosting (XGBoost): Machine learning model for analysing complex relationships.
- GARCH-X: Conditional volatility model with exogenous factors.

The combined application of these methodologies enables the execution of an exhaustive analysis of the relationships between the variables and markets under consideration. Furthermore, it facilitates the comparison of results derived from various models. The implementation of this approach enables the optimization of the strengths and limitations inherent in each model, thereby enhancing the effectiveness and efficiency of the overall analysis.

1.5Market Selection: Criteria and Motivation

The selection of the three markets referenced, EU-ETS, CA CaT, and K-ETS, is not arbitrary; it is the result of a methodological approach based on the principles of representativeness and comparative heterogeneity.

The methodology employed three criteria, which formed the foundation for a subsequent comparative analysis aimed at providing answers to a variety of questions.

1) *Geographic*: These three markets are considered to be strategic hubs of global significance. They are distinguished from one another by their distinct geographical characteristics and socio-economic dynamics. The three regions: Europe, North America, and Asia represent distinct economic contexts characterized by unique characteristics and viewpoints. This enables to observe how market behaviour is influenced by different contexts.
2) *Dimensional and Historical*: The three selected markets embody pioneering regional and global innovation. The European Union Emissions Trading Scheme (EU-ETS) has emerged as the preeminent global market in terms of institution. The CA CaT is the most regionally relevant and has been most extensively implemented in the United States. The K-ETS has been identified as the first Asian

ETS, and its implementation has led to the subsequent formation of several other markets.

3) *Regulatory and Institutional*: The markets in question vary considerably in terms of regulatory frameworks and institutional infrastructures, as illustrated by the subsequent data. The EU-ETS (European Union Emissions Trading Scheme) market functions as a supranational regulatory system. The oversight of this system is not entrusted to the same entities that manage markets in individual member countries. The K-ETS is a national market entity that is characterized by a high degree of centralization. In conclusion, the CA CaT represents a regional system that operates with a high degree of autonomy from the national context in which it is embedded. Consequently, this selection prioritized the examination of the impact of factors in disparate regulatory contexts, which, as will be elucidated subsequently, exert influence on its prices and volatility.

The selection of these markets was influenced by a multifaceted array of factors, with the objective of formulating a comparative analysis that encompassed not only economic variables but also regulatory frameworks and distinctive characteristics. The findings from the aforementioned analysis demonstrated its efficacy in elucidating not only the divergences but also the similarities between the variables examined and the specific markets.

A thorough delineation of the structural components and the operational mechanisms of the respective markets is provided in the third chapter, which initiates the section devoted to the methodology.

1.6Thesis Structure

The present thesis is divided into five chapters, each of which is designed to provide a progressive response to the research question.

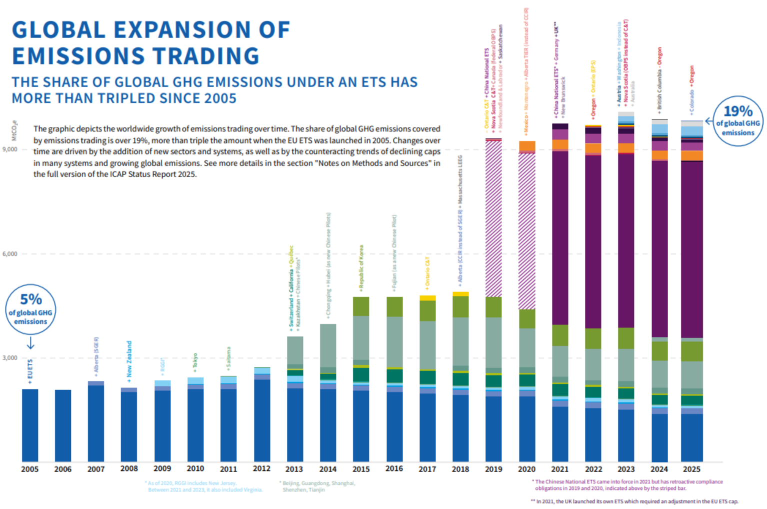
- Chapter 1 (Introduction): Introduction of the global context in the sphere of climate change, presentation of the role of ETS, definition of research objectives, market selection criteria and methodological approach

- Chapter 2 (Literature Review): Review of scientific literature, through analysis of scientific production on determinants of price and volatility, methodologies and comparisons. Theoretical gaps are also identified, and the research question is formulated
- Chapter 3 (Methodologies): Introduction the three ETS markets covered (EU-ETS, CA CaT, and K-ETS), dataset construction, variable selection, statistical transformations, and econometric models used
- Chapter 4 (Empirical Analysis): Presentation of results from the empirical analysis of the models used within the paper (OLS, GAM, XGBoost and GARCH-X). Results are compared between models and markets, and interpreted based on the literature
- Chapter 5 (Results Discussion): Findings from the analyses are summarized, research questions are answered. In addition, their theoretical and practical implications are discussed, through ideas for scholars and policy makers. Finally, the limitations of the research and possible future developments are indicated.
- Chapter 6 (Conclusion): The conclusion of the thesis offers a synthesis of the primary insights and contributions derived from the work, thereby providing a concise summary of its salient findings. A thorough examination of the primary findings is conducted, illuminating the added value contributed to the extant literature and policy discourse. Furthermore, the analysis meticulously delineates the analytical framework's pertinence within the ambit of environmental economics, accentuating its relevance and significance.

2. Literature Review

Subsequent to an exhaustive examination of ETS markets and their operation in the first chapter, the present section will direct its attention to the review of extant scientific literature. The objective of this chapter is to explore and synthesize the determinants of price and volatility in Emission Trading System (ETS) markets, as previously noted by other researchers. The project's scope encompasses dual, interrelated facets: initially, it aspires to critically synthesize the analyses previously executed by other scholars; secondly, it is designed to furnish a foundational theoretical framework for the empirical analysis, which will be elucidated in subsequent chapters. This analysis was conducted with the objective of delving further into the topic and providing a more comprehensive understanding of the phenomenon under study. Moreover, the objective is to address the existing lacunae in the extant literature, thereby offering a unique contribution to the corpus. The present study endeavours to elucidate the mechanisms that govern carbon allowance trading markets.

The necessity to comprehend the determinants of this phenomenon has increased in recent years. This shift can be attributed, in part, to an increased recognition of ETS markets as a pivotal instrument in the global effort to combat climate change. This assertion is further substantiated by the findings documented in the Emission Trading Status Report, a comprehensive analysis prepared by ICAP and released in April 2025[22]. As illustrated by Graph 1, there has been an increase in geographic spread and volume of emission covered in terms of $MtCO_2e$ by the markets.



Graph 1: Expansion of Emission Trading Systems. Source: Emission Trading Status Report ICAP (2025)

An understanding of the interactions between price and volatility is imperative to facilitate the efficacy of these systems, which is crucial for firms to make well-informed investment and risk management decisions, and for policymakers to implement consistent and timely regulatory changes.

In this preliminary section, a concise overview of the pivotal themes that will be examined in the subsequent chapter is provided. Consequently, an extensive analysis of scholarly literature pertinent to macroeconomic, energy, climate, and geopolitical factors, which exert an influence on the price and volatility of allowances within Emissions Trading System (ETS) markets, will be undertaken. The objective of this analysis is to identify

[22] **ICAP. (2025).** *Emissions Trading Worldwide: Status Report 2025*. Berlin: International Carbon Action Partnership. Available at https://icapcarbonaction.com/en/publications/emissions-trading-worldwide-icap-status-report-2025

emergent trends, contradictory findings, and research areas that have not yet been adequately explored.

In the following section, the primary econometric methodologies utilized in preceding academic studies will be examined. The objective is twofold: first, to underscore their strengths, and second, to elucidate their inherent limitations. Subsequently, a concise overview of previously conducted global comparative analyses of ETS markets will be presented.

In conclusion, the objective of the chapter is to underscore the distinctive features of the paper, which is notable for its pioneering effort to address lacunae that have come to the fore in the extant academic corpus. A close examination of the aforementioned points reveals three critical aspects that merit particular attention. Firstly, the dearth of analysis on markets other than the EU-ETS has been identified as a significant limitation, as it restricts the capacity to evaluate the comprehensive impact of economic policies and phenomena. Secondly, a lack of comparative analysis among diverse markets hinders the discernment of shared tendencies or notable variations. Finally, the restricted utilization of sophisticated econometric methodologies diminishes the capacity to predict and evaluate market conditions.

The proposed literature review facilitates the establishment of a robust framework. This methodological approach is indispensable for a critical interpretation of the analysis's findings.

2.1 Determinants of Price and Volatility in the ETS Market

The price of allowances in ETS markets is a pivotal variable in the effectiveness and stability of those markets. It has been demonstrated that this phenomenon acts as a market signal, thereby exerting its influence on the investment decisions made by corporations and their propensity to procure technologies that are capable of reducing emissions.

As demonstrated in the study conducted by the International Carbon Action Partnership (ICAP, 2017)[23], this assertion can be verified. According to the study, a well-functioning ETS market, characterized by stable prices, enables participants to develop expectations

[23] **ICAP. (2017).** *Emissions Trading and the Role of the Long-Run Carbon Price Signal*. Berlin: International Carbon Action Partnership. Retrivied from: https://icapcarbonaction.com/en/publications/emissions-trading-and-role-long-run-carbon-price-signal

regarding future prices. This capacity under discussion enables participants to make investment decisions with the prospect of future prices and abatement costs of the investment already in mind.

Recent studies lend further support to this hypothesis. A study by Günther et al. (2025)[24] found that the surge in prices in the EU-ETS market from 2017 to 2021 was indicative of heightened EU climate policy credibility, thereby influencing corporate investment decisions in the field.

Nonetheless, it is important to contemplate the potential deleterious ramifications of unrestrained price escalations. As indicated by the findings of the study conducted by Wang & Kuusi (2024)[25], which was carried out on the European market, while the endeavour resulted in a decline in carbon emissions, the researchers simultaneously demonstrated an escalation in the carbon content of EU imports. The aforementioned evidence indicates a phenomenon known as Carbon Leakage, which has the potential to compromise the efficacy of market mechanisms by relocating emissions to other regions.

These findings underscore the critical need for authorities to calibrate the price of allowances, thereby safeguarding the efficacy of the market in reducing greenhouse gas emissions and averting adverse consequences.

A comprehensive understanding of the determinants of price and volatility is therefore paramount for market assessment, forecasting trends, and optimizing policy/investment choices.

Since the establishment of the initial ETS market two decades ago, scholarly publications have identified numerous variables that influence price levels and fluctuations in carbon allowance markets.

One of the first contributions to the research is provided by the study of Chevallier (2011)[26]. The author emphasises that "*the level of emissions depends on a large number of factors, such as unexpected fluctuations in energy demand, energy prices (e.g. oil, gas, coal) and weather conditions (temperature, rainfall and wind speed)*". Furthermore, the

[24] **Günther, C., Pahle, M., Govorukha, K., Osorio, S., & Fotiou, T. (2025).** Carbon prices on the rise? Shedding light on the emerging second EU Emissions Trading System (EU ETS 2). *Climate Policy*. https://doi.org/10.1080/14693062.2025.2485196
[25] **Wang, M., & Kuusi, T. (2024).** Trade flows, carbon leakage, and the EU Emissions Trading System. Energy Economics, 134, 107556. https://www.sciencedirect.com/science/article/pii/S0140988324002640
[26] **Chevallier, J. (2011).** *Carbon price drivers: An updated literature review*. HAL. https://halshs.archives-ouvertes.fr/halshs-00586513

same author highlights that "*economic growth and financial markets [...] need to be further assessed in the academic community*". This underscores the necessity for incorporating macroeconomic indicators as explanatory variables within research frameworks. This viewpoint is further substantiated by a recent study undertaken by Li et al. (2021)[27], which underscores the dynamic nature of these factors' influence on price outcomes, stating "*The relationships between oil, gas, electricity, stock prices and carbon price exhibit significant time-varying characteristics [...]*" and further elaborating "*after the signing of the Paris Agreement in the second quarter of 2016, the carbon price has a greater response to changes in its drivers*"

Alberola, Chevallier and Chèze (2009)[28] conducted a sectoral analysis during Phase I of the EU-ETS, thereby confirming that "*fluctuations in the level of economic activity are a key determinant of the level of carbon price returns*".

Further evidence supporting the conclusions of the aforementioned three studies is provided by Liu et al. (2023)[29]. Within the context of the Chinese market, the authors demonstrate that "*China's carbon market is primarily influenced by the financial market and the energy market. The impact varies according to circumstances, such as varying time frequencies and market conditions*".

In addition to the aforementioned, the study conducted by Eslahi and Mazza (2023)[30] underscored how meteorological factors play a pivotal role in the examination of the growth of Emissions Trade System (ETS) markets. The authors contend that by examining weather variables, it becomes evident that during epochs of extreme weather events, the value of allowances within the market often exhibits an observable trend.

The extant literature emphasises the necessity of analysing not only macroeconomic factors, but also energy and climate factors.

In summary, the objective of this paper is to examine the impact of these factors on price formation and, by extension, market volatility in the context of the ETS market. The objective is to make a substantial contribution to the comprehensive understanding of the

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[27] **Li, P., Zhang, H., Yuan, Y., & Hao, A. (2021).** Time-Varying Impacts of Carbon Price Drivers in the EU ETS: A TVP-VAR Analysis. *Frontiers in Environmental Science*, 9, 651791. https://doi.org/10.3389/fenvs.2021.651791

[28] **Alberola, E., Chevallier, J., & Chèze, B. (2009).** Emissions compliances and carbon prices under the EU ETS: A country-specific analysis of industrial sectors. *Journal of Policy Modeling*, 31(3), 446–462. https://doi.org/10.1016/j.jpolmod.2008.12.004

[29] **Liu, Y., Zhang, J., & Fang, Y. (2023).** The driving factors of China's carbon prices: Evidence from using ICEEMDAN-HC method and quantile regression. *Finance Research Letters*, 54, 103756. https://doi.org/10.1016/j.frl.2023.103756

[30] **Eslahi, M., & Mazza, P. (2023).** Can weather variables and electricity demand predict carbon emissions allowances prices? Evidence from the first three phases of the EU ETS. *Ecological Economics, 214*, 107985. https://doi.org/10.1016/j.ecolecon.2023.107985

mechanisms that govern these markets. This, in turn, will provide firms and policymakers with valuable insights.

2.2 Econometric Models in the Literature

In the context of ETS markets, the analytical approaches employed have undergone a gradual progression, paralleling the development of the econometric literature. These phenomena are marked by a progressive sophistication in the utilization of econometric instruments.

This addition of complexity is evidenced by the mounting imperative for analysis of increasingly sophisticated and articulated factors that are arising from the consolidation of markets and the accessibility of present data.

The earliest studies were founded on models belonging to the OLS (Ordinary Least Squares) family. The utilization of models of this nature facilitates the examination of the linear relationship present among the variables under consideration. In their study, Aatola et al. (2013)[31] employed an OLS model to assess the impact of macroeconomic variables on the price of carbon allowances. The econometric approach under scrutiny is notable for its accessibility and ease of application, characteristics that are conducive to its utilization and extensive dissemination. Nonetheless, the authors themselves acknowledged the constraints of the aforementioned model in scenarios involving exogenous shocks and markets that have yet to reach full maturity.

It is important to acknowledge that the limitations of this model had previously been the subject of attention in a number of studies. These studies include those by Chevallier (2011)[32], Creti et al. (2012)[33], Lutz et al. (2013)[34]. The authors demonstrated the presence of asymmetrical relationships in the analysed materials. The existence of relationships that have been established in this manner serves as an intrinsic constraint within the model, thereby hindering its capacity to effectively delineate these relationships. This observation has been corroborated by subsequent studies, which have both validated the initial findings and expanded upon them. The investigation carried out by Adekoya

[31] **Aatola, P., Ollikainen, M., & Toppinen, A. (2013).** Price determination in the EU ETS market: Theory and econometric analysis with market fundamentals. *Energy Economics, 36*, 380–395. https://doi.org/10.1016/j.eneco.2012.09.009
[32] **Chevallier, J. (2011).** Evaluating the carbon-macroeconomy relationship: Evidence from threshold vector error-correction and Markov-switching VAR models. *Economic Modelling, 28*(6), 2634–2656. https://doi.org/10.1016/j.econmod.2011.08.003
[33] **Creti A, Jouvet PA, Mignon V (2012)** Carbon price drivers: Phase I versus Phase II equilibrium? Energ Econ 34: 327–334. http://dx.doi.org/10.1016/j.eneco.2011.11.001
[34] **Lutz BJ, Pigorsch U, Rotfuss W (2013)** Nonlinearity in cap-and-trade systems: The EUA price and its fundamentals. Energ Econ 40: 222–232. https://doi.org/10.1016/j.eneco.2013.05.022

(2021)[35] underscored the compelling need for models that can effectively address this limitation. Consequently, the exclusive utilization of linear models may lead to the loss of substantial information derived from data and market analysis.

In response to these emerging needs, which have been identified within the framework of OLS models, the extant literature has seen the emergence of a second generation of approaches. These approaches are founded on the premise of semiparametric modelling, which enables the analysis of nonlinear relationships. An illustration of the implementation of a semiparametric model is provided in the study conducted by Chu et al. (2020)[36]. In this study, the authors employed a semiparametric quantile regression model developed by Cai & Xiao (2012)[37]. This model's efficacy has been demonstrated particularly well in the context of analysing Chinese market dynamics, resulting in the scholars' identification of numerous previously unnoticed pieces of evidence.

This phenomenon has previously been documented by Chevallier (2011)[38]. In his research, the author implemented a nonlinear autoregressive (NAR) model. This approach yielded a reduction in prediction error of at least 15 percent compared to conventional linear models.

This assertion finds support in contemporary research conducted by Moulim et al. (2025)[39], which validates the emergence of a novel paradigm involving the implementation of semiparametric models, such as Autoregressive Distributed Lag (ARDL), for driver analysis in the specific context of the Emission Trading System (ETS) market.

Despite the advances achieved by the aforementioned approaches, they are encumbered by intrinsic limitations, largely stemming from the substantial demands and the focus required of research practitioners. It is essential to acknowledge that the efficacy of these models is contingent upon the validity of certain assumptions regarding the variables employed. In accordance with the assumptions inherent to OLS models, there are two additional conditions to be fulfilled. Firstly, stationary variables are required. Secondly,

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[35] **Adekoya, O. B. (2021).** Predicting carbon allowance prices with energy prices: A new approach. *Journal of Cleaner Production, 282*, 124519. Retrivied from: https://doi.org/10.1016/j.jclepro.2020.124519
[36] **Chu, W., Chai, S., Chen, X., & Du, M. (2020).** Does the Impact of Carbon Price Determinants Change with the Different Quantiles of Carbon Prices? Evidence from China ETS Pilots. *Sustainability*, *12*(14), 5581. https://doi.org/10.3390/su12145581
[37] **Cai, Z., & Xiao, Z. (2012).** Semiparametric quantile regression estimation in dynamic models with partially varying coefficients. *Journal of Econometrics, 167*(2), 413-425. https://doi.org/10.1016/j.jeconom.2011.09.025
[38] **Chevallier, J. (2011).** Nonparametric modeling of carbon prices. *Energy Economics, 33*(6), 1267–1282. https://doi.org/10.1016/j.eneco.2011.03.003
[39] **Moulim, A., Soumbara, S.-A., & El Ghini, A. (2025).** Cointegration analysis of fundamental drivers affecting carbon price dynamics in the EU ETS. *AIMS Environmental Science, 12*(1), 165–192. https://doi.org/10.3934/environsci.2025008

multicollinearity must be absent. Finally, the models must undergo meticulous tuning in order to achieve maximum functionality.

In light of these critical issues, recent years have witnessed the emergence of a novel generation of analytical tools. These tools are predicated on complex computational models, including deep learning and machine learning, to confirm nonlinearity in larger contexts. The necessity for this has arisen as a result of the emergence of critical issues in preceding models. This development has led to a need to guarantee greater accuracy and reliability. Semi-parametric models have been demonstrated to be capable of overcoming the linearity constraints imposed by OLS models; however, they are incapable of overcoming constraints related to variable shape. These challenges can be successfully addressed by Machine Learning (ML) and Deep Learning (DL) models. These models possess the capability for autonomous management of the idiosyncrasies present in each variable, thereby conferring a measure of operational liberty to researchers. A plethora of studies have been conducted by Hao & Tian (2020)[40], Zhou et al. (2019)[41], Atsalakis (2016)[42], Xu et al. (2020)[43] e Feng et al (2011)[44] which have revealed a variety of machine learning and deep learning models characterized by distinctive peculiarities. Nonetheless, these models continue to exhibit substantial limitations that impede their broader implementation. It is evident that such frameworks are inadequate in elucidating the underlying motivations that underpin the relationships they ascertain. These motivations, consequently, prove to be challenging to interpret, except via the application of metrics furnished by the model itself or metrics external to it.

In the context of the evolution of models for price analysis, the prevailing focus within the extant literature on ETS markets volatility analysis appears to have remained consistently on a particular, singular technique that belongs to the GARCH-type family. Despite the persistence of a singular model, scholars have identified variations over time. This has led to the utilization of different versions (including GARCH, GARCH-E, APARCH, etc.) among others, by scholars in the field.

[40] **Hao, Y., & Tian, C. (2020).** A hybrid framework for carbon trading price forecasting: The role of multiple influence factor. *Journal of Cleaner Production, 262*, 120378. https://doi.org/10.1016/j.jclepro.2020.120378.
[41] **Zhou, J., Huo, X., Xu, X., & Li, Y. (2019).** Forecasting the Carbon Price Using Extreme-Point Symmetric Mode Decomposition and Extreme Learning Machine Optimized by the Grey Wolf Optimizer Algorithm. *Energies*, *12*(5), 950. https://doi.org/10.3390/en12050950
[42] **Atsalakis, G. S. (2016).** Using computational intelligence to forecast carbon prices. *Applied Soft Computing, 43*, 107–116. https://doi.org/10.1016/j.asoc.2016.02.029
[43] **Xu, H., Wang, M., Jiang, S., & Yang, W. (2020).** Carbon price forecasting with complex network and extreme learning machine. *Physica A: Statistical Mechanics and Its Applications, 545*, 122830. https://doi.org/10.1016/j.physa.2019.122830
[44] **Feng, Z.-H., Zou, L.-L., & Wei, Y.-M. (2011).** Carbon price volatility: Evidence from EU ETS. *Applied Energy, 88*(3), 590–598. https://doi.org/10.1016/j.apenergy.2010.06.017

In order to provide an illustrative illustration of the analyses conducted through the use of such methodologies for examining volatility, it is possible to mention the studies of Byun & Cho (2013)[45], Chen et al. (2013)[46] Chevallier (2011)[47], Rannou & Barneto (2016)[48]. These studies make use of models belonging to the GARCH family.

Moreover, research findings by Wu et al. (2022)[49] underscore the necessity of incorporating external factors to enhance the efficacy of volatility analysis. In contexts marked by the high volatility and susceptibility to external influences that typify the ETS market, the employment of such instruments assumes a pivotal role in ensuring market stability and efficiency.

This section aims to offer a complementary analysis of the findings derived from a thorough literature review. These results were obtained by examining the drivers identified in the selected studies. Moreover, the econometric methodologies employed were thoroughly examined as well. The following Tables, 1 and 2, will serve as a summary of the concepts discussed. They will provide the reader with a solid and immediate basis for understanding the analyses developed in the following chapters.

Drivers	***Most used***	***Representative Papers***
Macroeconomics	GDP, IPI, M2, Interest Rate	Chevallier (2011)[50]; Li et al. (2021)[51]; Alberola, Chevallier and Chèze (2009)[52]
Energy	Coal Price, Carbon Price	Liu et al. (2023)[53]
Climate	Mean temperature, Rainfall, extreme temperature	Eslahi & Mazza (2023)[54]

Table 1: Summary of factors identified in the literature.

Models	***Strengths***	***Weaknesses***	***Representative Papers***

[45] **Byun, S. J., & Cho, H. (2013).** Forecasting carbon futures volatility using GARCH models with energy volatilities. *Energy Economics, 40*, 207–221. https://doi.org/10.1016/j.eneco.2013.06.017
[46] **Chen, X., Wang, Z., & Wu, D. D. (2013).** Modeling the Price Mechanism of Carbon Emission Exchange in the European Union Emission Trading System. *Human and Ecological Risk Assessment: An International Journal*, *19*(5), 1309–1323. https://doi.org/10.1080/10807039.2012.719389
[47] **Chevallier, J. (2011).** Detecting instability in the volatility of carbon prices. *Energy Economics, 33*(1), 99–110. https://doi.org/10.1016/j.eneco.2010.09.006
[48] **Rannou, P., & Barneto, A. (2016).** Futures trading with information asymmetry and OTC predominance: Another look at the volume/volatility relations in the European carbon markets. *Energy Economics, 53*, 159–174. https://doi.org/10.1016/j.eneco.2014.10.010
[49] **Wu, X., Yin, X. & Mei, X. (2022).** Forecasting the volatility of European Union allowance Futures with Climate policy uncertainty using the EGARCH-MIDAS Model. Sustainability, 14, 4306. https://doi.org/10.3390/su14074306
[50] **Chevallier, J. (2011).** *Carbon price drivers: An updated literature review*. HAL. https://halshs.archives-ouvertes.fr/halshs-00586513
[51] **Li, P., Zhang, H., Yuan, Y., & Hao, A. (2021).** Time-Varying Impacts of Carbon Price Drivers in the EU ETS: A TVP-VAR Analysis. *Frontiers in Environmental Science*, 9, 651791. https://doi.org/10.3389/fenvs.2021.651791
[52] **Alberola, E., Chevallier, J., & Chèze, B. (2009).** Emissions compliances and carbon prices under the EU ETS: A country-specific analysis of industrial sectors. *Journal of Policy Modeling*, 31(3), 446–462. https://doi.org/10.1016/j.jpolmod.2008.12.004
[53] **Liu, Y., Zhang, J., & Fang, Y. (2023).** The driving factors of China's carbon prices: Evidence from using ICEEMDAN-HC method and quantile regression. *Finance Research Letters*, 54, 103756. https://doi.org/10.1016/j.frl.2023.103756
[54] **Eslahi, M., & Mazza, P. (2023).** Can weather variables and electricity demand predict carbon emissions allowances prices? Evidence from the first three phases of the EU ETS. *Ecological Economics, 214*, 107985. https://doi.org/10.1016/j.ecolecon.2023.107985

Parametric (i.e. OLS)	Interpretability, Ease of use	Linearity, sensibility to non-stationary variables	Aatola et al. (2013)[55]
Semi-Parametric (i.e. Quantile regression, GAM)	Non-Linearity, Interpretability	Tuning, Variables Modellation	Chu et al. (2020)[56]; Chevallier (2011)[57]; Moulim et al. (2025)[58]
Machine Learning / Deep Learning (i.e. Random Forest, XGBoost, ANN)	Complex-Pattern, High-Performance, No variables Modification	Difficulty of Interpretation	Hao & Tian (2020)[59], Zhou et al. (2019)[60], Atsalakis (2016)[61], Xu et al. (2020)[62] e Feng et al (2011)[63]
GARCH-type (i.e. GARCH, EGARCH, GARCH-X)	Volatility Analysis, Inclusion of Variables (GARCH-X)	Limitation for little dataset	Byun & Cho (2013)[64], Chen et al. (2013)[65] Chevallier (2011)[66], Rannou & Barneto (2016)[67]

Table 2: Summary of Econometric model implemented in the literature.

2.3 Structural Differences between ETS Markets

As delineated in the initial chapter of this thesis, the distinctive institutional and industrial characteristics of the three markets under examination have been previously expounded.

Accordingly, the present chapter will not undertake a thorough examination of the technical particulars associated with cap, free allocation, auction specifics, and industry elements contemplated within the markets. The discussion will centre on an analysis of the implications arising from the differences in the empirical evidence reported in the extant literature.

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[55] **Aatola, P., Ollikainen, M., & Toppinen, A. (2013).** Price determination in the EU ETS market: Theory and econometric analysis with market fundamentals. *Energy Economics, 36*, 380–395. https://doi.org/10.1016/j.eneco.2012.09.009
[56] **Chu, W., Chai, S., Chen, X., & Du, M. (2020).** Does the Impact of Carbon Price Determinants Change with the Different Quantiles of Carbon Prices? Evidence from China ETS Pilots. *Sustainability*, *12*(14), 5581. https://doi.org/10.3390/su12145581
[57] **Chevallier, J. (2011).** Nonparametric modeling of carbon prices. *Energy Economics, 33*(6), 1267–1282. https://doi.org/10.1016/j.eneco.2011.03.003
[58] **Moulim, A., Soumbara, S.-A., & El Ghini, A. (2025).** Cointegration analysis of fundamental drivers affecting carbon price dynamics in the EU ETS. *AIMS Environmental Science, 12*(1), 165–192. https://doi.org/10.3934/environsci.2025008
[59] **Hao, Y., & Tian, C. (2020).** A hybrid framework for carbon trading price forecasting: The role of multiple influence factor. *Journal of Cleaner Production, 262*, 120378. https://doi.org/10.1016/j.jclepro.2020.120378.
[60] **Zhou, J., Huo, X., Xu, X., & Li, Y. (2019).** Forecasting the Carbon Price Using Extreme-Point Symmetric Mode Decomposition and Extreme Learning Machine Optimized by the Grey Wolf Optimizer Algorithm. *Energies*, *12*(5), 950. https://doi.org/10.3390/en12050950
[61] **Atsalakis, G. S. (2016).** Using computational intelligence to forecast carbon prices. *Applied Soft Computing, 43*, 107–116. https://doi.org/10.1016/j.asoc.2016.02.029
[62] **Xu, H., Wang, M., Jiang, S., & Yang, W. (2020).** Carbon price forecasting with complex network and extreme learning machine. *Physica A: Statistical Mechanics and Its Applications, 545*, 122830. https://doi.org/10.1016/j.physa.2019.122830
[63] **Feng, Z.-H., Zou, L.-L., & Wei, Y.-M. (2011).** Carbon price volatility: Evidence from EU ETS. *Applied Energy, 88*(3), 590–598. https://doi.org/10.1016/j.apenergy.2010.06.017
[64] **Byun, S. J., & Cho, H. (2013).** Forecasting carbon futures volatility using GARCH models with energy volatilities. *Energy Economics, 40*, 207–221. https://doi.org/10.1016/j.eneco.2013.06.017
[65] **Chen, X., Wang, Z., & Wu, D. D. (2013).** Modeling the Price Mechanism of Carbon Emission Exchange in the European Union Emission Trading System. *Human and Ecological Risk Assessment: An International Journal*, *19*(5), 1309–1323. https://doi.org/10.1080/10807039.2012.719389
[66] **Chevallier, J. (2011).** Detecting instability in the volatility of carbon prices. *Energy Economics, 33*(1), 99–110. https://doi.org/10.1016/j.eneco.2010.09.006
[67] **Rannou, P., & Barneto, A. (2016).** Futures trading with information asymmetry and OTC predominance: Another look at the volume/volatility relations in the European carbon markets. *Energy Economics, 53*, 159–174. https://doi.org/10.1016/j.eneco.2014.10.010

A broad consensus exists among researchers regarding the EU-ETS market, which is regarded as the most mature system on a global scale. Consequently, the majority of studies on ETS markets concentrate on the EU-ETS market. In this context, price and volatility have been demonstrated to be associated with a variety of heterogeneous factors, which are subject to influences from macroeconomic, energy, and climate-related aspects.

The establishment of the market in 2005, which was the inaugural Emissions Trading Scheme (ETS) market on a global scale, has given rise to a substantial corpus of empirical analysis. This wealth of in-depth research has contributed to the formation of a vast and exhaustive body of literature.

Conversely, the K-ETS market, established in 2015, operates within an economic environment significantly distinct from the EU-ETS market. The research conducted underscores the paramount role that the political context plays in influencing market dynamics. The issues of low data availability and political influences have a substantial effect on the complexity of empirical analysis and the necessity to develop alternative methods. This results in a paucity of empirical studies. The extant research in this area demonstrates the significant impact of policy decisions on the market, as well as its connection to broader internal factors, such as GDP, Inflation, and area-specific climatic variables.

The California Cap-and-Trade (CA CaT) market is located at the midpoint between the two aforementioned markets. The market was founded in 2012 and has since experienced significant growth, including the establishment of a partnership with the Quebec market in 2014. The market in question exhibits a high degree of stability, a conclusion that has been substantiated by a series of studies. While the aforementioned stability is substantial, it is imperative to acknowledge that it remains contingent upon ongoing processes of consolidation. According to the most recent studies, the stability of the system is still developing and has not yet reached a state of total consolidation. The existing body of research on this specific market is, at present, limited in scope. However, extant studies indicate that market performance is significantly influenced by energy-related variables (i.e., coal and oil prices) and climate variables (i.e., Temperature and Rainfall).

In sum, the European Union Emissions Trading Scheme (EU-ETS) has been identified as the most advanced market in this area, exhibiting the highest degree of liquidity and being under the direction of supranational entities.

The California Cap-and-Trade (CA CaT) market exhibits a substantial correlation with the domestic environment, particularly with the energy factors that influence its dynamics. With regard to the aforementioned aspect, it should also be noted that, due to its nature as a regional market, the phenomenon under consideration is significantly affected by macroeconomic factors of a national matrix, which exert a significant influence on the overall performance of the market itself.

The K-ETS market is considered the most recent of those examined, as well as subject to more restrictive political regulations. It possesses distinctive peculiarities that characterize its uniqueness within the context of the markets considered. The aforementioned element is instrumental in elucidating the profound impact of political events occurring on the national level on the dynamics of the market.

These structural and institutional disparities are pivotal to an adequate understanding of the findings presented in this thesis.

For an exhaustive examination of the institutional and regulatory functioning of these markets, refer to Chapter 1.

2.4Research Gap

The examination of extant literature on the subject of ETS (Emission Trading System) markets has yielded significant insights regarding the contributions made by scholars to the understanding of allowance market dynamics. Nevertheless, despite the mounting academic enthusiasm for these markets, owing to their ongoing expansion, significant lacunae persist within extant studies. These limitations impinge upon the extent to which they can provide meaningful explanatory power. An analysis of these discrepancies reveals that they can be attributed to three primary domains. These domains can be encapsulated as follows:

- Limited geographic coverage
- Lack of comparisons between markets

- Partial use of advanced econometric tools and comparisons among them

The aforementioned limitations will be further delineated in the following section.

1) *Limited geographic coverage*

A notable limitation in extant literature pertains to the geographical scope of the analyses conducted. The extant studies primarily concentrate on the EU-ETS market and the Chinese market. From this standpoint, the term "Chinese market" does not denote a singular entity, but rather, it functions as a conceptual oversimplification that encompasses a broader and more intricate economic reality. In 2021, the People's Republic of China implemented a unified emissions trading system, designated as the China National Emissions Trading System (China National ETS), which governs the nation's greenhouse gas emissions. The genesis of this economic scenario stems from the analysis of smaller regional markets, such as Shanghai and Shenzhen, where the system has been piloted. These markets persist in their activity and will function in synergy with the primary market, thereby providing coverage of sectors that have not been addressed by the national market. The preponderant presence of these markets in comparison to other global markets can be attributed to their size and time of formation. These two factors have led to their significant global impact. The EU-ETS market was distinguished as the most prominent market in terms of the quantity of emissions under management prior to the establishment of the China National Emissions Trading System. Notably, the EU-ETS market was also significant for its pioneering role in establishing the first market of that nature, which occurred in 2005. As was the case with the complex under review, the Chinese regional markets have a common foundation year, which is conventionally set at 2013. These markets record a total value1416.45 $MtCO_2$[68]. In contrast, the CA CaT, and K-ETS markets currently exhibit a paucity of documented research, with only a limited number of scientific studies providing an in-depth explanation of the fundamental determinants driving their performance.

This imbalance in the presentation of information poses a significant risk of leading to erroneous generalizations. Policymakers and corporate entities engaged in market

[68] **International Carbon Action Partnership (ICAP). (2020).** *Emissions trading worldwide: ICAP status report 2020*. ICAP. Retrieved from https://icapcarbonaction.com/en/publications/emissions-trading-worldwide-icap-status-report-2020

activities may be impelled to form conclusions based on a fragmented perspective, thereby overlooking local dynamics that could prove to be pivotal in determining outcomes.

Consequently, there is a pressing need to enhance the inclusivity of geographic studies in order to comprehensively analysed markets that have historically been understudied. The necessity of this initiative is further underscored by the evident expansion experienced by these markets, both regionally and on a global scale.

2) *Lack of comparisons between markets*

A secondary constraint that was identified in the course of the literature review is the absence of systematic comparative studies between markets. An initial analysis of the extant literature reveals a predominant focus on the examination of individual markets, with a paucity of attention given to the interrelationships between these markets. This focus is further evidenced by the adoption of methods that are specific to each market analysed. This form of analysis does not consider the potential for creating harmonization among the elements in question. Consequently, the ability to make direct and consistent comparisons is hindered, as the same methodologies and variables are utilized. In the rare instances where a comparison is attempted, it is approached with inadequate indicators, which hinders the ability to perform in-depth analysis.

The prevailing conclusion is that extant literature production, at present, fails to offer a comprehensive and systematic overview. Instead, the extant literature is limited to detailed descriptions of specific market aspects. The aforementioned limitation has the effect of hindering the capacity of practitioners to identify patterns, both common and specific, across diverse contexts. The utilization of a comparative perspective could prove to be of considerable use in academic contexts. Moreover, this comparative approach could also benefit policymakers and various industries. By employing a comparative method, these actors would have the opportunity to apply lessons learned from one specific context to another.

3) *Partial use of advanced econometric tools and comparisons among them*

A final limitation pertains to the methodological level. Despite the evident interest in price and volatility dynamics within ETS markets, a significant portion of the research fails to adequately focus on high-complexity models to determine even the most intricate interactions.

As evidenced by the analyses conducted on the subject, the architecture of ETS markets is characterized by complex features that necessitate constant attention and investigation. A substantial body of emerging research points to the necessity of employing methodologically sophisticated models to comprehensively grasp the idiosyncrasies that are characteristic of such financial markets. Nonlinearities, intricate interactions of determinant variables, and challenging-to-observe effects collectively pose additional challenges that must be addressed. Consequently, the employment of semiparametric models and machine learning techniques emerges as a pivotal strategy to capture the unique characteristics inherent in each market examined.

A prevailing finding was that the utilization of an econometric model was predominant in the majority of the analyses reviewed. Nevertheless, the capacity of such a model to unveil market characteristics remains constrained, as it is capable of depicting only a fraction of these characteristics. Consequently, the concurrent implementation of multiple analytical methodologies is imperative to formulate comprehensive conclusions and obtain a comprehensive overview of the object of analysis.

Moreover, the extant literature contains a paucity of analyses that concurrently examine the factors determining price and volatility. The discrepancy in the analysis of these two factors diminishes the explanatory effectiveness of the analysis, thereby leaving pertinent inquiries regarding the impact of the factors on the market.

Having identified these gaps in the current literature, it is evident that further research is necessary to address these knowledge gaps.

- Extend the analyses performed to less explored markets as well
- Apply common methodologies across markets so that a systematic comparison can be made

- Use heterogeneous and advanced models that can capture the peculiarities of each market from different points of view
- Analyse the determinants of price and volatility in an integrated way, overcoming the current dichotomy in the literature.

2.5 Research Questions

In view of the lacunae that have come to light in the extant literature, it is possible to formulate a research question. The central question to which this paper will contribute is as follows.

What are the main determinants that influence the price and volatility of allowances in carbon trading markets and how do these differ in the EU-ETS, CA CaT and K-ETS systems?

A series of subsequent inquiries can be formulated by distilling essential elements from the central question. These distilled inquiries are known as assistant questions, and their articulation enables the formulation of three distinct hypotheses that further explore the central question. It is important to note that the hypotheses formulated in this paper do not postulate unidirectional cause-effect relationships (positive or negative). Rather, the hypotheses are intended to serve as exploratory guides for empirical analysis. The necessity of this approach is predicated on the paper's objective, which is to augment descriptive and systematic knowledge in high-complexity contexts. This is accomplished to ensure a thorough and accurate understanding of the phenomena examined.

The following research questions have been identified as the primary focus for the present study:

1) **Which Drivers affect price in ETS market?**

According to the extant literature on the subject, the valuation of allowances in ETS (Emissions Trading System) markets is influenced by a plurality of macroeconomic, energy, and climate variables. However, the characteristics of these relationships remain ambiguous, and there is no consensus among experts regarding which relationships are observable. The present study aims to utilize an empirically based approach to explore the relationships in question within the three ETS markets examined.

H1: *Are allowance prices in ETS markets affected specific determinants? If this is the case, what are the characteristics and in what way does it manifest itself?*

2) Which drivers affect volatility in ETS market?

Consistent with the preceding research question and as indicated by the extant scientific literature, ETS markets exhibit volatility that is influenced by a multitude of variables that determine its performance. In this regard, the necessity for further in-depth analyses is underscored, ensuring a comprehensive and exhaustive assessment.

H2: *Is volatility in ETS markets influenced by specific determinants? In the event that this occurs, what are the characteristics and how does it manifest itself?*

3) What situations are present in the ETS market?

An analysis of scientific productivity reveals that, from a structural standpoint, each market is characterized by its own unique institutional and regulatory infrastructure. The aforementioned characteristics precipitate substantial discrepancies in the markets' responses to exogenous drivers. The aforementioned dissonances are further exacerbated by the geographical differences in the operational environment of each market, thereby generating a distinctly uneven surrounding ecosystem. Such an environment can exert a considerable influence on the responses of these respective markets. The objective of this study is to delineate and explicate the discrepancies that were ascertained via a comparative inquiry amongst the markets that are the subject of this paper.

H3: *What differences emerged from the analysis of the determinants of price and volatility between the EU-ETS, CA CaT, and K-ETS markets considered?*

3. Methodology

The objective of this paper is to analyse the determinants of price and volatility in the market of Emissions Trading System (ETS) by comparing three selected markets:

1) *European Emission Trading System (EU-ETS)*
2) *California Cap-and-Trade (CA CaT)*
3) *Korea Emission Trading Scheme (K-ETS)*

In order to provide an answer to this question, this study adopts a quantitative approach based on different econometric techniques applied to a dataset consisting of monthly time series.

Before proceeding with the presentation of the dataset and the methodologies applied in this study, it is essential to learn more about the markets examined.

3.1 European Emission Trading System (EU-ETS)

The EU-ETS is noteworthy as the first ETS market of its kind, having been initiated in 2005. It is widely acknowledged as the primary instrument of the European Union's climate policy aimed at reducing greenhouse gas (GHG) emissions. As previously mentioned, the market is a supranational entity that brings together the constituent nations of the European Union, as well as Iceland, Liechtenstein, and Norway.

At present, the market provides coverage for approximately 40% of the total emissions within the European Union, encompassing over 10,000 installations and operators across a range of energy-intensive sectors, including:

- Power;
- Industry;
- Domestic aviation (from 2012);

- Maritime (from 2024);

The EU Emissions Trading System (EU-ETS) is a market based on a Cap-and-Trade system, in which allowances (EUAs - European Union Allowance) are allocated through auctions and free allocations. The cap established for this market undergoes a linear annual reduction, currently set at 4.3% (expected to increase to 4.4% in 2028). The final target aligns with the European Climate Law Regulation (ECLR) 2021/1119[69]aiming for a 55%, reduction in carbon emissions from 1990 levels.

The market has undergone several stages of development:

- Phase 1 (2005-2007): Experimental market phase
- Phase 2 (2008-2012): The initial phase of effective market operation is aligned with the initial phase of Kyoto Protocol[70] implementation.
- Phase 3 (2013-2020): Introduction of a single supranational cap, making auctions the default method for allocation of allowances.
- Phase 4 (2021-2030): Current stage of the market which has undergone major changes to adapt to the "Fit for 55"[71]. The Fit for 55 are a series of proposals by the European commission to reform European climate and energy policies. In fact, in this area the following have been added through 2023 reforms:

    - Reform to increase the ambitions of the EU-ETS. Directive (EU) 2023/959[72]
    - Reform to fortify the Market Stability Reserve. Decision (EU) 2023/852[73]
    - Reform to introduce the aviation sector. Directive (EU) 2023/958[74]
    - Reform for monitoring, verification and carryover rules. Regulation (EU) 2023/957[75]

[69] **European Parliament & Council of the European Union. (2021).** *Regulation (EU) 2021/1119 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999*. Official Journal of the European Union, L 243, 1–17. Retrieved from https://eur-lex.europa.eu/eli/reg/2021/1119/oj/eng
[70] **United Nations Framework Convention on Climate Change (UNFCCC). (n.d.).** *Kyoto Protocol - Targets for the first commitment period*. Retrieved from https://unfccc.int/process-and-meetings/the-kyoto-protocol/what-is-the-kyoto-protocol/kyoto-protocol-targets-for-the-first-commitment-period
[71] **European Commission. (2025).** *Fit for 55: Delivering on the proposals*. Retrieved from https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/delivering-european-green-deal/fit-55-delivering-proposals_en
[72] **European Parliament & Council of the European Union. (2023).** *Directive (EU) 2023/959 amending Directive 2003/87/EC on greenhouse gas emission allowance trading and Decision (EU) 2015/1814 on the market stability reserve*. Official Journal of the European Union, L 130, 134–202. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32023L0959
[73] **European Parliament & Council of the European Union. (2023).** *Decision (EU) 2023/852 amending Decision (EU) 2015/1814 as regards the number of allowances to be placed in the market stability reserve for the Union greenhouse gas emission trading system until 2030*. Official Journal of the European Union, L 110, 21–24. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32023D0852
[74] **European Parliament & Council of the European Union. (2023).** *Directive (EU) 2023/958 amending Directive 2003/87/EC as regards aviation's contribution to the Union's economy-wide emission reduction target and the appropriate implementation of a global market-based measure*. Official Journal of the European Union, L 130, 115–133. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32023L0958
[75] **European Parliament & Council of the European Union. (2023).** *Regulation (EU) 2023/957 amending Regulation (EU) 2015/757 to include maritime transport activities in the EU Emissions Trading System and to monitor, report, and verify emissions of additional greenhouse gases and ship types*. Official Journal of the European Union, L 130, 105–114. Retrieved from https://eur-lex.europa.eu/eli/reg/2023/957

- Reform for the introduction of a Climate Fund. Regulation (EU) 2023/955[76]
- Reform for the introduction of Carbon Border Adjustment Mechanism. Regulation (EU) 2023/956[77]

During the final phase of the program, the auctioned allowances constituted 57 percent of the total, leading to an accumulated revenue since 2013 surpassing 200 billion euros. Of the revenues received, member states were required to allocate a minimum of 50% to initiatives focused on climate change and energy. As of 2023, there was an amendment to this legislation. Specifically, Directive (EU) 2023/959[78] increased the limit to 100%. With regard to these funds, member states provided confirmation of their support for the following projects, which are specifically identified. According to the ICAP status report, program intervention areas for 2025 include: "energy supply, grids and storage (43%), public transport and mobility (23%), social support and just transition (12%), energy efficiency, cooling and heating in buildings (10%) and industry decarbonisation (3%) as well as other purposes (9%)" (ICAP status report, 2025)[79].

With regard to the utilization of offset credits, the European Commission has formally declared their prohibition in the Phase 4 of the market. In parallel, Borrowing has been prohibited, while Banking remains a permitted practice.

Additionally, the compliance period has been established at one year. Companies that fail to comply with the surrender of used emission allowances are subject to financial penalties. The penalty for exceeding the limit is €100 for each $MtCO_2e$ in excess. It should be noted that the aforementioned penalty will be subject to adjustment in accordance with the European inflation rate.[80]

3.2 California Cap-and-Trade Program (CA CaT)

[76] **European Parliament & Council of the European Union. (2023).** *Regulation (EU) 2023/955 establishing a Social Climate Fund and amending Regulation (EU) 2021/1060*. Official Journal of the European Union, L 130, 1–51. Retrieved from https://eur-lex.europa.eu/eli/reg/2023/955/oj/eng
[77] **European Parliament & Council of the European Union. (2023).** *Regulation (EU) 2023/956 establishing a carbon border adjustment mechanism*. Official Journal of the European Union, L 130, 52–104. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32023R0956
[78] **European Parliament & Council of the European Union. (2023).** *Directive (EU) 2023/959 amending Directive 2003/87/EC on greenhouse gas emission allowance trading and Decision (EU) 2015/1814 on the market stability reserve*. Official Journal of the European Union, L 130, 134–202. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32023L0959
[79] **International Carbon Action Partnership (ICAP). (2025).** *Emissions trading worldwide: ICAP status report 2025*. Retrieved from https://icapcarbonaction.com/en/publications/emissions-trading-worldwide-icap-status-report-2025
[80] **European Commission. (n.d.).** *Monitoring, reporting and verification under the EU Emissions Trading System (EU ETS)*. Retrieved from https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/monitoring-reporting-and-verification_en

The California Cap-and-Trade (CA CaT) program began operating in 2012. This development is a consequence of the framework promoted by the California government to reduce greenhouse gas emissions. The framework under consideration is AB 32, also known as the California Global Warming Solutions Act of 2006 (California State Legislature, 2006)[81], which states: “The bill would require the state board to adopt a statewide greenhouse gas emissions limit equivalent to the statewide greenhouse gas emissions levels in 1990 to be achieved by 2020” (California State Legislature, 2006)[82].

The California Air Resources Board (CARB)[83] has decided to implement a cap-and-trade market system in order to meet the goals set in AB32. The state has already achieved these goals four years ahead of schedule in the year 2016. The program's success prompted the further development of ambitious goals through the updating of AB32. The new AB 1279[84] aims to reduce greenhouse gas (GHG) emissions by 85% from 1990 levels.

Turning our attention back to the CA CaT market, it is important to mention that this market is currently under the administration of CARB. The market currently covers 76% of the state's greenhouse gas (GHG) emissions, involving more than 400 facilities. As of January 2014, the market has officially linked its program with Quebec, marking a significant development in their business operations.

The market is comprised of the following sectors:

- Agriculture and/or forestry fuel use
- Mining and extractives
- Transport
- Buildings
- Industry
- Power

The market is based on a cap-and-trade system, similar to the EU-ETS. The initial emissions cap was set at 168.8 $MtCO_2$ in 2013. By 2014, due to expansion into new

[81] **California State Legislature. (2006).** *AB 32: California Global Warming Solutions Act of 2006*. Retrieved from https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=200520060AB32
[82] **California State Legislature. (2006).** *AB 32: California Global Warming Solutions Act of 2006*. Retrieved from https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=200520060AB32
[83] **California Air Resources Board. (n.d.).** *California Air Resources Board homepage*. Retrieved from https://ww2.arb.ca.gov/
[84] **California State Legislature. (2022)**. *AB 1279: The California Climate Crisis Act*. Retrieved from https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=202120220AB1279

sectors, the cap had increased to a value of 394.5 $MtCO_2$ As with the previous market, however, this value is decreasing year by year. In the 2021-2030 period, the reduction is estimated to be around 4%. The goal is to reach a total value of 200.5 $MtCO_2$ by 2030.

The market has undergone several phases, which in this case correspond to compliance periods:

- 1st compliance period (2013-2014)
- 2nd compliance period (2015-2017)
- 3rd compliance period (2018-2020)
- 4th compliance period (2021-2023)
- 5th compliance period (2024-2026)

The key aspect of the market under consideration pertains to the allocation of allowances. Two alternative methods of allocation can be distinguished:

1) *Free allocations*: Allowances are provided to companies free of charge to help mitigate the potential effects of "carbon leakage".
2) *Auction allocation*: The allowances are traded through auctions that are held in conjunction with trades conducted in the Québec market. It is important to note that not all of these allowances are owned by the California Air Resources Board (CARB), as some are managed on account of sale by the companies that hold them. For the 2024 calendar year, the allowances made available for auction accounted for approximately 65% of total allowances, with 36% owned by CARB and the remaining 26% transferred by companies.

In addition to allowances, offsetting credits with a maximum limit of 4% in the 2021-2025 period and a subsequent rise to 6% in the 2026-2030 period, have been authorized in the CA CaT market. However, these credits are subject to two additional limitations:

Primarily, they must generate direct, tangible environmental benefits for the State of California (DEBS)[85]. Secondly, the companies are subject to the Buyer Liability rule. This rule stipulates their responsibility for verifying the credit.

Regarding the revenues generated by the auctions, which currently total $31.38 billion since their introduction, it should be noted that these are allocated to the Greenhouse Gas Reduction Fund[86]. According to current regulations, at least 35% of the total sum must be allocated to projects involving disadvantaged or low-income communities. Subsequently, the funds are allocated to California Climate Investments[87]. This program provides financial support to projects that promote environmental, economic, and public health benefits throughout the state.

When analysing the possibility of banking and borrowing, an analogous situation is noted as observed in the European market. In the California market, while the practice of Borrowing is formally prohibited, Banking is allowed, albeit with significant restrictions.

The compliance period is three years. During that time, there are annual obligations to return units, corresponding to 30% of the allowances issued. In the event that a company is unable to deliver the required allowances on time, it faces an obligation to deliver the missing allowances. For the unavailable allowances, three additional compliance instruments must be provided for each non-delivered item, as required by current regulations. In the case of noncompliance, including the nonreturn of these items, the company may be subject to penalties as outlined in "Health and Safety Code section 38580"[88].[89;90]

3.3 Korea Emission Trading System (K-ETS)

The Korea Emission Trading Scheme (K-ETS) was established in 2015 and is the first system of a nationwide ETS market in Asia. As outlined in the Framework Act on Low Carbon Green Growth (2010)[91], the government established a goal to achieve carbon

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[85] **California Air Resources Board. (n.d.).** *Direct Environmental Benefits in the State (DEBS) under the Compliance Offset Program*. Retrieved from https://ww2.arb.ca.gov/our-work/programs/compliance-offset-program/direct-environmental-benefits
[86] **U.S. Environmental Protection Agency. (n.d.).** *Greenhouse Gas Reduction Fund*. Retrieved from https://www.epa.gov/greenhouse-gas-reduction-fund
[87] **California Climate Investments. (n.d.).** *California Climate Investments homepage*. Retrieved from https://www.caclimateinvestments.ca.gov/
[88] **California State Legislature. (2024).** *California Health and Safety Code § 38580: Enforcement under the California Global Warming Solutions Act of 2006*. Retrieved from https://law.justia.com/codes/california/code-hsc/division-25-5/part-6/section-38580/
[89] **International Carbon Action Partnership (ICAP). (n.d.).** *USA - California Cap-and-Trade Program*. Retrieved from https://icapcarbonaction.com/en/ets/usa-california-cap-and-trade-program
[90] **California Air Resources Board. (n.d.)**. *Cap-and-Trade Regulation*. Retrieved from https://ww2.arb.ca.gov/our-work/programs/cap-and-trade-program/cap-and-trade-regulation
[91] **Republic of Korea. (2010).** *Framework Act on Low Carbon, Green Growth (Act No. 9931, amended by Act No. 16133, 2018)*. Retrieved from https://elaw.klri.re.kr/eng_mobile/viewer.do?hseq=49999&type=part&key=39

neutrality for the country by 2050. This objective was further detailed in the "Carbon Neutral Framework Act"[92] in 2021.

According to the most recent data, in 2022 the market covered approximately 79% of the nation's greenhouse gas emissions from the 816 major emitters.

The following sectors are covered by this market:

- Power
- Industry
- Buildings
- Transport
- Aviation
- Maritime
- Waste

The market has evolved significantly since the cap's introduction in 2015, with several expansions having taken place. The current cap is set at 567.1 $MtCO_2e$, and the present year marks the final year of the third phase of the market. Contrary to the observations in the EU-ETS and CA CaT markets, it is not feasible to provide an annual cap reduction value in this instance. This is due to the fact that, in contrast to the aforementioned markets, the Korean government does not set this value on an annual basis. Rather, it is established over the course of the entire market phase. The current reduction rate is set at 4%, a significant departure from rates recorded in Western markets, where rates are considerably higher.

As previously stated, the market is divided into stages, which are outlined below:

- Phase 1 (2015-2017)
- Phase 2 (2018-2020)
- Phase 3 (2021-2025)
- Phase 4 (2026-2030): The government is setting a new stage for the market with the fourth "Basic Plan for the Emissions Trading System"[93], a policy document

[92] **Republic of Korea. (2021).** *Framework Act on Carbon Neutrality and Green Growth for Coping with Climate Crisis (Act No. 18469, Sep. 24, 2021)*. Retrieved from https://elaw.klri.re.kr/eng_mobile/viewer.do?hseq=59958&type=part&key=39
[93] **Ministry of Environment, Republic of Korea. (2025).** *4th Basic Plan for the Emissions Trading System*. Retrieved from https://me.go.kr/home/web/policy_data/read.do?pagerOffset=0&maxPageItems=10&maxIndexPages=10&menuId=10259&condition.deleteYn=N&seq=8383

that sets guidelines for emissions reduction and adaptation to climate change. However, the specific details of these changes remain undisclosed at this moment. What is emphasized is that the recently implemented measures will be more rigorous to achieve the 2050 target[94].

The examination of documentation revealed that the market in question is comparatively new, as indicated by its relatively recent development compared to other markets. This condition suggests that the market is currently at a stage of development and not full maturity. The allocations in this market fall into two categories:

1) *Free Allocation*: The Korean government has identified certain sectors as EITE (Energy Intensive and Traded Exposed) in order to prevent carbon leakage. In addition, the Grandparenting technique was used extensively. However, a paradigm shift was observed in the third phase, with a transition towards Benchmarking technique.
2) *Auction Allocation*: Consistent with the findings in the previously analysed markets, there is indication of an allocation system involving auctions. In this particular instance, however, this system encompasses only 10% of the total allowances issued by the market. As this phase begins, it is anticipated that there will be a substantial increase in the share price.

In addition to allowances, the K-ETS market permits the utilization of offset credits. There are two main categories to consider:

- National (KOCs)
- International (KCUs)

As with the CA CaT market, offset credits in this one are subject to qualitative and quantitative restrictions. Due to the quantitative limit, these items are restricted to a maximum of 5% of the overall total. The qualitative limits are to be regarded as relative, as they apply to companies that demonstrate a certain degree of Korean ownership.

[94] **Asia Society Policy Institute. (n.d.).** *ETS Status: South Korea*. Retrieved from https://asiasociety.org/policy-institute/ets-status-south-korea

Proceeds from these auctions are allocated to the Climate Response Fund, a financial mechanism aimed at promoting low-carbon innovation, developing infrastructure, and supporting small and medium-sized enterprises.

With regard to Banking and Borrowing practices, it should be noted that such practices may be permitted, subject to the imposition of stringent restrictions, in order to prevent any negative repercussions on the proper functioning of the market.

Finally, the compliance period is not aligned with the phase due to its annual nature. In the event that Korean companies do not comply with the regulations, they will be subject to fines. The maximum amount of these penalties cannot exceed three times the average market price for that year or 100,000 KRW, equivalent to 73.39$.[95]

After gaining a more profound understanding of the markets evaluated in this study, we will proceed to the description of the dataset and the methodologies applied.

3.4Dataset Creation

To conduct the aforementioned econometric analysis, it was necessary to create an original dataset that included the three Emissions Trading Systems (ETS), and the factors considered in the study. The period examined extended from 1st January 2014 to 30th November 2024, with some exceptions due to the historical availability of data for each market[96]. However, a monthly data frequency was guaranteed, which was necessary due to the availability of drivers only on this time scale. The necessity for the aforementioned time scale was guaranteed by the implementation of data interpolation and editing operations, which will be explained in the following analytical sections. These operations were carried out using the statistical software R Studio.

3.5ETS Price

As previously stated, the objective of this paper is to analyse the factors influencing price and volatility within the selected ETS markets. The initial step in constructing the dataset was to obtain price data in these markets. The three markets considered (EU-ETS, California Cap-and-Trade, K-ETS) exhibit significant differences in terms of institutional

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[95] **International Carbon Action Partnership (ICAP). (n.d.).** *Korea Emissions Trading System (K-ETS)*. Retrieved from https://icapcarbonaction.com/en/ets/korea-emissions-trading-system-k-ets

[96] For Korean market, the beginning of primary market prices is scheduled for February 2019, while the secondary market is set to begin in February 2015.

and administrative structure, allocation system and market maturity. To ensure the homogeneity of the data, a single source was utilised for data retrieval: the International Carbon Action Partnership (ICAP)[97].

3.5.1 ETS Price Source (ICAP)

The establishment of ICAP was driven by the overarching objective of "*facilitating cooperation between countries, sub-national jurisdictions and supranational institutions that have established or are actively pursuing carbon markets through mandatory cap-and-trade systems*"[98].

The following procedure, as outlined on their website, is to be followed:

- *Technical Dialogue*: ICAP provides a platform for its members and observers to facilitate the exchange of knowledge and debate on the ETS. The dialogue is not limited to them but is intended to be open to any expert or stakeholder in the carbon markets.
- *Sharing knowledge*: ICAP acts as a repository of information on ETSs, promoting them as a tool to tackle climate change.
- *Capacity building*: ICAP is not just an information and discussion tool. Over time, it has also developed training courses for policymakers and private sector representatives on all aspects of the ETS.

The "*ETS prices*" section of the website under review was used to obtain updated monthly values for carbon allowances in the European Emission Trading System, California Cap-and-Trade and Korea Emission Trading System markets.

3.5.2 Primary and Secondary Market

Carbon allowance price data for all three markets were collected for both the primary market (where available) and the secondary market.

It is important to note that the California Cap-and-Trade market does not possess data regarding the secondary market. As stated in ICAP's official documentation[99], allowance auctions are organised on a quarterly basis through a centralised mechanism managed by

[97] **International Carbon Action Partnership. (n.d.).** *International Carbon Action Partnership (ICAP)*. https://icapcarbonaction.com/en
[98] **International Carbon Action Partnership. (n.d.).** *About us*. https://icapcarbonaction.com/en/about-us
[99] **ICAP. (2023).** *USA - California Cap-and-Trade Program*. International Carbon Action Partnership (Factsheet No. 45). Retrieved from https://icapcarbonaction.com/en/ets/usa-california-cap-and-trade-program

the Western Climate Initiative Inc[100] in cooperation with the California Air Resources Board (CARB)[101]. These auctions are governed by the logic of sealed-bid auctions, commonly known as "*sealed-bid*" auctions[102]. The auctions include both state-owned allowances, represented by permits held by the State of California, and allowances allocated by utility companies. Although the latter allowances are received free of charge by the companies, they are compulsorily auctioned, since the proceeds of the sale are redistributed directly to the citizens. This aspect, however, has the effect of reducing the transparency of the auctions.

ICAP, in fact, has specified that:

- "***Primary****: Allowances are made available through sealed-bid auctions. State-owned and consigned allowances are offered through quarterly allowance auctions organized jointly with Québec."*

  […]
- *"**Secondary**: Allowances, offset credits, and financial derivatives are traded in the secondary market on the Intercontinental Exchange (ICE), CME group, and Nadal Exchange Platform" [(ICAP, 2023, p. 9)].*

As stated in the ICAP documentation mentioned above, although the California Cap-and-Trade market includes a secondary market, the relevant data were not available in the official ICAP documentation. Furthermore, it has been established that secondary market prices encompass derivative instruments and offset credits, the composition of which is considerably divergent from that of allowances in the primary market.

Consequently, the decision was taken to conduct the analysis exclusively for the primary market. The rationale behind this choice is to ensure the maintenance of comparative consistency and inherent homogeneity in the study.

3.5.3 Data Interpolation and Modification

[100] **Western Climate Initiative, Inc. (n.d.).** *Home*. https://wci-inc.org/
[101] **California Air Resources Board. (n.d.).** *California Air Resources Board (CARB)*. https://ww2.arb.ca.gov/
[102] "A type of auction in which each buyer sends in a written bid that is unknown to the other buyers." **Cambridge Dictionary. (n.d.).** *Sealed-bid auction*. In Cambridge Dictionary. Retrieved, from https://dictionary.cambridge.org/dictionary/english/sealed-bid-auction

The initial data, downloaded from the ICAP website, proved to be unsuitable for the subsequent analysis conducted in the paper. These data were available in a daily format or were incomplete, depending on the specific types of auctions in the respective markets.

So, to ensure homogeneity over time and comparability between markets, it was necessary to subject the data to a treatment and harmonisation process, differentiated for each market considered. The following operations were performed:

- *EU-ETS*

Data were presented in a daily format for both the primary and secondary markets. In such circumstances, it was deemed unnecessary to interpolate the variables in either market; instead, the simple average of all monthly values was sufficient to obtain a single value for the month.

- *CA CaT*

Secondary market allowance data exhibited a discontinuous coverage over time, with numerous missing months. To address this, a script was developed within the statistical software R Studio to obtain a complete data set necessary for the analysis. Initially, a comprehensive time series extending from January 2014 to November 2024 was constructed. The original dataset was then integrated into this time series, and in months where no values were present, these were replaced with NA. To fill in the gaps, linear interpolation was applied using R's approx() function, which estimated the absent values based on the immediately preceding and subsequent values. The data thus obtained were aggregated to ensure a monthly observation. Finally, to assess the accuracy of the interpolation, a comparative graphical representation was used (Figure 7), which showed visual consistency between the original and estimated values.

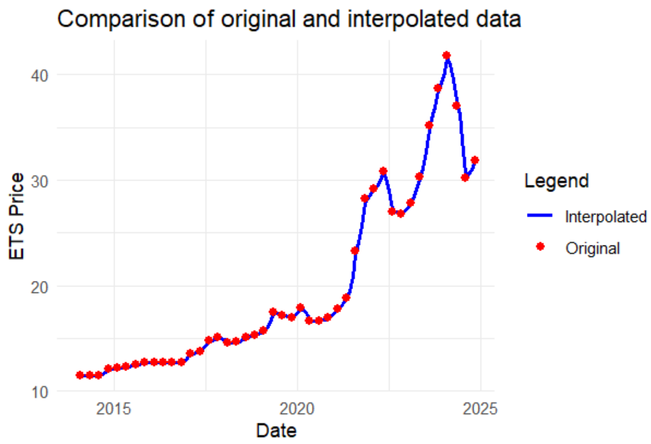

Figure 7: Interpolated data for California Cap-and-Trade Market. Source: Internally Elaborated

- *K-ETS*

In the case of the Korean market, as was the case in the California Cap-and-Trade market, it was necessary to use statistical techniques to obtain a monthly dataset for prices. In this specific case, however, a distinction must be made between primary and secondary markets.

- **Primary market**:

Data demonstrated discontinuities, time jumps and null values. In this scenario, the implementation of linear interpolation, although a fundamental technique, proved insufficient. Consequently, additional methods, listed in a hierarchical order, had to be employed to obtain more accurate results.

1) *Linear interpolation*: was performed via the approx() function to estimate values based on adjacent points.
2) *Substitution of the values resulting as 0:* was achieved by means of a 3-month centred moving average via the rollmean() function to maintain consistency of the series.
3) *Directional filling:* via locf() of residual missing values, forward or backward, was also employed.

In conclusion, a graph was generated (Figure 8) in accordance with the established protocol to substantiate the actions that had been executed.

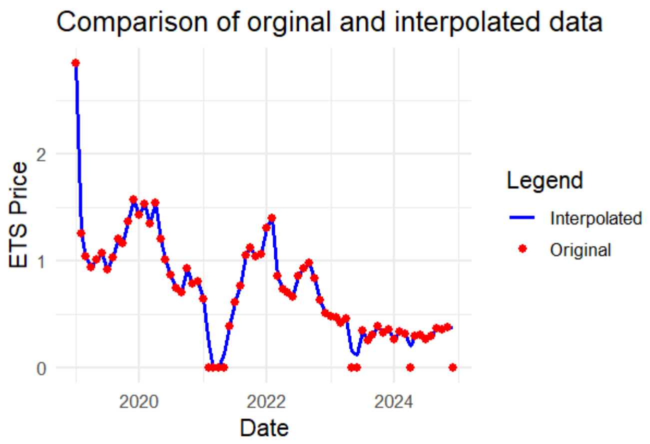

Figure 8: Interpolated data for Korea-ETS Market. Source: Internally Elaborated

- **Secondary Market**:

Secondary market data were available in a daily format. Consequently, it was not necessary to apply any statistical technique other than simple monthly averaging in order to obtain a complete dataset.

3.6Drivers

The selection of drivers is of paramount importance when conducting a thorough and robust study using econometric models. The methodological approach adopted for the selection is based on an extensive review of existing academic literature (Chapter 2, section 2.1), which has highlighted how CO_2 price dynamics are influenced by a complex set of macroeconomic, energy, climate, financial and institutional factors.

In this case, it was essential to transform the theoretical insight into a consistent and operational set of variables, customized to the empirical framework of the study.

To this end, all influencing factors were integrated into the study, as summarised in the following Table 3. Furthermore, the table specifies which influencing factors were selected, as they may vary in some cases, in order to ensure geographical consistency for these specific countries.

3.6.1 Driver Specifications

In consideration of the disparities identified in the selection of drivers, with the objective of maintaining consistency with the particularities of the geographical contexts examined, a summary table is provided. This table contains the comprehensive list of drivers utilised, with the intention of facilitating comprehension of the paper.

EU-ETS	**California Cap-and-Trade**	**K-ETS**	**Description**
Inflation rate	Inflation rate	Inflation rate	Percentage
Industrial production index (IPI)	Industrial production index (IPI)	Industrial production index (IPI)	Index
Gross Domestic Product	Gross Domestic Product	Gross Domestic Product	Value in the country's currency
M2	M2	M2	Value in the country's currency
Retail Sales Index	Retail Sales Index	Retail Sales Index	Index
Economic sentiment	Economic sentiment	Economic sentiment	Index
Exports	Exports	Exports	Change MoM
Unemployment Rate	Unemployment Rate	Unemployment Rate	Change MoM
Refinancing Rate	Effective Federal Funds Rate	Base Rate	Percentage
Newcastle Coal price	Richards Bay Coal price	Newcastle Coal price	Price
TTF natural gas price	Henry Hub natural gas price	LNG Japan Korea Natural gas Price	Price
Brent Oil price	WTI Oil price	Brent Oil Price	Price
Temperature	Temperature	Temperature	Celsius

Precipitation	Precipitation	Precipitation	Millimetres
EU-Shocks	CA-Shocks	Korea-Shocks	Dummy
Temperature Anomalies	Temperature Anomalies	Temperature Anomalies	Dummy

Table 3: Drivers

3.6.2 Driver Interpolation and Modification

In accordance with the preceding modifications to market prices, it was imperative that the drivers underwent statistical recalibration to ensure temporal congruence with the other indicators and for their comparability.

As previously stated, the special case pertained to the EU-ETS market, comprising the nations that are members of the European Union, in addition to Liechtenstein, Norway and Iceland. It was imperative that the values of each respective driver from the various nations under consideration be revised. In order to ascertain a unique value for the market, the following methodologies were employed:

1) The drivers of GDP and M2 were aggregated by the simple sum of all values from the 30 countries that were the subject of the analysis.
2) For all other drivers, to determine a weighted average, the total CO_2 emissions for one year for each country in question were taken into account. The countries with the highest levels of pollutant emissions were assigned a higher weighting, while those with the lowest emissions were assigned a lower weighting.

To facilitate the comparison of the values of the drivers both temporally and as absolute values, the following transformations were performed on them:

- *Gross Domestic Product (GDP)*

As is well established, Gross Domestic Product (GDP) is calculated on a quarterly basis by a range of statistical entities worldwide. In view of the above, a code was developed in R studio that could guarantee monthly values through an indirect temporal disaggregation process. In particular, the tempdisagg package was used, which enables the estimation of a high-frequency (monthly) series, consistent with low-frequency (quarterly) constraints, by exploiting the use of correlated variables already available on a monthly basis.

In this context, the term “*correlated variables*” refers to those previously mentioned in the table, which are associated with macroeconomic variables, thereby excluding energy and weather factors.

In terms of disaggregation, 15 methods were put through their paces during the course of the study. These are listed as follows:

1) "dynamic-maxlog",
2) "dynamic-minrss",
3) "dynamic-fixed",
4) "chow-lin-fixed",
5) "chow-lin-maxlog",
6) "chow-lin-minrss-ecotrim",
7) "chow-lin-minrss-quilis"
8) "fernandez",
9) "litterman-minrss",
10) "litterman-maxlog",
11) "litterman-fixed",
12) "fast",
13) "uniform",
14) "ols",
15) "structural"

For each methodological approach, the code estimated the monthly series, providing an $R^2_{adj.}$ value, and then verified the consistency with the quarterly series (through reconstruction of the quarterly value based on the sum of the three months). The model selection was performed on the basis of the given metric, in order to assess the accuracy of the estimate. Finally, the selected method was applied in the three markets considered, with the aim of assessing the performance offered by the reference models.

- *Economic Sentiment*

The present study has adopted a simplified approach in contrast to the official European Commission methodology for calculating the ESI, which is based on the aggregation of standardised sectoral balances[103]. In the absence of disaggregated balances, Economic Sentiment as expressed by different countries was used and then transformed to ESI scale by means of a standardised z-score. The formula adopted replicates the ESI metric (mean 100, standard deviation 10) and it was necessary to ensure consistency across countries and harmonisation when comparing macroeconomic drivers.

$$ESI_t = \left(\frac{X_t - \mu}{\sigma}\right) * 10 + 100 \quad (1)$$

In which:

- X_t *is the sentiment value in month* t
- μ *is the mean of the observed series*
- σ *is its standard deviation*

- *Temperature & Precipitation*

In this instance, the two drivers were retrieved as the daily value of the capitals of each nation belonging to the specified markets. Consequently, for the EU-ETS market, an arithmetic mean was determined, once more utilising CO_2 equivalent consumption as a weight of the weighted average.

3.7Dataset Preparation

The empirical analysis of the data was conducted using statistical models, selected to cover the entire spectrum of possibilities offered by the data. These models include linear, non-linear and complex relationships.

Three models were therefore chosen, namely:

1) *Linear Regression Model (OLS):* for the study of linear relationships between variables
2) *Generalized Additive Model (GAM):* for the study of non-linear relationships
3) *eXtreme Gradient Boosting model (XGBoost):* for the study of complex non-linear relationships

[103] **Eurostat. (n.d.).** *Business and consumer surveys - economic sentiment indicator (ESI)*. Retrieved from https://ec.europa.eu/eurostat/cache/metadata/en/ei_bcs_esms.htm

To analyse the models under consideration, it was necessary to transform the variables in order to ensure that the results obtained are not subject to spurious regressions, which could compromise the validity of the results. The first two models, OLS and GAM, in fact, require the transformation of the variables to avoid such issues. In contrast, the machine learning model XGBoost is able to handle the transformation of the variables independently, thus obviating the need for such a transformation.

In order to achieve a comprehensive analysis covering every possible facet, it was decided to segment the code into two distinct blocks:

1) Block 1 stationary variables
2) Block 2 non-stationary variables

3.7.1 Dependent Variables Creation

With the intention of conducting the analysis as described above, this paper adopted two separate transformations of the variable "Price", to address the requirement for analysing both the determinants of price and determinants of volatility.

- *Log_Price*

For the analysis of the impact of the drivers on the carbon price level, the natural logarithm of the price (Log_Price) was used as the dependent variable in the OLS, GAM and XGBoost models. This choice was motivated by two factors. Firstly, the high econometric interpretability of the coefficients in terms of semi-logarithmic elasticity. Secondly, its effectiveness in improving the normality of the residuals and reducing heteroscedasticity (Lin & Jia, 2019)[104]. The utilisation of such a transformation for the present study has been corroborated by Ji et al. (2021)[105], who employed price logarithms to model the long-term relationships between economic variables and the price of CO2.

- *Returns*

To analyse conditional volatility, a transformation into logarithmic returns was employed.

This was calculated as follows:

[104] **Lin, B., & Jia, Z. (2019).** *Impacts of carbon price level in carbon emission trading market*. Applied Energy, 239, 157–170 https://doi.org/10.1016/j.apenergy.2019.01.194
[105] **Ji, C.-J., Hu, Y.-J., Tang, B.-J., & Qu, S. (2021).** *Price drivers in the carbon emissions trading scheme: Evidence from Chinese emissions trading scheme pilots*. Journal of Cleaner Production, 278, 123469. https://doi.org/10.1016/j.jclepro.2020.123469

$$returns_t = \log(Price_t) - \log(Price_{t-1}) \tag{2}$$

This investigation constitutes a component of a well-established strand of research endeavours focused on the comprehension of financial markets' volatility. This methodological approach has garnered substantial validation through the findings of studies undertaken by Chevallier (2009)[106], who conducted an analysis of the EU-ETS market through "*carbon features are computed as the logreturn*" (p. 618).

In summary, the decision to implement two distinct transformations is consistent with the econometric literature applied to the field of exchange rate dynamics and financial markets. This approach facilitates the effective management of issues related to non-stationarity and the interpretability of the coefficients, thereby ensuring the robustness and reliability of the analysis.

3.8 Preliminary Tests

Prior to embarking on a comprehensive evaluation of the statistical models employed in this study, the objective of this section is to elucidate the assessments conducted during the preparatory phase. These assessments were undertaken with the intention of preparing the data necessary for conducting an econometric analysis on models that are robust and stable.

3.8.1 ADF Test

As previously mentioned, in this initial block, OLS and GAM models were estimated, under the assumption that the variables were stationary. To obtain variables that were deemed to be stationary, it was necessary to apply the Augmented Dickey-Fuller (ADF) test to each variable using a code in R Studio. Subsequent to the execution of the test, if the p-value was greater than 0.05, the variable was considered non-stationary and was placed in a designated list for differentiation. In the end, the variables were differentiated to first order using the formula:

$$X'_t = X_t - X_{t-1} \tag{3}$$

[106] **Chevallier, J. (2009).** *Carbon futures and macroeconomic risk factors: A view from the EU ETS*. Energy Economics, 31(4), 614–625. https://doi.org/10.1016/j.eneco.2009.02.008

The aforementioned procedure aligns with the findings reported by Pinho & Madaleno (2011)[107]. In their study, the authors assert that "*energy series and carbon prices are non-stationary [...] the series are integrated of order one, I(1), or first-difference stationary*". Consequently, they substantiate the utilisation of differentiation to ensure the validity of the econometric models employed.

Subsequently, a new ADF analysis was conducted to assess whether the variables had attained a stable state. In the event that they had not, the variables would be incorporated into a new list for the second differentiation.

The second differentiation is then undertaken using the following formula:

$$X_t'' = X_t' - X_{t-1}' = (X_t - X_{t-1}) - (X_{t-1} - X_{t-2}) \quad (4)$$

Finally, a third ADF test was performed in order to verify the actual stability of all variables.

This approach was applied to all ETS markets examined in a consistent and systematic manner for the primary (where available) and secondary market.

At this point, the variables were considered to be stationary, and the models could be used without the concern of generating spurious regressions.

3.8.2 VIF Test

Following the acquisition of the transformed variables and their subsequent transformation into a stationary state, the collinear variables were eliminated through an iterative process. This process was facilitated by the utilisation of the Variance Inflation Factor (VIF), which enabled the removal of variables with values exceeding 10.

The process was conducted in the following manner:

1) Removal of variables with variance close to zero
2) Automatic OLS model creation
3) VIF calculation and iterative removal of the most collinear variable

[107] **Pinho, C., & Madaleno, M. (2011).** *CO2 emission allowances and other fuel markets interaction*. Environmental Economics and Policy Studies, 13, 259–281. https://doi.org/10.1007/s10018-011-0014-2

The process was terminated for each market when all variables had a VIF below the settled threshold. This approach was consistent with previous research conducted by Zhao et al. (2018)[108], who, in their study of Chinese ETSs, stated that they adopted the VIF method to test for multicollinearity, and that values below 10 ensure the absence of it and the robustness of the estimated coefficients.

3.9Models

The present section of the paper is devoted to the theoretical explanation of the models employed.

3.9.1 Stationary Models

- *OLS Model*

In the context of the present study, a linear regression model (OLS) was estimated for each ETS market that was examined. As outlined above, the objective of this study is to identify the impact of the economic factors on the CO_2 allowance price level. The dependent variable used was the natural logarithm of the price (*Log_Price*).

The general formula for the applied model is as follows:

$$\log(Price_t) = \beta_0 \sum_{i=1}^{k} \beta_1 X_{i,t} + \gamma_1 D_{temp,t} + \gamma_2 D_{shock,t} + \varepsilon_t \qquad (5)$$

In which:

- $X_{i,t}$ $represent\ the\ set\ of\ independent\ regression\ variables\ (drivers)$
- $D_{temp,t}$ $dummy\ variable\ for\ temperature\ related\ anomalies$
- $D_{shock,t}$ $dummy\ variable\ for\ market\ changes$
- ε_t $random\ error\ with\ zero\ mean\ and\ constant\ variance$

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108 **Zhao, Y., Wang, C., Sun, Y., & Liu, X. (2018).** *Factors influencing companies' willingness to pay for carbon emissions: Emission trading schemes in China*. Energy Economics, 75, 357–367. https://doi.org/10.1016/j.eneco.2018.09.001

The estimation of the coefficients was conducted through the utilisation of the ordinary least squares (OLS) method, while the assessment of the validity of the model was performed through the following methods:

- Adaptation coefficient R^2_{adj}
- Root Mean Squared Error: RMSE
- Mean Absolute Error: MAE

- *GAM Model*

The generalised additive model (GAM) can be regarded as a flexible generalisation of the linear model. It was designed to model non-linear relationships between an independent variable and a set of predictors. GAM was first introduced by Hastie and Tibshirani (1986)[109], and it allows linear terms to be replaced with smooth non-parametric functions, one per predictor, while maintaining the additive model structure.

The general formula of the model is:

$$g(\mathbb{E}[Y]) = \alpha + \sum_{j=1}^{k} s_j(X_j) \qquad (6)$$

In which

- $Y \; is \; the \; dependent \; variable$
- $g(.) \; is \; the \; link \; function \; (identity \; in \; Gaussian \; models)$
- $\alpha \; is \; the \; intercept$
- $X_j \; are \; the \; explanatory \; variables$
- $s_j(.) \; are \; non-parametric \; smooth \; functions \; estimated \; from \; the \; drivers$

In the context of this paper, the link function utilised was the identity function, as a normal error distribution is assumed. The model was applied directly to the logarithm of the price, the formula for which is as follows:

$$\log(Price_t) = \alpha + \sum_{i=1}^{k} s(X_{i,t}) + \gamma_1 D_{temp,t} + \gamma_2 D_{shocks,t} + \varepsilon_t \qquad (7)$$

[109] **Hastie, T., & Tibshirani, R. (1986).** Generalized Additive Models. *Statistical Science*, 1(3), 297–310. https://doi.org/10.1214/ss/1177013604

In which:

- $s(X_{i,t})$ $represents\ a\ smooth\ spline\ function\ for\ each\ continuous\ driver\ X_i, estimated\ non-parametrically$
- $D_{temp,t}$ $dummy\ variable\ for\ temperature\ related\ anomalies$
- $D_{shock,t}$ $dummy\ variable\ for\ market\ changes$

The function under consideration was used to model the non-linear behaviour of each explanatory variable, and the functions in question were represented by means of splines. Splines consist of pieces of polynomials joined at specific points, called knots, with the condition of continuity and derivability.

Furthermore, as demonstrated in the formula, the model would also contain control dummy variables. By its own nature, the GAM model would not include them in the calculation of continuous variables but would treat them as linear variables. This was due directly to the nature of the dummy variables (binary variables with values 0, 1), which would not allow for the estimation of smooth continuous variables.

- *GARCH-X Model*

The GARCH-X model, an extension of the classical GARCH (1,1) model (Bollerslev, 1986)[110], was utilised for the analysis of the conditional volatility of ETS market returns. This model facilitates the incorporation of exogenous variables in the variance dynamics, thereby enabling the capture of the effect of observable external shocks on volatility.

The model is specified as follows:

$$\varepsilon_t = \sigma_t z_{t,} \quad z_t \sim \mathcal{N}(0,1) \tag{8}$$

$$\sigma_t^2 = \omega + \alpha\varepsilon_{t-1}^2 + \delta' X_t \tag{9}$$

In which:

- ε_t $are\ the\ residuals\ of\ logarithmic\ returns$
- σ_t^2 $represents\ the\ conditional\ variance\ estimated\ at\ time\ t$
- X_t $is\ a\ vector\ of\ exogenous\ variables$
- δ $is\ the\ vector\ of\ parameters\ associated\ with\ the\ external\ drivers$

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[110] **Bollerslev, T. (1986).** *Generalized Autoregressive Conditional Heteroskedasticity*. *Journal of Econometrics*, 31(3), 307–327. https://doi.org/10.1016/0304-4076(86)90063-1

- ω, α, β *are the classic parameters of the GARCH model*

The application of the GARCH-X model in this study was substantiated by its capacity to model volatility influenced by macroeconomic, energy and climate variables, thereby surpassing the limitations of conventional GARCH models. Researchers such as Han and Kristensen (2015)[111] had demonstrated how the incorporation of exogenous variables can enhance the explanatory capacity of volatility. Furthermore, Yeasin (2022)[112] emphasized the effectiveness of GARCH-X in capturing the impact of external factors in financial markets.

3.9.2 Non-Stationary Models

In the second analysis block, the XGBoost (Extreme Gradient Boosting) model was implemented. This is considered to be one of the most effective Machine Learning techniques for non-linear regressions.

- *XGBoost Model*

XGBoost (Extreme Gradient Boosting) is an algorithm based on tree boosting, i.e. a model that autonomously detects weaknesses in the previous decision tree, excludes them and continues its process. It is highly optimised and designed for high performance in terms of accuracy and computational efficiency (Chen & Guestrin, 2016)[113].

In contrast to linear models, XGBoost does not necessitate standardisation of variables, a finding corroborated by Castilho, C. M. (2020)[114]. In his research on the comparison of statistical models, he observed that the XGBoost model can effectively handle non-stationary data. These claims were further substantiated by an earlier study by März, A. (2019)[115], who emphasised the flexibility of the model and its ability to handle complex features such as non-stationarity.

As mentioned above, regarding tree boosting, the algorithm progressively develops a series of decision trees, where each new tree corrects the inaccuracies of the previous one.

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[111] **Han, H., & Kristensen, D. (2015).** *Semiparametric multiplicative GARCH-X model: Adopting economic variables to explain volatility*. Working paper. Retrieved from https://creates.au.dk
[112] **Yeasin, M., Singh, K. N., Lama, A., & Paul, R. K. (2020).** *Modelling Volatility Influenced by Exogenous Factors using an Improved GARCH-X Model*. Retrieved from https://www.researchgate.net/publication/348163301_Modelling_Volatility_Influenced_by_Exogenous_Factors_using_an_Improved_GARCH-X_Model
[113] **Chen, T., & Guestrin, C. (2016).** *XGBoost: A scalable tree boosting system*. arXiv preprint arXiv:1603.02754. https://arxiv.org/pdf/1603.02754
[114] **Castilho, C. M. (2020).** *Time series forecasting with exogenous factors: Statistical vs. machine learning approaches* (Master's thesis, University of Porto). Repositório Aberto da Universidade do Porto. https://repositorio-aberto.up.pt/bitstream/10216/141197/2/433647.pdf
[115] **März, A. (2019).** *XGBoostLSS: An extension of XGBoost to probabilistic forecasting* [Preprint]. arXiv. https://arxiv.org/pdf/1907.03178

This process was achieved by minimising a loss function and a complexity regularisation term.

The general function of the algorithm is the following:

$$L^{(t)} \sum_{i=1}^{n} l\left(y_{i,}\hat{y}_i^{(t-1)} + f_t(x_i) + \Omega(f_t)\right) \tag{10}$$

In which:

- $l(.)\ is\ the\ loss\ function\ (in\ this\ case, the\ mean\ square\ error)$
- $\hat{y}_i^{(t-1)}\ is\ the\ cumulative\ prediction\ up\ to\ the\ previous\ iteration$
- $f_t(x_i)\ is\ the\ added\ tree\ at\ step\ t$
- $\Omega(f_t)\ penalises\ the\ complexity\ of\ the\ new\ tree, avoiding\ overfitting$

In the present study, the algorithm was trained on a set of hyperparameters calibrated to circumvent model overfitting, a phenomenon associated with limited data availability. These hyperparameters were optimised through the implementation of early stopping.

The following hyperparameters were employed:

- Learning rate (eta) = 0.1
- Maximum tree depth (max_depth) = 6
- Fraction of random data used by each tree (subsample) = 0.8
- Fraction of variables randomly selected at each iteration (colsample_bytree) = 0.8
- Maximum number of iterations (nrounds) = 500
- Early stopping criterion in case of non-improvement (early_stopping_rounds) = 20

In addition, to ensure the robustness of the model, different hyperparameters were tested by means of their automatic optimisation using Grid Search, Random Search and Bayesian Optimisation. In accordance with the findings of recent studies (Hosseini et al., 2024[116]; Kaur & Gill, 2024[117]), automatic optimisation did not enhance initial predictive

[116] **Hosseini Sarcheshmeh, A., Etemadfard, H., Najmoddin, A., & Ghalehnovi, M. (2024).** *Hyperparameters' role in machine learning algorithm for modeling of compressive strength of recycled aggregate concrete*. Innovative Infrastructure Solutions, 9(212). https://doi.org/10.1007/s41062-024-01471-z
[117] **Kaur, A., & Gill, K. S. (2024).** *ESPM: A Model to Enhance Stroke Prediction with Analysis of Different Machine Learning Approaches and Hyperparameter Tuning*. International Journal of Mathematical Sciences and Computing, 10(2), 49–64. https://doi.org/10.5815/ijmsc.2024.02.05

performance. Indeed, the application of such methods reduced the coefficient of determination (R^2) in some cases. This resulted in diminished stability of the models. This outcome was consistent with the observations reported by Hosseini et al. (2024), who found that in high-complexity contexts with limited datasets, excessive tuning can result in models that are overly predictable and less generalisable. Consequently, the decision was made to employ the initial parameterisation, which was found to be more stable and efficient.

To complete the analysis, 5-fold cross-validation was introduced to assess the stability and generalisability of the model. The methodology is based on dividing the dataset into five identical subsets. The model was then trained on four of these and tested on the fifth. This process was repeated five times, with the subset to be tested being changed in each iteration. The metrics obtained in the five trials were then transformed into averages, providing a stable and generalizable estimate.

The application of 5-fold Cross-Validation (CV) was determined by empirical considerations regarding the limited size of the dataset. It was determined that each market contains a maximum of 132 observations on a monthly basis. The employment of more sophisticated techniques, such as 10-fold Cross-Validation (CV), might have yielded smaller subsets, thereby compromising the reliability of the model.

Furthermore, the implementation of CV on time series necessitates meticulous examination, as the randomisation of the folds has the potential to modify the temporal structure of the data, thereby diminishing the inferential validity of the technique. To circumvent these challenges, this study opted for a static, randomised CV with a fixed seed, taking into account the methodological limitations emphasised in the extant literature (Bergmeir & Benítez, 2012)[118] while ensuring the reliability of the estimates.

This approach was found to confirm the robustness of the performance obtained, and to identify an optimal number of iterations. It also provided an estimate of the mean error (RMSE) on an out-of-sample basis that was consistent with previous results.

[118] **Bergmeir, C., & Benítez, J. M. (2012).** *On the use of cross-validation for time series predictor evaluation*. Information Sciences, 191, 192–213. https://doi.org/10.1016/j.ins.2011.12.028

In the specific context of ETS markets, the application of this algorithm can yield substantial advantages, including the following:

- The capacity to model non-linear and complex relationships between drivers
- The absence of assumptions regarding data distribution, thereby eliminating the necessity for data transformation
- The automatic management of variable interactions, a capability that is not feasible in linear models
- The automatic selection of relevant features via importance measures derived from tree structure

3.10 Conclusion

In summary, Chapter 3, which is addressed above, detailed the methodological approaches that will be followed for the analyses conducted in this paper.

The initial segment of the discussion focused on the establishment of the database comprising the variables, underscoring the meticulous methodology employed to formulate these selections.

Secondly, the selection of models utilized was made explicit, with the implementation of a heterogeneous approach encompassing traditional methods (OLS), flexible models for nonlinear relationships (GAM), machine learning models for complex relationships (XGBoost), and models for the analysis of volatility conditional on variables (GARCH-X). The application of these models established a substantial foundation for deriving salient insights from the analysis of variables. The utilization of this model facilitates the exposition of the numerous distinctive effects offered by the markets.

The inherent limitations of the study must be taken into account, including database restrictions, the necessity to transform the variables, and the unavoidable variability inherent in models. Notwithstanding the aforementioned limitations, this study provides a solid basis for future comparative analyses, with the objective of formulating useful insights for policymakers and firms operating in the markets under consideration.

4. Empirical Analysis

The present chapter will present the empirical analysis aimed at providing answers to the research questions of this paper.

The analysis will be conducted on the three carbon trading markets (ETS) under consideration: These are the European Union Emissions Trading System (EU-ETS), California Cap-and-Trade (CA CaT) and the Korean Emissions Trading System (K-ETS). The analysis will focus on the results derived from the statistical models run on the dataset constructed for the study, focusing on the markets as a whole and the comparison between them.

This approach was necessitated by the substantial differences in terms of market structure, auction type and maturity. Given the dissimilar geographical contexts of the markets (Europe, America, and Asia), it is important to acknowledge that they face different political, economic and energy challenges, despite the common goal of reducing the greenhouse gas impact through a cap-and-trade mechanism.

A comprehensive understanding of the factors influencing prices and market volatility is imperative to accurately assess the unique characteristics of each market. This methodological approach enables companies to make informed decisions and provides policymakers with a valuable reference point for specific decision-making.

4.1 Explanation of the Chapter Setting

The objective of this section was to estimate and interpret the impact of selected factors (macroeconomic, energy and climate) on the price level of carbon allowances in the three markets. This impact will be analysed through a range of econometric approaches.

The following subsections will then elucidate:

1) Preparatory test:
    - ADF Test (section 4.2.1)
    - VIF Test (section 4.2.2)

2) Block 1 analysis of stationary variables (section 4.3):
    - OLS Model
    - GAM Model
3) Block 2 analysis of non-stationary variables (section 4.4):
    - XGBoost Model

Following the conclusion of the analytical process for each model, a comparative analysis of the various approaches will be conducted. This will be followed by a final account of the comparisons made between the three markets. The most significant empirical differences that emerged from the study will also be explained.

4.2 Preparatory Test

The chapter on methodology clearly outlines how it was necessary to conduct a preliminary analysis of the data in order to make them stationary. The objective of these preliminary analyses was twofold: firstly, to make the data manageable and secondly, to make the data analysable by the models themselves.

4.2.1 ADF Test

Initially, an Augmented Dickey-Fuller (ADF) test was conducted in order to assess the stability of the variables. The test would detect a non-stationary variable if the significance level exceeded 0.05 (5%). Subsequent to this, the variable was differentiated. This process was repeated up to a maximum of two differentiations for each market.

The results obtained for each market are shown in Table 4 below:

- *First ADF Test*

The presence of an X in the table will indicate that the values were non-stationary (p-value > 0.05). Conversely, the presence of a ✓ will indicate that the values were stationary (p-value < 0.05).

Drivers	***Primary market EU-ETS***	***Secondary market EU-ETS***	***Primary market CA CaT***	***Primary Market K-ETS***	***Secondary market K-ETS***
Inflation	X	X	X	X	✓
IPI	✓	✓	✓	✓	✓
M2	X	X	X	X	X
Retail sales	X	X	X	X	X
Sentiment	X	X	X	X	X
Export	✓	✓	X	✓	✓
Unemployment	X	X	X	✓	✓
GDP	X	X	X	X	X

Interest Rate	X	X	X	X	X
Coal Price	X	X	X	X	✓
Oil price	X	X	X	X	X
Natural gas price	X	X	X	X	X
Temperature	✓	✓	✓	✓	✓
Precipitation	✓	✓	✓	✓	✓

Table 4: Stationary variables after first ADF test

As was stated in Chapter 3 (entitled 'Methodology'), following the implementation of the test, the initial differentiation of the variables was conducted to render them stationary.

The differentiation formula is:

$$X_t' = X_t - X_{t-1} \tag{3}$$

Following the differentiation of the variables, there was a reiteration of the ADF test; the findings of said test are presented in Table 5 below.

- *Second ADF Test*

Drivers	***Primary market EU-ETS***	***Secondary market EU-ETS***	***Primary market CA CaT***	***Primary Market K-ETS***	***Secondary market K-ETS***
Inflation	✓	✓	✓	✓	✓
IPI	✓	✓	✓	✓	✓
M2	X	X	✓	✓	✓
Retail sales	✓	✓	X	✓	✓
Sentiment	✓	✓	✓	✓	✓

Export	✓	✓	✓	✓	✓
Unemployment	X	X	✓	✓	✓
GDP	✓	✓	✓	✓	✓
Interest Rate	✓	✓	X	X	X
Coal Price	✓	✓	✓	X	✓
Oil price	✓	✓	✓	X	✓
Natural gas price	✓	✓	✓	X	✓
Temperature	✓	✓	✓	✓	✓
Precipitation	✓	✓	✓	✓	✓

Table 5: Stationary variables after second ADF test

As indicated by the data presented in the table, a secondary differentiation procedure was implemented for those variables that had not yet attained stability.

The differentiation formula is:

$$X_t'' = X_t' - X_{t-1}' = (X_t - X_{t-1}) - (X_{t-1} - X_{t-2}) \quad (4)$$

Having carried out the second differentiation, a further ADF test was conducted to check the presence of residual non-stationary variables. The outcomes of this evaluation are presented in Table 6 below.

- *Third ADF Test*

Drivers	***Primary market EU-ETS***	***Secondary market EU-ETS***	***Primary market CA CaT***	***Primary Market K-ETS***	***Secondary market K-ETS***
Inflation	✓	✓	✓	✓	✓
IPI	✓	✓	✓	✓	✓
M2	✓	✓	✓	✓	✓
Retail sales	✓	✓	✓	✓	✓

Sentiment	✓	✓	✓	✓	✓
Export	✓	✓	✓	✓	✓
Unemployment	✓	✓	✓	✓	✓
GDP	✓	✓	✓	✓	✓
Interest Rate	✓	✓	✓	✓	✓
Coal Price	✓	✓	✓	✓	✓
Oil price	✓	✓	✓	✓	✓
Natural gas price	✓	✓	✓	✓	✓
Temperature	✓	✓	✓	✓	✓
Precipitation	✓	✓	✓	✓	✓

Table 6: Stationary variables after third ADF test

It can be stated with a high degree of confidence that the system was in a state of equilibrium. The variables had reached a certain level of stability and were ready to be used in the analysis with the aforementioned models.

4.2.2 VIF Test

However, before proceeding with the analysis, it was first necessary to check for potential multicollinearity in the current version of the data set, which now contains only stationary variables.

This investigation was undertaken utilising the Variance Inflation Factor (VIF) test. The analysis process was conducted in accordance with the established methodology chapter.

The findings of the study are to be exhibited in tabular form. Said table will comprise all three of the ETS markets that were the focus of the research.

To ensure simplicity and synthesis, only the results of those variables eliminated during the process will be presented. It was imperative to emphasise that the elimination of variables was contingent upon the attainment of a VIF value that exceeds 10, as this value is indicative of a high degree of collinearity.

Market	*Primary/Secondary*	*Driver Removed*
EU-ETS	Primary	Export (VIF=19)
	Secondary	Export (VIF=19)

CA CaT	Primary	GDP (VIF=12.31)
K-ETS	Primary	GDP (VIF=14.03)
	Secondary	GDP (VIF=11.64)

Table 7: VIF test results

Subsequent to the elimination of collinear variables, the dataset was deemed suitable for performing the analysis.

4.3 Price Determinants Analysis

In order to provide a comprehensive and meticulous analysis and to respond to the research questions posed in this paper, the results of the analysis will be elucidated in the following section.

4.3.1 OLS Model General Results

The first of these is the Ordinary Least Squares (OLS) model, a linear regression model that enables the analysis of linear relationships between variables in the three markets (EU ETS, California Cap-and-Trade and Korea ETS).

In accordance with the methodology outlined in the preceding chapter, the analysis will use equation 5, where the dependent variable is the price (Log_Price), and the independent variables are macroeconomic, energetic and climatic factors. Two dummy variables will also be considered as control variables (dummy market shocks, dummy temperature anomalies).

The principal outcomes of the OLS model are outlined in Table 8:

Market	***Primary/ Secondary***	R^2_{adj}	***RMSE***	***MAE***
EU-ETS	Primary	0.361	0.792	0.271
	Secondary	0.363	0.788	0.269
CA CaT	Primary	-0.051	0.369	0.106
K-ETS	Primary	-0.091	0.616	5.181
	Secondary	0.170	0.380	0.236

Table 8: OLS general results

From the analysis of the general results, two relevant aspects emerged.

Firstly, it is evident from the R^2_{adj}[119] coefficients, that the models do not attain elevated performance, with a maximum value of 36.37%, as evidenced by the most effective estimates (EU-ETS, secondary market).

Secondly, in two specific markets - namely, the California Cap-and-Trade and Korea-ETS (Primary market) - the coefficient assumes a negative value. This is indicative of its explanatory capacity, which is deemed to be limited.

Finally, it must be noted that an aspect that will be revealed in the subsequent analyses concerning the drivers, and their significance is the remarkable similarity between the EU-ETS markets in the primary and secondary markets (36.19% and 36.37%, respectively).

This similarity is not present in the Korean market, which, between the primary and secondary markets, even shows a change of sign. This outcome indicates that the OLS model is incapable of elucidating the impact of drivers on price in the primary market (-9.12%), while in the secondary market, there is a marginal explanatory capacity (17.04%).

The examination of drivers will be accomplished through a meticulous investigation of individual markets. This will subsequently be followed by further comparison between said markets.

Within the analytical paradigm, the interpretation of the significance coefficients is pivotal for facilitating comprehension. As elucidated in the ensuing Table 9, the coefficients are to be interpreted with particular attention to their highlighted attributes. Henceforth, these coefficients will be uniformly applied to all models, thereby ensuring methodological consistency and continuity.

Significance Level	*Coefficient*
0	***
0.001	**
0.01	*
0.05	.

[119] The term "measures the fraction of deviance explained" is understood to signify the proportion of variability X "explained" by the independent variable Y.

0.1	

Table 9: Significance Level Coefficient

- *OLS EU-ETS Results*

The following analysis presents the results of the European Union Emissions Trading System (EU-ETS), with findings delineated separately for the primary and secondary markets. The OLS model is employed in order to ascertain the existence of potential linear relationships between carbon allowance prices and the selected macroeconomic, energy, and climate variables. This analysis is conducted for both market segments.

— *EU-ETS Primary Market*

Driver	***Estimate***	***Std. Error***	***T value***	***Pr(>t)***	***Sign.***
Retail Sales	1.389e-01	7.518e-02	1.848	0.067	.
Interest Rate	3.748e-01	5.563e-02	6.737	7.50e-10	***
Temperature	-2.760e-02	1.518e-02	-1.818	0.071	.
Dummy Temperature Anomalies	6.457e-01	2.372e-01	2.722	0.007	**

Table 10: OLS EU-ETS Primary Market results

— *EU-ETS Secondary Market*

Driver	***Estimate***	***Std. Error***	***T value***	***Pr(>t)***	***Sign.***
Retail Sales	1.386e-01	7.484e-02	1.851	0.066	.
Interest Rate	3.746e-01	5.538e-02	6.765	6.55e-10	***
Temperature	-2.857e-02	1.512e-02	-1.890	0.061	.
Dummy Temperature Anomalies	6.480e-01	2.362e-01	2.744	0.007	**

Table 11: OLS EU-ETS Secondary Market results

In the context of the EU-ETS market, as demonstrated in the preceding tables, a marked similarity is evident between the primary and secondary markets. This finding is corroborated by the OLS model analysis, which demonstrates a congruence in the determinants, equivalent levels of significance, a shared sign, and strikingly analogous estimation values.

Among these, the European Central Bank (ECB) Refinancing Rate (Interest Rate) emerges as the most significant driver (p-value < 0.001, ***), with a positive coefficient (0.374). This finding indicates that an increase in the ECB interest rate is associated with an increase in carbon allowance prices within the market. This finding is consistent with the results reported in the analysis conducted by Chung et al. (2018)[120]. The researchers found a positive correlation between the interest rate and the price within the EU-ETS market.

Furthermore, an additional variable that is statistically significant (p-value < 0.01, **) with a positive coefficient (0.648) is the Dummy Temperature Anomalies. This finding indicates a potential correlation between extreme weather events and an increase in the price of allowance.

Finally, two additional variables have been identified as being of marginal significance. These are as follows:

Temperature (p-value ≈ 0.061, .) with a negative coefficient (-0.002). It is evident from this that, in contrast to extreme climatic events, mean temperature has a contrary effect, resulting in a decline in demand during periods of higher temperature.

Retail sales, (p-value ≈ 0.066, .) with a positive coefficient (0.138), indicating that as the Retail Sales Index rises, and thus during an increase in the economy, there is also an increase in carbon shares. Despite the absence of exhaustive scientific documentation pertaining to the utilisation of this driver within the specified context, research conducted by authors such as Lovcha et al. (2022)[121] has unveiled auspicious trends with regard to economic efficiency and market prices for carbon allowances.

Turning once more to the climate-related variables, the results obtained are consistent with those previously reported by Eslahi e Mazza (2023)[122]. That study found a significant, non-linear relationship between temperature and price, thus demonstrating how anomalies can significantly influence price dynamics.

To summarise, the findings indicate a high degree of consistency between the primary and secondary markets within the EU-ETS, suggesting a comparable response of these markets to the considered variables. The analysis demonstrates a notable similarity in the

[120] **Chung, C. Y., Jeong, M., & Young, J. (2018).** The price determinants of the EU allowance in the EU Emissions Trading Scheme. Sustainability, 10(11), 4009. https://doi.org/10.3390/su10114009

[121] **Lovcha, Y., Perez-Laborda, A., & Sikora, I. (2021).** The determinants of CO2 prices in the EU emission trading system. *Applied Energy*, *305*, 117903. https://doi.org/10.1016/j.apenergy.2021.117903

[122] **Eslahi, M., & Mazza, P. (2023).** Can weather variables and electricity demand predict carbon emissions allowances prices? Evidence from the first three phases of the EU ETS. *Ecological Economics, 214*, 107985. https://doi.org/10.1016/j.ecolecon.2023.107985

results obtained, reflecting the reliability and robustness of the research methodology employed.

- *OLS CA CaT results*

This section presents the findings derived from the application of the Ordinary Least Squares (OLS) model in the context of the California Cap-and-Trade market. The model is utilized to estimate the influence of selected explanatory variables on the price of carbon allowances in the primary market, which is the only segment that has consistent data availability.

— *CA CaT Primary Market*

Driver	***Estimate***	***Std. Error***	***T value***	***Pr(>t)***	***Sign.***
Dummy Temperature Anomalies	4.478e-01	2.199e-01	2.036	0.044	*

Table 12: OLS CA CaT results

The R^2_{adj} values presented in Table 12 for the California Cap-and-Trade market underscore the limited capacity of the applied OLS model to elucidate price variations in a substantial manner. This limitation can be attributed to the unique structure of the market, which precludes the identification of linear relationships between variables. Consequently, a more in-depth analysis employing sophisticated models is imperative to identify potential relationships between determinants and price.

The model returns only one variable as statistically significant (p-value < 0.05, *), and this is the Dummy control variable relating to Temperature Anomalies. This variable assumes a positive value (0.447), thereby indicating that during periods of temperature anomalies, the market responds with an increase in prices. Despite the market's distinct characteristics, the findings of Eslahi e Mazza (2023)[123] substantiate this trend, as previously referenced.

- *OLS K-ETS results*

[123] **Eslahi, M., & Mazza, P. (2023).** Can weather variables and electricity demand predict carbon emissions allowances prices? Evidence from the first three phases of the EU ETS. *Ecological Economics, 214*, 107985. https://doi.org/10.1016/j.ecolecon.2023.107985

The Korean Emissions Trading System (K-ETS) is analysed using the OLS model across both the primary and secondary markets. This analysis explores the potential for linear relationships between drivers and carbon prices in a policy-driven and relatively nascent carbon market, as determined by the subsequent evaluation of results.

— *K-ETS Primary Market*

Driver	***Estimate***	***Std. Error***	***T value***	***Pr(>t)***	***Sign.***
Unemployment Rate	22.580	12.528	1.802	0.077	.

Table 13: OLS K-ETS Primary Market results

— *K-ETS Secondary Market*

Driver	***Estimate***	***Std. Error***	***T value***	***Pr(>t)***	***Sign.***
Unemployment Rate	3.869e+01	6.981e+00	5.542	2.430e-07	***
Coal Price	1.486e-03	5.377e-04	2.764	0,006	**

Table 14: OLS K-ETS Secondary Market results

With regard to the South Korean market, a distinct situation is observed between the two domestic markets within the same country:

- **Primary market:**

The findings yielded by the model demonstrate a resemblance to the observations made in the context of the California Cap-and-Trade market, where R^2_{adj} emerged as negative. This underscores the model's limited capacity to capture linear interactions between the factors under consideration and price. Consequently, there is a compelling need to investigate these relationships in the market using more advanced statistical methods.

- **Secondary market:**

In this particular instance, the situation assumes markedly different connotations. The R^2_{adj} coefficient is positive, although the model's explanatory power is found to be limited (17.07%). In this case, two statistically significant variables emerge: Unemployment Rate (p-value < 0.001, ***) with a positive coefficient (38.690) and Coal Price (p-value < 0.01, **) with a positive coefficient (0.001). The first variable (Unemployment Rate) suggests that an increase in unemployment is associated with an increase in the price of carbon shares. This counterintuitive outcome can be attributed to several factors, as highlighted in the study conducted by Joo et al. (2023)[124]. The Korean market is characterised by strong government intervention. This environment fosters a possible disconnect between traditional economic shocks, leading to an increase in carbon shares in conjunction with domestic economic contractions and, consequently, rising unemployment. The second factor (Coal Price) indicates a correlation between an increase in coal prices and an increase in the price of carbon allowances. This conventional relationship continues to be explained by the work of Joo et al. (2023)[125], who, as mentioned earlier, analysed the Korean market, and identified a dynamic particularly evident in the electricity sector, characterised by a regulatory regime. This aspect contributes to a slowing energy transition, with coal remaining a dominant element in energy-intensive industries.

- *OLS Comparison Between Markets*

In conclusion, the application of the OLS model to the three markets considered in this paper (EU-ETS, CA CaT, and K-ETS) demonstrates a limited ability to identify significant linear relationships among the factors under consideration and, consequently, the determinants of price within the markets. Despite the limitations of this preliminary analysis, significant disparities have emerged among in terms of statistically significant factors.

In the case of the EU-ETS market, climate factors and interest rate were found to be statistically significant and consistent with existing literature.

Conversely, the analysis of the California and Korean markets revealed a lack of consistency, primarily due to the paucity of academic studies in these areas, which consequently limited the robustness of the analyses conducted in this paper. Nevertheless, the evidence for the Korean market highlighted its obvious differences from the European market. In this context, the presence of national macroeconomic and energy variables is observed. The unemployment variable also generates a counterintuitive relationship, but this can be explained through a significant domestic component of support for the activities present in the markets.

[124] **Joo, J., Paavola, J., & Van Alstine, J. (2023).** The divergence of South Korea's Emissions Trading Scheme (ETS) from the EU ETS: An institutional complementarity view. Politics &Amp Policy, 51(6), 1155–1173. https://doi.org/10.1111/polp.12566
[125] **Joo, J., Paavola, J., & Van Alstine, J. (2023).** The divergence of South Korea's Emissions Trading Scheme (ETS) from the EU ETS: An institutional complementarity view. Politics &Amp Policy, 51(6), 1155–1173. https://doi.org/10.1111/polp.12566

It is evident from the analysis that the OLS model, while useful as a preliminary analysis phase, was inadequate in capturing the complex dynamics exhibited by the target markets. Consequently, there is a necessity for the employment of more flexible and complex methodologies in order to enhance the predictive and explanatory capacity of the determinants.

4.3.2 GAM Model

In this section, the Generalised Additive Model (GAM) will be applied. The objective of this model is to surmount the limitations of the OLS model through its capacity to flexibly model, potentially nonlinear relationships between dependent and independent variables. This is achieved by employing smoothing spline functions.

Subsequently, in the paper will be examined the potential for non-linear relationships between the dependent variable (Log_Price) and the independent variables (drivers). This will involve the analysis of relationships that do not have a significant effect on the OLS model, or that only have a linear effect.

In accordance with the procedure previously outlined, the following Table 15 offers a synthesis of the model's results in the three markets under consideration:

Market	***Primary/ Secondary***	R^2_{adj}	***RMSE***	***MAPE***
EU-ETS	Primary	0.756	0.521	0.176
	Secondary	0.747	0.529	0.180
CA CaT	Primary	0.197	0.343	0.090
K-ETS	Primary	0.337	0.545	7.022
	Secondary	0.554	0.298	0.091

Table 15: GAM general results

The Generalised Additive Model (GAM) provides results of considerable interest. As demonstrated by the results previously outlined, the model attains a notably elevated coefficient R_{adj}^2 in all three markets, accompanied by reduced RMSE and MAE values when compared to preceding models.

This finding indicates that the model demonstrates a superior capacity to capture the specific dynamics of the markets under consideration and is able to identify nuances that could not be captured by the OLS model.

The ensuing discussion of the results generated by the model will adhere to the same structure previously employed in the description of the OLS model.

Concerning the explanation, it will be necessary to take into account the presence of dummy control variables, as explained in the methodology section of the GAM model. These variables will be handled by the model itself as if they were linear, by virtue of their nature (i.e. binary variables with values of 0 and 1). However, in this section, these variables will not be considered since they have already been examined in the Ordinary Least Squares (OLS) model for the analysis of linear relationships, which produced coincident results.

- *GAM EU-ETS Results*

A close examination of the results reveals a striking similarity between the primary and secondary markets, a finding that aligns with the observations made in the OLS model. For the sake of brevity and simplification, the markets will be treated together, with examination of the differences when present. In the explanation of the variables, the sequence of reporting information will be in this order (primary and secondary).

The Tables 16 and 17 below provide a visual representation of the outcomes derived from the model's estimation of the smooth terms for the primary and secondary markets.

— *EU-ETS Primary Market*

Driver	***EDF[126]***	***F-value***	***p-value***	***Sign.***

[126]The effective degrees of freedom (edf) estimated from generalized additive models were used as a proxy for the degree of non-linearity in stressor-response relationships. (a) An edf of 1 is equivalent to a linear relationship, (b) an edf > 1 and ≤ 2 is a weakly non-linear relationship, and (c) an edf > 2 indicates a highly non-linear relationship. **Alain F. Zuur, Ieno, E. N., Walker, N., Saveliev, A. A., & Smith, G. M. (2009).** *Mixed Effects Models and Extensions in Ecology with R*. Springer Verlag. https://doi.org/10.1007/978-0-387-87458-6

s(Inflation Rate)	1.946	3.229e-01	0.074	.
s(Economic Sentiment)	3.231	1.017	0.002	**
s(Interest Rate)	1.241	4.152e+01	0.000	***
s(Coal Price)	1.307	1.357	0.017	*
s(Natural Gas Price)	4.980	6.387	0.000	***
s(Temperature)	1.189	1.477	0.001	**

Table 16: GAM EU-ETS Primary Market results

— EU-ETS Secondary Market

Driver	***EDF***	***F-value***	***p-value***	***Sign.***
s(Inflation Rate)	1.920	3.097e-01	0.080	.
s(Economic Sentiment)	2.614	1.672	0.010	*
s(Interest Rate)	1.227	3.879e+01	0.000	***
s(Coal Price)	1.205	1.180	0.023	*
s(Natural Gas Price)	5.033	6.928	0.000	***
s(Temperature)	1.210	1.592	0.001	**

Table 17: GAM EU-ETS Secondary Market results

A detailed and technical elucidation is provided to specify the findings outlined in the model results:

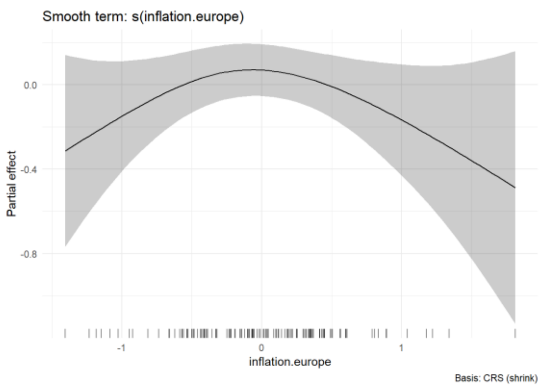
- *Inflation Rate:*

The variable, which has an EDF of (1.946 and 1.920), reveals a weakly linear relationship; the p-value (0.074 and 0.080) suggests marginal significance (. and .). Further insights can be gleaned from the graphical representation of the model's generated function. Inflation Rate in the two markets with an inverted U-shaped curve tends to stabilise around the average rate, while a negative effect is observed in the tails for low and high values of inflation, which could potentially result in lower share prices. However, the confidence interval (grey area of the graph) exhibits expansion precisely in the tails, indicating uncertainty in the estimate, likely attributable to the limited quantity of observations in this area.

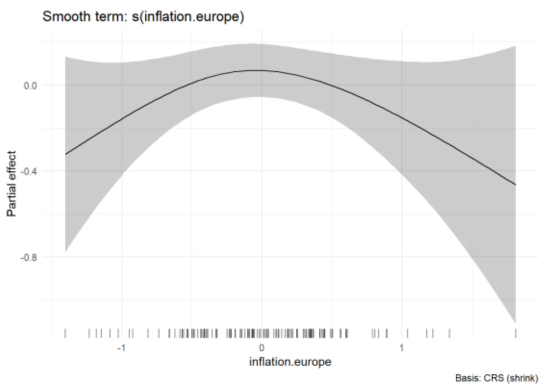
It is thus suggested that the behaviour of the curve indicates that, in stationary economic situations, energy demand remains constant. However, in extreme cases, two distinct scenarios can be postulated:

1) In circumstances where inflation is minimal (or deflationary), it is possible for the level of output to decline as a consequence of fundamental economic deficiencies.
2) In circumstances of elevated levels of inflation, a restrictive monetary policy may result in a decline in demand. Such a decline can in turn precipitate a decline in production, consequently giving rise to a diminution in demand for allowance.

Preliminary examination of the relevant literature indicates a congruence with the findings of the analysis. The impact of the variable is particularly pronounced in pre-2020 studies, exhibiting a marginal and nonlinear pattern. One of the studies carried out by Hintermann (2010)[127], assumed indirect effects via aggregate demand. Moreover, the recent analysis by Roncalli and Semet (2024)[128] asserts that "inflationary pressures are marginal at the global level" yet simultaneously acknowledges that "producer inflation is concentrated in European economies," exhibiting asymmetric effects across sectors. Consequently, it can be concluded that inflation does not appear to be a systematic driver, as evidenced by recent studies in which it is not identified as a determining factor.



Graph 2: Smooth Curve Inflation Rate EU-ETS Primary Market. Source: Internally Elaborated



Graph 3: Smooth Curve Inflation Rate EU-ETS Secondary Market. Source: Internally Elaborated

- *Economic Sentiment:*

The variable has an EDF of (3.231 and 2.614), indicating a markedly nonlinear relationship with the dependent variable. The p-value is observed to be one of the few

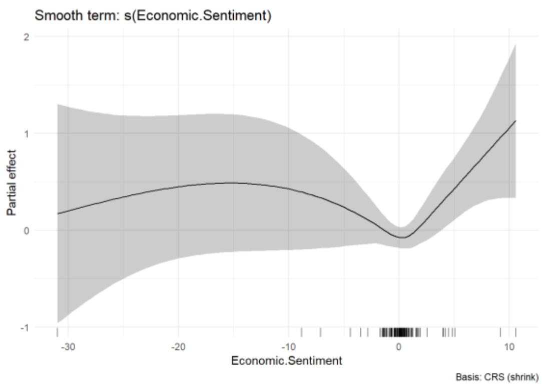
[127] **Hintermann, B. (2010).** Allowance price drivers in the first phase of the EU ETS. Journal of Environmental Economics and Management, 59(1), 43–56. https://doi.org/10.1016/j.jeem.2009.07.002
[128] **Roncalli, T., & Semet, R. (2024).** The economic cost of the carbon tax. SSRN Electronic Journal. https://doi.org/10.2139/ssrn.4755259

significant differences detected in this market, with values of (0.002 and 0.010), indicating a greater degree of significance for the primary market (** and *).

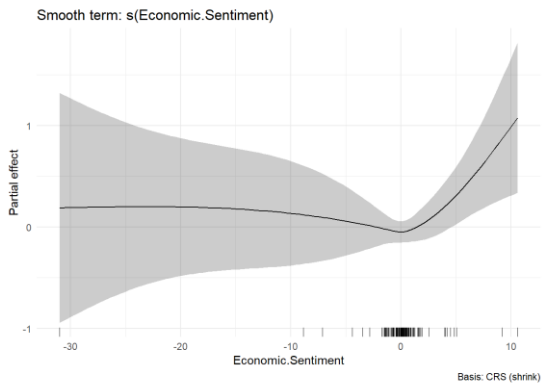
A further analysis of the correlated graphs reveals a particularly relevant trend.

- For Economic Sentiment variable values that are below average, the effect is found to be negligible or slightly negative. This finding indicates that during periods of diminished economic confidence, there is an absence of impact on allowance price or a slight decrease.
- For above-average values, a significant increase in curve growth is observed, with a marked positive trend. This phenomenon suggests that during periods of economic confidence, there is a rapid escalation in the price of carbon allowances, which is associated with an increase in demand for production.

A review of the available literature did not reveal any consistent results with those studied in this paper. The study conducted by Huang and Zhang (2024)[129], examined Chinese market Economic Sentiment and confirmed the findings of this analysis; however, the European market has not yet been analysed with this variable.



Graph 4: Smooth Curve Economic Sentiment EU-ETS Primary Market. Source: Internally Elaborated



Graph 5: Smooth Curve Economic Sentiment EU-ETS Secondary Market. Source: Internally Elaborated

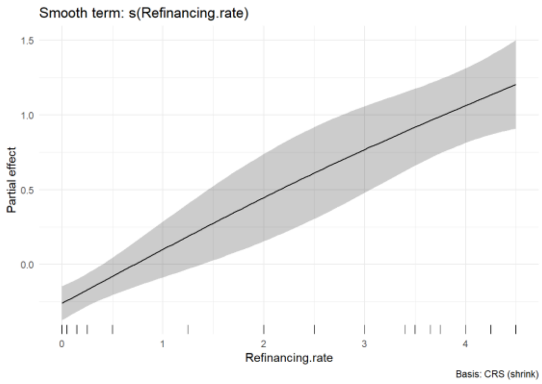
- *Interest Rate:*

The variable has an EDF of (1.241 and 1.227), indicating a nearly linear relationship. The p-value is found to be extremely low at (0.000 and 0.000), thus indicating an extremely high statistical significance (*** and ***).

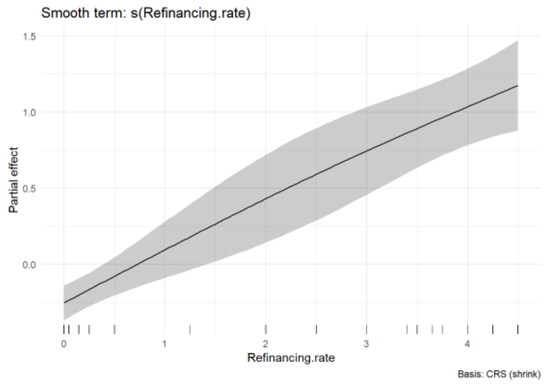
[129] **Huang, Z., & Zhang, W. (2024).** Forecasting carbon prices in China's pilot carbon market: A multi-source information approach with conditional generative adversarial networks. Journal of Environmental Management, 359, 120967. https://doi.org/10.1016/j.jenvman.2024.120967

The analysis of the graph of the smooth function for the variable corroborates these findings. The relationship appears to be linear and monotonically increasing; that is, as the ECB main refinancing rate increases, the price of carbon allowances increases. A rise in interest rates could signal stronger expected economic growth, with higher expectations for production and a necessary use of allowances. This analysis confirms the results obtained with the OLS model, and the almost straight line shown in the graph seems to confirm that the previous model would be sufficient for the analysis of this variable.

Moreover, there is a high degree of concordance between the present analysis and studies undertaken by Campiglio et al. (2017)[130] and Wei et al. (2024)[131] which employed both linear and nonlinear models.



Graph 6: Smooth Curve Interest Rate EU-ETS Primary Market. Source: Internally Elaborated



Graph 7: Smooth Curve Interest Rate EU-ETS Secondary Market. Source: Internally Elaborated

- *Coal Price:*

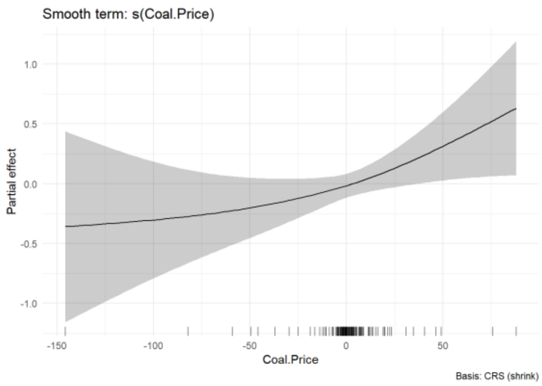
The variable under consideration has an EDF of (1.307 and 1.205), which indicates a minor deviation from linearity. The p-value is (0.017 and 0.023), proving to be statistically significant (* and *).

The analysis of the graph of the smooth function of the variable reveals an increasing concave shape, suggesting that as the price of coal increases, there is a corresponding increase in carbon allowance prices. This dynamic of substantial increase after a certain threshold can be interpreted with energy switching. When coal prices remain low, coal is competitive, and companies tend to use it. Conversely, in the event of elevated coal prices,

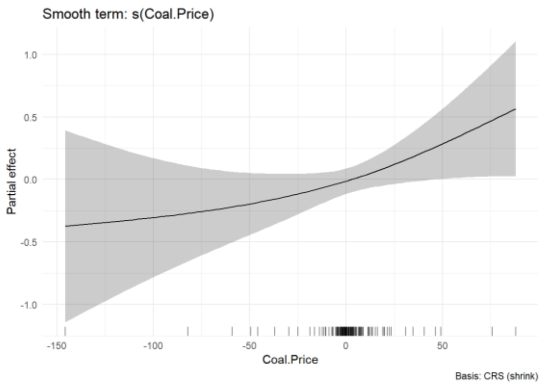
[130] **Campiglio, E., Godin, A., Kemp-Benedict, E., & Matikainen, S. (2017).** The tightening links between financial systems and the Low-Carbon transition. In Springer eBooks (pp. 313–356). https://doi.org/10.1007/978-3-319-60459-6_8
[131] **Wei, P., Zhou, J., Ren, X., & Huynh, L. D. T. (2024).** Financialisation of the European Union Emissions Trading System and its influencing factors in quantiles. International Journal of Finance & Economics. https://doi.org/10.1002/ijfe.2950

companies are likely to seek alternative fuels, though this process is associated with additional costs. This dynamic, due to its non-instantaneous nature, gives rise to an anticipated surge in demand, attributable to the rigidity of supply.

The existing literature confirms the minor importance of this variable within the context of the EU-ETS market. In the aforementioned study by Hintermann (2010)[132], the author identified fossil fuels, and more specifically coal, as a driver in Phase I of the EU-ETS market. Furthermore, the study undertaken by Lovcha et al. (2022)[133] asserts that although the influence of coal has historically been negligible, it is currently gaining relevance, especially during periods of protracted shocks.



Graph 8: Smooth Curve Coal Price EU-ETS Primary Market. Source: Internally Elaborated



Graph 9: Smooth Curve Coal Price EU-ETS Secondary Market. Source: Internally Elaborated

- *Natural Gas Price:*

The variable under scrutiny represents a particularly intriguing and intricate element within the context of the market under study. The analysis conducted revealed a strongly nonlinear relationship, with an EDF of (4.980 and 5.033). Furthermore, the p-value is found to be low at (0.000 and 0.000), thereby indicating an exceedingly elevated level of significance for both markets under consideration (*** and ***).

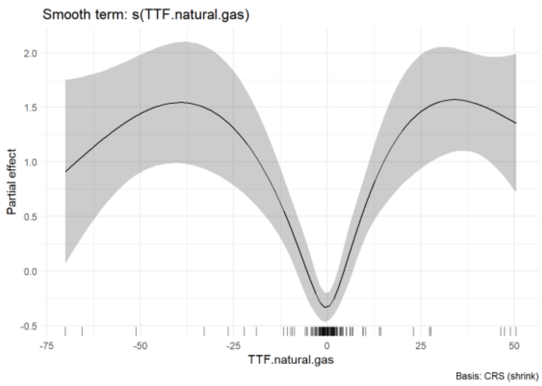
The graphical analysis reveals a V-shaped trend, with a low point at which the impact on share price is significantly reduced, sometimes even negative. At points above and below the average, a rapid surge is observed, suggesting that declines and rises in the price of

[132] **Hintermann, B. (2010).** Allowance price drivers in the first phase of the EU ETS. Journal of Environmental Economics and Management, 59(1), 43–56. https://doi.org/10.1016/j.jeem.2009.07.002
[133] **Lovcha, Y., Perez-Laborda, A., & Sikora, I. (2021).** The determinants of CO2 prices in the EU emission trading system. *Applied Energy*, *305*, 117903. https://doi.org/10.1016/j.apenergy.2021.117903

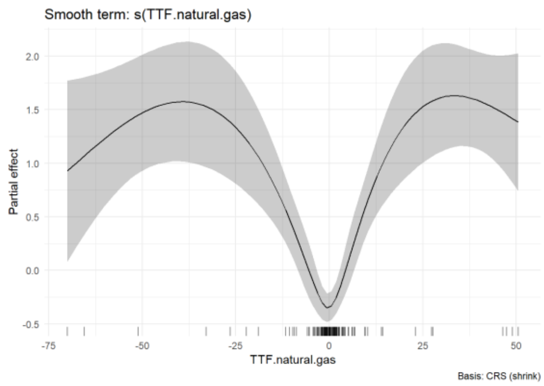
natural gas exert a direct influence on carbon allowance prices. This phenomenon manifests itself in two distinct ways:

1) Lower prices indicate possible higher natural gas consumption and thus, greater need for emission allowances.
2) Higher prices bring with them external macroeconomic pressures that push the value of allowance upward.

The extant research corroborates this finding; the study by et al. (2024)[134] links more natural gas price peaks to shocks and changes in the EU-ETS market price. This finding is further substantiated by the model's capacity to predict such price fluctuations with a high degree of precision, as evidenced by the graphical representation.



Graph 10: Smooth Curve Natural Gas Price EU-ETS Primary Market. Source: Internally Elaborated



Graph 11: Smooth Curve Natural Gas Price EU-ETS Secondary Market. Source: Internally Elaborated

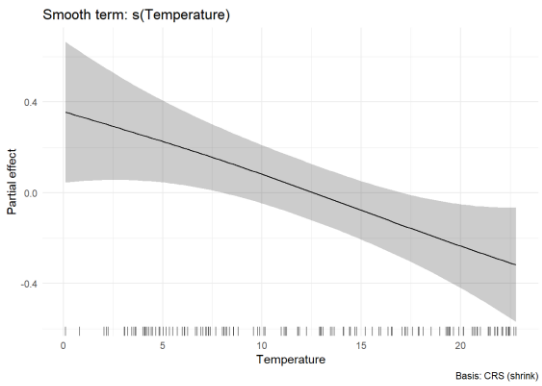
- *Temperature:*

The variable in question displays an EDF of (1.189 and 1.210), indicating an almost linear function. The p-value was determined to be (0.001 and 0.001), indicating that both are statistically significant (**, **).

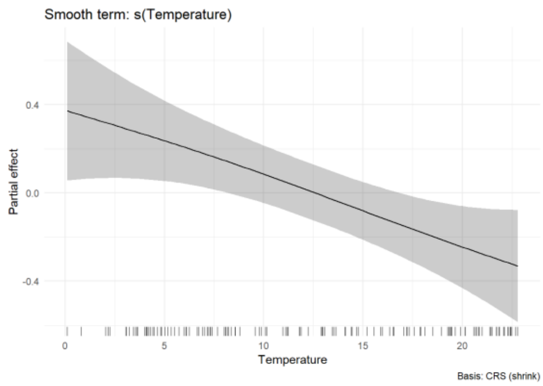
A further analysis of the graphs corresponding to the model's associated smooth function, reveals a monotonic decrease. Additionally, an observed trend indicates a decrease in carbon allowance prices with rising temperatures. This phenomenon can be attributed to the increased energy consumption during colder periods, which subsequently leads to elevated pollution levels and heightened demand for carbon allowances.

[134] **Jeitschko, T. D., Kim, S. J., & Pal, P. (2024).** Curbing price fluctuations in cap-and-trade auctions under changing demand expectations. Energy Economics, 139, 107804. https://doi.org/10.1016/j.eneco.2024.107804

The extant literature corroborates the findings in this particular variable as well as in the control dummy variable. Indeed, even not very recent studies, such as those by Hintermann (2010)[135] e Daskalakis et al. (2009)[136], have indicated that this trend is more evident during the winter months than during the summer months. This phenomenon can be attributed to the increased need for heating, which results in higher levels of energy consumption. It is noteworthy that even during summer months, there are discernible trends, particularly during periods of peak consumption, attributed to the increased demand for cooling. This observation aligns with the findings reported by the Dummy Temperature Anomalies, underscoring the reliability and consistency of the data.



Graph 12: Smooth Curve Temperature EU-ETS Primary Market. Source: Internally Elaborated



Graph 13: Smooth Curve Temperature EU-ETS Secondary Market. Source: Internally Elaborated

- *GAM CA CaT results*

The second system analysed using the Generalized Additive Model (GAM) is the California Cap-and-Trade market (CA CaT). The results of the study highlight nonlinear relationships between specific drivers and carbon prices in the primary market segment.

— *CA CaT Primary Market*

Driver	***EDF***	***F-value***	***p-value***	***Sign.***
s(Coal Price)	2.217	2.995	0.002	**
s(Oil Price)	2.340	1.051	0.040	*

Table 18: GAM CA CaT results

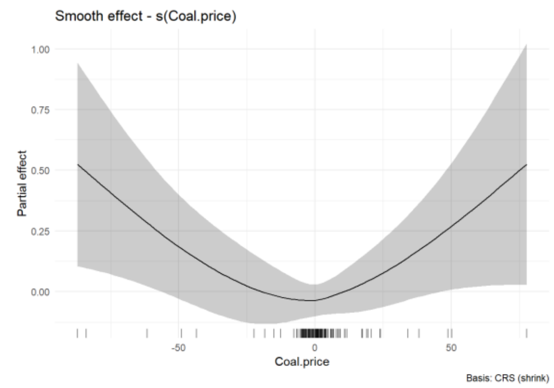
- *Coal Price:*

[135] **Hintermann, B. (2010).** Allowance price drivers in the first phase of the EU ETS. Journal of Environmental Economics and Management, 59(1), 43–56. https://doi.org/10.1016/j.jeem.2009.07.002
[136] **Daskalakis, G., Psychoyios, D., & Markellos, R. N. (2009).** Modeling CO2 emission allowance prices and derivatives: Evidence from the European trading scheme. Journal of Banking & Finance, 33(7), 1230–1241. https://doi.org/10.1016/j.jbankfin.2009.01.001

The variable has been found to have a value of EDF of 2.217, which indicates a non-linear relationship between it and the dependent variable. The p-value of 0.002 is statistically significant at the (**) level, indicating a high degree of statistical relevance.

The analysis of the generated graph reveals a U-shaped curve, indicative of a negligible effect of Coal Price on the dependent variable when the mean value is maintained. Conversely, deviations from the mean value of Coal Prices result in a rapid escalation of carbon allowance price. A comparison of the function in this market with that of the EU-ETS market reveals a high degree of similarity.

In conclusion, analysis lends further support to the findings of the study by Jeitschko et al. (2024)[137], which utilized a comprehensive data set from California's Cap-and-Trade market auctions. The study revealed a non-linear relationship between changes in commodity prices and allowance prices, extending the insights of earlier research.



Graph 14: Smooth Curve Coal Price CA CaT. Source: Internally Elaborated

- *Oil Price:*

The variable demonstrated an EDF coefficient of 2.340, thereby suggesting a nonlinear relationship between the price of West Texas Intermediate (WTI) oil and the dependent variable. The term is statistically significant (*), with a p-value of 0.040.

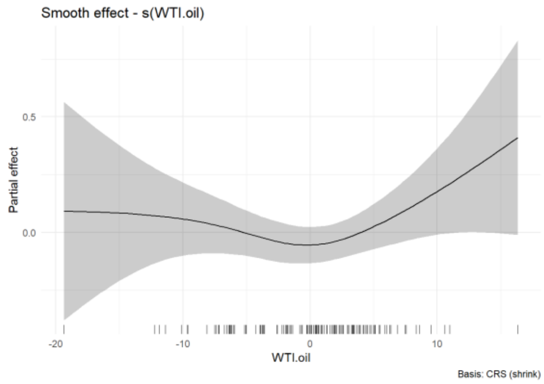
A visual examination of the graph reveals the presence of two distinct segments:

- From below-average prices down to zero, the price of WTI oil is static and almost irrelevant.

[137] **Jeitschko, T. D., Kim, S. J., & Pal, P. (2024).** Curbing price fluctuations in cap-and-trade auctions under changing demand expectations. Energy Economics, 139, 107804. https://doi.org/10.1016/j.eneco.2024.107804

- Above the mean value, the effect is increasing, indicating that as the price of oil increases, there is an increase in the price of carbon allowances. This phenomenon could be attributed to a strategic switch in the energy mix of companies. This transition could be driven by a shift in energy sources, leading to an increased consumption of alternative fuels or costs associated with switching between oil and its substitutes.

Moreover, as Jeitschko et al. (2024)[138] previously demonstrated, the notion that oil prices are influenced by nonlinear market mechanisms remains substantiated.



Graph 15: Smooth Curve Oil Price CA CaT. Source: Internally Elaborated

- *GAM K-ETS Results*

The Korean Emissions Trading System (K-ETS) is the third market examined under the General Additive Model (GAM). The present analysis incorporates both the primary and secondary markets, emphasizing non-linear dynamics among macroeconomic, energy, and climate variables.

— K-ETS Primary Market

Driver	***EDF***	***F-value***	***p-value***	***Sign.***
s(Unemployment)	1.098	2.462	0.027	*
s(Interest rate)	2.810	5.947	0.000	***

Table 19: GAM K-ETS Primary Market results

- *Unemployment Rate:*

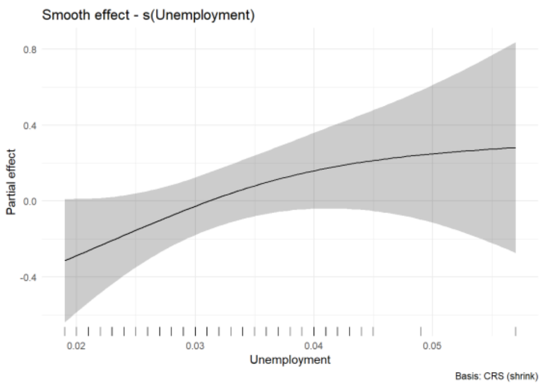
[138] **Jeitschko, T. D., Kim, S. J., & Pal, P. (2024).** Curbing price fluctuations in cap-and-trade auctions under changing demand expectations. Energy Economics, 139, 107804. https://doi.org/10.1016/j.eneco.2024.107804

The variable's estimated (EDF) is 1.098, suggesting an almost-linear relationship with the dependent variable under consideration. The p-value of the same is 0.027, indicating its statistical significance (*).

A visual examination of the graph generated by the smooth function, indicates that the almost-linearity is respected. The function is found to be monotonic increasing, meaning that as the Unemployment Rate increase, the price of carbon allowances increases.

This phenomenon might initially appear counterintuitive; however, it can be rationalized by the established relationship between unemployment and decreased production, which should concomitantly lead to a reduction in demand for quotas. However, this phenomenon could be attributed to a variety of underlying factors:

1) In South Korea, the ETS market is demonstrably linked to the nation's environmental and green policies. Despite economic downturns, characterized by rising unemployment, the government has maintained its stranglehold on CO2 production limits, compelling companies to seek more stringent restrictions.
2) Certain sectors may not be adversely affected by rising levels of unemployment. Conversely, sectors characterized by substantial energy intensity may not experience a need for reduced production, consequently leading to a decline in permit demand.



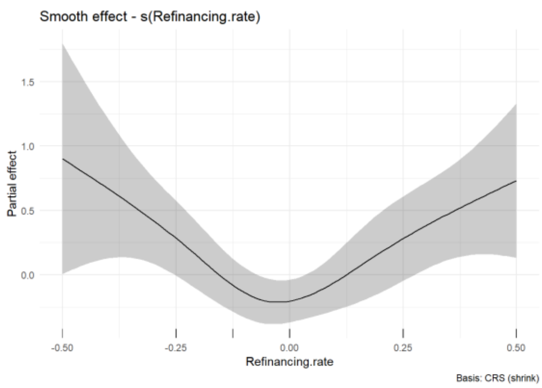
Graph 16: Smooth Curve Unemployment K-ETS Primary Market. Source: Internally Elaborated

- *Interest Rate:*

The variable has an EDF of 2.810, thus indicating a strong nonlinear relationship with the dependent variable. The statistical significance of this relationship is indicated by a p-value of 0.000, which is considered highly statistically significant (**).

The subsequent analysis of the graph reveals a U-shaped curve, thereby confirming the hypothesis that was previously postulated through the EDF. The graph's shape indicates that the value of the carbon price tends to increase in the tails of the function, thus for values above or below the mean, while it maintains stability for mean values. This phenomenon can be explained in two distinct ways:

1) Extremely low interest rate can be indicative of a highly expansionary monetary policy, frequently implemented in response to weak economic conditions. Conversely, in an environment characterized by minimal financing costs, firms may identify prospects for leveraging soft credit to sustain or augment their production levels.
2) High interest rates, conversely, may be observed in an economy characterized by robust growth or inflationary pressures, prompting the central bank to implement tight monetary policies. While this does lead to an increase in the cost of capital, firms may still elect to invest if they foresee robust demand, thereby maintaining high production levels and, consequently, the necessity for allowances.



Graph 17: Smooth Curve Interest Rate K-ETS Primary Market. Source: Internally Elaborated

— *K-ETS Secondary Market*

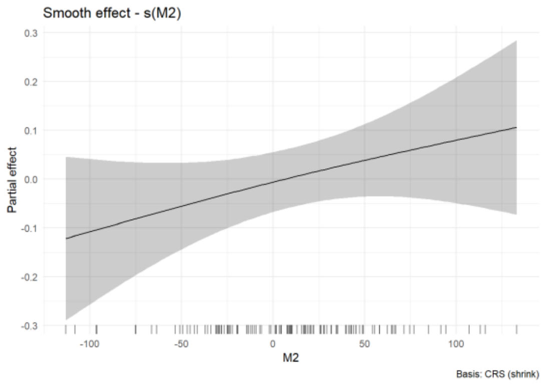
Driver	***EDF***	***F-value***	***p-value***	***Sign.***
s(M2)	8.455e-01	1.330	0.061	.
s(Unemployment Rate)	1.204	1.528	0.009	**
s(Interest Rate)	1.853	7.411	0.000	***
s(Coal Price)	6.176	3.155	0.000	***

Table 20: GAM K-ETS Secondary Market results

- *M2:*

The variable reveals an EDF of 0.8455, signifying a robust linear relationship with the dependent variable. The statistical significance of this relationship is negligible, as indicated by a p-value of 0.061, which corresponds to a significance level of (.).

The graph confirms the linearity hypothesis, demonstrating an almost monotonically increasing straight line, thereby indicating an increase in allowance prices with an increase in M2. Two possible explanations for this phenomenon are considered: an expansive economic condition indicative of a growing economy, or accommodative monetary policies that benefit firms and promote their continued growth.

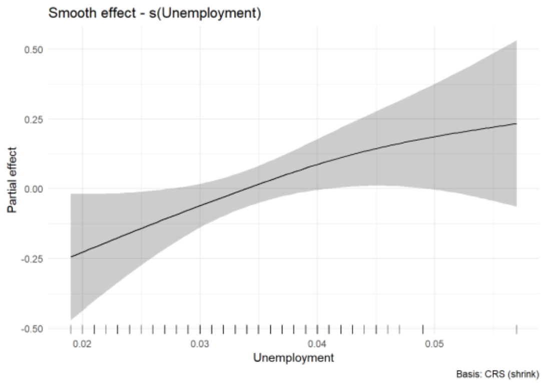


Graph 18: Smooth Curve M2 K-ETS Secondary Market. Source: Internally Elaborated

- *Unemployment Rate:*

The variable with an EDF of 1.204 demonstrates a nearly linear relationship with the dependent variable. The statistical significance, as indicated by a p-value of 0.009, is deemed to be highly significant (**).

A thorough examination of the graph reveals a monotonic increase in the price of carbon allowances price as the Unemployment Rate rises. This phenomenon mirrors the dynamics observed in the primary market, and the underlying rationale remains consistent with the preceding analysis.

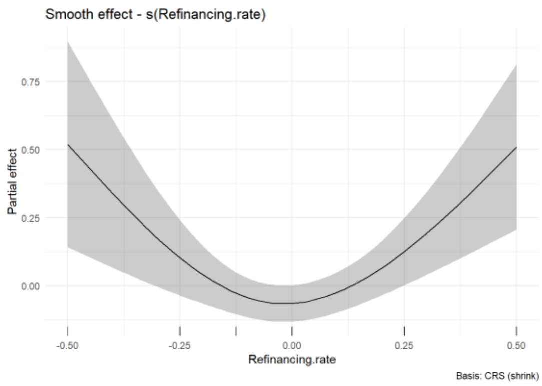


Graph 19: Smooth Curve Unemployment K-ETS Secondary Market. Source: Internally Elaborated

- *Interest Rate:*

The variable has an EDF of 1.853, indicating a nonlinear relationship with the dependent variable. Its statistical significance is high, as indicated by a p-value of 0.000, thus meeting the criteria for a level of (***).

A visual examination of the graph reveals a U-shaped curve derived from the model. This means a minimal influence at the mean values and an increase in the positive and negative tails. The explanation for this phenomenon remains consistent with the rationale provided for the primary market.

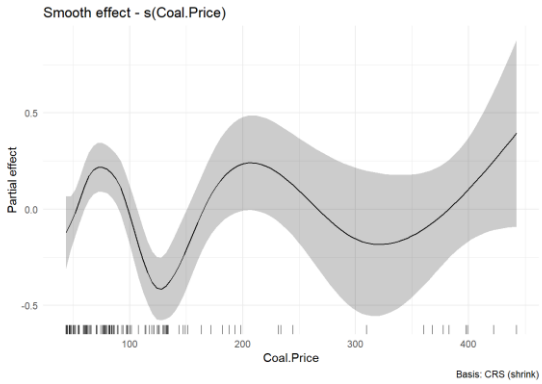


Graph 20: Smooth Curve Interest Rate K-ETS Secondary Market. Source: Internally Elaborated

- *Coal Price:*

This variable is of particular interest within the context of the market, as evidenced by its EDF of 6.176. This indicates a significant degree of flexibility, resulting in a pronounced nonlinear relationship. The variable also exhibits high statistical significance, as evidenced by its p-value of 0.000, thus meeting the criteria for statistical significance at the (***) level.

The graph is equally intriguing, as it displays markedly nonlinear behaviour, with fluctuations varying along its entire axis. This observation suggests the presence of non-trivial dynamics, which may be associated with distinct convenience thresholds. Further investigation is warranted to elucidate the underlying mechanisms and their implications.



Graph 21: Smooth Curve Coal Price K-ETS Secondary Market. Source: Internally Elaborated

A preliminary investigation of the existing literature reveals a paucity of studies related to the analysis of the Korean market.

Nevertheless, a study by Tan et al. (2024)[139], confirms systematic relationships between macroeconomic factors and carbon shares in the Korean ETS market. Notably, their study identified a positive correlation between unemployment and prices. Additionally, the U-shaped relationship of the interest rate reflects distortions related to extreme monetary policies. In contrast, the dynamics related to coal prices are justified by the different sectoral elasticity documented in the study.

In conclusion, it is evident that the GAM model demonstrates superiority over the OLS model in its application. A notable aspect of the GAM model is its consideration of variables that were not included in the linear regression model. This underscores the necessity for more flexible models in contexts involving complex markets, such as the EU-ETS.

- *GAM Comparison Between Markets*

The employment of the Generalized Additive Model (GAM) to examine the three Emissions Trading System (ETS) markets contemplated in this dissertation (EU-ETS,

[139] **Tan, X., Wang, R., Choi, Y., & Lee, H. (2024).** Does Korea's carbon emissions trading scheme enhance efficiency for sustainable energy and utilities? Utilities Policy, 88, 101752. https://doi.org/10.1016/j.jup.2024.101752

California Cap-and-Trade, and Korea-ETS) enabled the identification of shared behaviours and discrepancies. The resulting reports present a wide array of insights, stimulating further reflection and suggesting avenues for additional research.

First, the model provides insights into the degree of linearity and nonlinearity observable in the different variables among the markets. The market with the greatest degree of nonlinearity is the EU-ETS, indicating a higher level of complexity compared to the others. Within the EU-ETS market, several variables (e.g., Economic Sentiment, Natural Gas price, and Interest Rates) exhibit high EDF values, serving as indicators of nonlinearity. This observation underscores the dynamic nature of the European market, a characteristic attributable to its maturation and intricate structure. Conversely, the K-ETS market demonstrates a preponderance of linear or near-linear relationships, signifying a less intricate structure. A substantial proportion of the variables examined manifest an almost unitary EDF (EDF ≈ 1), suggesting the presence of linear or near-linear relationships (as evidenced by Unemployment and M2). This observation suggests an evolving market in which macroeconomic variables are transmitted more directly. This substantial difference can be attributed to the distinct structural environment of the respective markets. The European market, for instance, is heavily influenced by structural changes dictated by market design, resulting in a notable presence of nonlinear relationships, as evidenced by the study conducted by (2013)[140]. The study by Joo et al. (2023)[141], focuses on the Korean market and states that the strong institutional presence in the market influences it, leading to a more direct transmission of macroeconomic dynamics.

The Californian market, by contrast, occupies a median position between the two, exhibiting notable variables inherent to the energy sector, though with a non-linearity that is less pronounced (the highest EDF value in the California Cap-and-Trade market is 2.340, while the highest value in the EU-ETS market is approximately 5). This observation underscores the inherent complexity of the Californian market, which, however, has not yet reached the level of development of the European market, as

[140] **Lutz, B. J., Pigorsch, U., & Rotfuß, W. (2013).** Nonlinearity in cap-and-trade systems: The EUA price and its fundamentals. Energy Economics, 40, 222–232. https://doi.org/10.1016/j.eneco.2013.05.022
[141] **Joo, J., Paavola, J., & Van Alstine, J. (2023).** The divergence of South Korea's Emissions Trading Scheme (ETS) from the EU ETS: An institutional complementarity view. Politics &Amp Policy, 51(6), 1155–1173. https://doi.org/10.1111/polp.12566

confirmed by the study by Lyu and Scholtens (2023)[142]. Despite the system's status as one of the most substantial markets in terms of volume and coverage, it has yet to attain the level of maturity exhibited by the European market.

A substantial discrepancy is evident in the outcomes and behaviours of energetic variables across different markets. Specifically, the price of natural gas demonstrates a substantial impact within the EU-ETS and California Cap-and-Trade markets, exhibiting a V-shaped relationship in both contexts. In the first case, the shape of the function is more pronounced and evident, thus emphasizing the influence of the same variable for both below and above average price values. In the second case, this relationship is evident only in the positive tail and almost absent in the negative tail. Coal price emerges as a significant variable for the EU-ETS and K-ETS markets, but with almost opposite characteristics. While the European market demonstrates an almost linear (positive and increasing) relationship, the Korean market exhibits a greater degree of flexibility and erratic behaviour, suggesting constant technological and energy shifts. Furthermore, the Oil Price variable is statistically significant only in the California market, suggesting a correlation between the strong energy dependence of the US use of Oil and ETS market performance. A further examination of the macroeconomic variables reveals additional disparities among the markets. Specifically, the California Cap-and-Trade market demonstrates an absence of substantial macroeconomic variables, a phenomenon that is not observed in the other two markets.

With regard to the variables, the behaviour of the Interest Rate reveals a result of particular interest. Indeed, this rate assumes considerable significance in both the EU-ETS and K-ETS markets, although it behaves differently: it assumes an almost linear form in the EU market and a U-shape in the Korean market. This observation suggests that the transmission of monetary policy in the European context appears to be oriented in a single direction, in contrast to the multifaceted dynamics observed in the Asian market. The significance of variables such as M2 and the unemployment rate is exclusive to the Korean market, indicating that the impact of monetary and unemployment dynamics is contingent on the institutional form and the developmental level of the market itself.

[142] **Lyu, C., & Scholtens, B. (2023).** Integration of the international carbon market: A time-varying analysis. Renewable and Sustainable Energy Reviews, 191, 114102. https://doi.org/10.1016/j.rser.2023.114102

It can be concluded that the identification of a lowest common denominator among all markets is a possibility. This is represented by the statistical uncertainty present in the tails of the smoothed functions, that is, in the extreme values of each variable. This phenomenon suggests a paucity of observations regarding the extreme values of the variables, but also a structural instability or dependence on exogenous events that can significantly influence the behaviours of these markets.

The GAM model revealed the presence of common factors within the markets examined; however, the patterns of response, in terms of direction, intensity, and form, are extremely diverse. This heterogeneity can be attributed to a variety of geographic, institutional, regulatory, and energy-related factors. These findings underscore the heterogeneity of ETS markets worldwide, providing substantial insights for the development of more targeted regulatory strategies by policymakers and investment strategies for companies operating in these markets. Nevertheless, to attain a comprehensive understanding of the dynamics of price prediction and the influence of several factors in ETS markets, it was deemed necessary to continue the analysis through the use of machine learning techniques. In this direction, the integration of the XGBoost model facilitates the more precise capture of the intricacies inherent in nonlinear variables and their interrelations, thereby enhancing the accuracy of forecasting.

4.4Block 2 Analysis of Non-Stationary Variables

In this section of the paper, we will undertake a rigorous examination of the results obtained from analyses conducted on the examined dataset. In this instance, the analysis will be conducted using a model that does not necessitate the stability condition for the analysis itself.

4.4.1 XGBoost Model

The Extreme Gradient Boosting (XGBoost) model employed in this section, which belongs to the category of Machine Learning algorithms, is distinguished by its high predictive capabilities, effective handling of complex datasets, and ability to analyse nonlinear relationships and interactions between variables.

In view of these premises and the results that have emerged from previous analyses, it was deemed appropriate to investigate further through the application of this model in order to assess its effectiveness and limitations.

- *XGBoost General results*

The performance of the model was evaluated using several metrics, as was the case with previously discussed models. These metrics included: R^2, Root Mean Squared Error (RMSE) e Mean Absolute Percentage Error (MAPE).

Market	***Primary/ Secondary***	R^2	***RMSE***	***MAPE***
EU-ETS	Primary	0.988	0.112	0.032
	Secondary	0.989	0.107	0.033
CA CaT	Primary	0.994	0.027	0.006
K-ETS	Primary	0.775	0.236	1.890
	Secondary	0.910	0.136	0.041

Table 21: XGBoost general results

Preliminary observation suggests that the XGBoost model demonstrates notable efficacy in data analysis. This model is distinguished by its high accuracy and its capacity to accommodate the data, even in the absence of transformations of the variables.

The observation of R^2 values greater than 0.90 across almost all cases signifies a nearly perfect correspondence between the model and the data. However, this extreme precision does not guarantee high predictive accuracy, as it may indicate model overfitting[143] (an overly faithful or exact fit to the training data).

4.4.2 Robustness Analysis - 5-Fold Cross-Validation

In order to verify the robustness of the results obtained, a 5-fold Cross-Validation (CV) was performed following the training of the model. This approach enabled the estimation of the model's performance across various subdivisions of the dataset, thereby reducing the reliance of the data on arbitrary tests. This procedure was deemed essential to ensure

[143] **Canchila, S., Meneses-Eraso, C., Casanoves-Boix, J., Cortés-Pellicer, P., & Castelló-Sirvent, F. (2024).** Natural language processing: An overview of models, transformers and applied practices. Computer Science and Information Systems. https://doi.org/10.2298/csis230217031c

the robustness of the results, taking into account the high value of the R^2 in the models and the possible presence of overfitting.

Preliminary findings suggest that the mean square error estimated through cross-validation remained consistent, thereby demonstrating the model's capacity for reliable generalisation.

The results of the latter are summarised in Table 22 below:

Market	***Primary/ Secondary***	***RMSE***	***Boosting rounds***[144]
EU-ETS	Primary	0.142	91
	Secondary	0.134	84
CA CaT	Primary	0.048	143
K-ETS	Primary	0.332	40
	Secondary	0.183	88

Table 22: 5-Fold Cross-Validation results

The results obtained thus far offer a preliminary indication of the dynamics of the market:

- *CA CaT:*

In this case, the market is evidenced to have higher predictive accuracy (RMSE = 0.0486). Concurrently, a substantial number of boosting rounds (143) have been observed, indicating a tendency towards gradual and sustained learning processes.

- *EU-ETS:*

The market evolves to become the middle market, demonstrating robust performance with an RMSE of approximately (0.14) for both markets, and exhibiting a substantial number of boosting rounds (91 and 84, respectively).

- *K-ETS:*

[144] The amount of trees that have been trained in a sequential manner within the XGBoost model. **Ibm (Ed.). (n.d.).** *Overfitting*. https://www.ibm.com/it-it/think/topics/overfitting

The market that suggests greater complexity or noise in the data. This is evident in the elevated RMSE value, particularly in the primary market (RMSE: 0.3324), and not a high number of boosting rounds

In conclusion, the findings of the cross-validation study demonstrate the XGBoost model's predictive reliability.

We shall now undertake a thorough examination of the results obtained from the model in question. This examination follows the same methodical approach previously applied in the OLS and GAM models.

4.4.3 Analysis Explanation

The identification of the most influential drivers through the model necessitated an in-depth analysis of the variables (i.e. feature importance[145]), utilising the metrics provided by the XGBoost framework:

- *Gain*: measures the reduction in error that each variable makes when used to make a split in tree construction.
- *Cover*: The fraction of observations affected by splits on a variable.
- *Frequency*: The number of times a variable is used as a split criterion.

The metrics that are used in this way cover complementary aspects: while Gain measures the informational contribution of a variable, Cover and Frequency help to understand how it spreads within the ensemble structure.

The selection of all three graphs generated by the model is not arbitrary; indeed, certain variables may be highly frequent but have marginal informational contribution, or vice versa. The presence of a discrepancy may indicate the existence of localized effects that cannot be excluded.

To facilitate visual understanding, three side-by-side graphs were generated containing the top five most influential variables for each metric. This methodological approach

[145] **XGBoost Developers. (n.d.).** XGBoost Documentation — xgboost 3.0.0. Retrieved from https://xgboost.readthedocs.io/en/release_3.0.0/

enables the highlighting of the most significant variables for the model while maintaining simplicity in interpretation.

4.4.4 XGBoost Market Results

- *XGBoost EU-ETS Results*

The ensuing discourse will present the outcomes yielded by the employment of the eXtreme Gradient Boosting (XGBoost) model in the context of the European Union Emission Trading System (EU-ETS). The assessment of non-linear and high-complexity interactions among drivers is achieved by evaluating both the primary and secondary markets.

— *EU-ETS Primary Market*

Graph 22: Feature importance EU-ETS Primary Market results. Source: Internally Elaborated

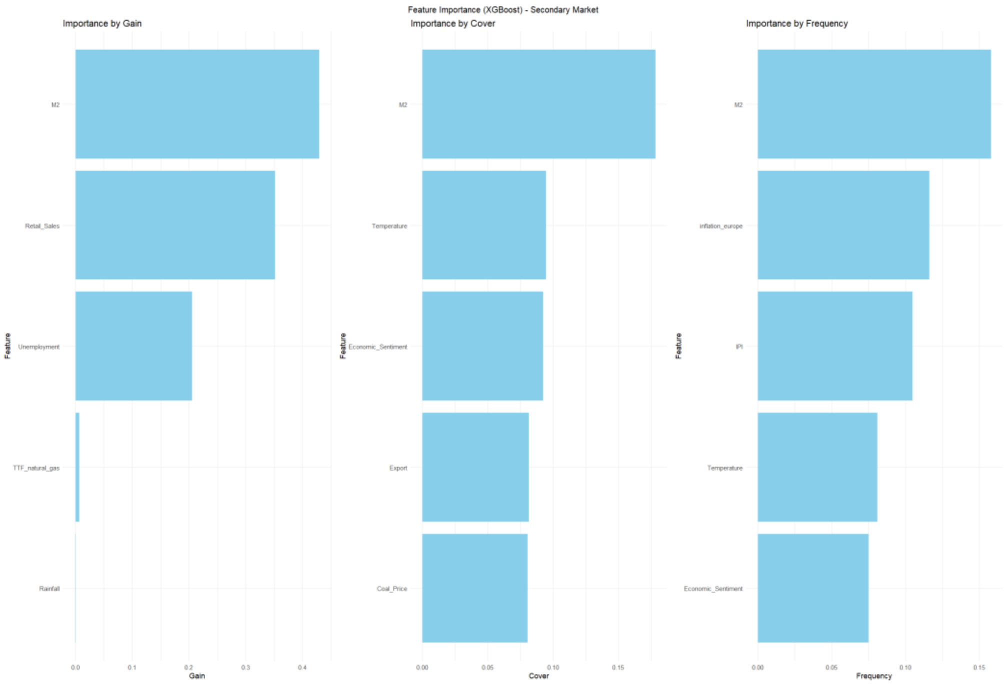
The analysis indicates that variable M2 is the most significant variable in all three metrics (Gain, Cover and Frequency), playing a pivotal role in the forecasting process. Its contribution is particularly evident in the rankings generated by the metric Gain, with a value above 40 percent, indicating a significant ability to reduce forecast error in the model. This finding, in conjunction with its presence in the other rankings, suggests a robust and significant association between the variable and share pricing in the primary market.

Referring back to Gain's ranking, the most significant variables appear to be Retail Sales and Unemployment Rate, suggesting their influence in the model's error reduction process. However, their absence from the top five positions in the other three metrics suggests that their discriminating power is localized. That is, their influence is confined to specific contexts within the model, rather than being applicable in all situations.

An analysis of the rankings generated by Cover and Frequency reveals the emergence of variables such as Coal Price, Economic Sentiment, Export, IPI, and Inflation. The diversity and variability of the drivers result in heterogeneity of the variables present, acting diffusely but with marginal impacts on the loss function. Consequently, these variables facilitate the model's construction of pertinent partitions, even in the absence of a direct impact on the loss function.

Finally, the Rainfall variable, although with modest values, emerges in the rankings. This observation indicates the necessity for further examination of this variable, given its notable impact, albeit understated. This assertion is further substantiated by the findings of Eslahi and Mazza (2023)[146], which revealed relationships, albeit limited in scope within the European context.

— *EU-ETS Secondary Market*



Graph 23: Feature importance EU-ETS Secondary Market results. Source: Internally Elaborated

A thorough examination of the secondary EU-ETS market revealed a substantial congruence in the information structure with that of the primary market. However, notable distinctions emerged concerning particularities associated with climatic factors and a more pronounced heterogeneity across variables.

M2 has been confirmed as the central variable, thereby validating the hypothesis that the liquidity level of the European financial system exerts a substantial influence on share price in both the primary and secondary markets.

Subsequently, the presence of Retail Sales and Unemployment Rate, the other two significant variables within the Gain metric, is demonstrated to be significant. It is noteworthy that these two variables, despite being utilized less frequently in the model,

[146] **Eslahi, M., & Mazza, P. (2023).** Can weather variables and electricity demand predict carbon emissions allowances prices? Evidence from the first three phases of the EU ETS. *Ecological Economics*, *214*, 107985. https://doi.org/10.1016/j.ecolecon.2023.107985

play a pivotal role in the loss function. As previously observed in the primary market, these variables are confirmed to be significant localized discriminants.

A continuation of the analysis of the other two metrics reveals the presence of the same variables previously observed in the primary market, including Coal Price, Economic Sentiment, Export, IPI, and Inflation. This further corroborates their pertinence in the European market, even within the context of the secondary market.

The substantial difference between these two markets is highlighted by the Temperature variable, which is found to be significant in the secondary market, while the Rainfall variable remains significant but is found to have a marginal contribution in the Gain importance ranking.

In summary, it can be concluded that the primary and secondary markets of the EU-ETS demonstrate a highly analogous predictive structure. In both segments, the M2 variable exhibits a predominant influence over all others, followed by Retail Sales and Unemployment Rate. This finding aligns with the conclusions of the study by Li et al (2021)[147], which underscored the role of macroeconomic factors in the EU-ETS market context. Notwithstanding the inclusion of two distinct climate-related variables (Temperature and Rainfall), these variables exert a negligible effect on the prevailing market trend.

The prevailing conclusion is that the markets inherent within the EU-ETS are subject to conventional economic logic. Despite a different pattern of variable activation, they exhibit a stable predictive structure relying mainly on macroeconomic factors.

- *XGBoost CA CaT results*

The California Cap-and-Trade market constitutes the second system subjected to evaluation through the implementation of the XGBoost model. The present analysis is oriented toward a focused investigation of the primary market, with the objective of identifying and quantifying patterns of a complex nature that may not be fully captured by linear and non-linear models.

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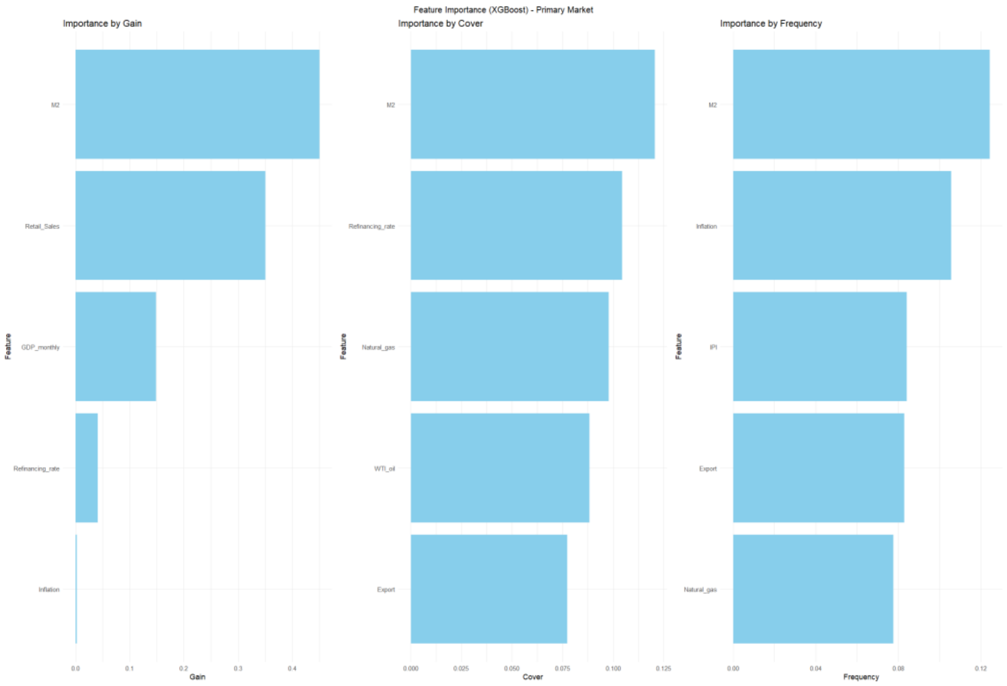
[147] **Li, P., Zhang, H., Yuan, Y., & Hao, A. (2021).** Time-Varying Impacts of carbon price Drivers in the EU ETS: A TVP-VAR analysis. *Frontiers in Environmental Science*, *9*. https://doi.org/10.3389/fenvs.2021.651791

— CA CaT Primary Market



Graph 24: Feature importance CA CaT results. Source: Internally Elaborated

The analysis conducted on the California Cap-and-Trade market demonstrated a correlation with the data observed in the European market. Of the metrics considered, the M2 variable was identified as the most significant. Its centrality across all three metrics underscores its direct influence on price forecasts and its profound structural integration within the model's internal decision-making process.

It is also shown that other variables are significant within the Gain metric. In this regard, a parallel can be drawn with the European market, wherein Retail Sales emerges as a pivotal factor in specific nodes, though not at the structural level. This variable's influence is less pronounced in the other two metrics, and it is excluded from the top five metrics in terms of Cover and Frequency.

Contrary to the EU-ETS market trends, GDP emerges in this context as a variable that is only activated in high variance contexts. Analogous to the case of Retail Sales, this variable has not found to be fundamental at the structural level; however, it becomes central at specific nodes for the purpose of error reduction. The presence of this variable is consistent with the hypothesis that an increase in the economy leads to an increase in demands for emission allowances.

In the Cover metric, variables such as Natural Gas Price, Oil Price, Export, and Interest Rate emerge as notable contributors. These variables, while not included among the primary variables in the Gain metric, are frequently utilized in the upper nodes of decision trees. This observation indicates that these variables can effectively segment the data space into homogeneous regions from the initial stages of decision tree construction.

In particular, the first two Natural Gas Price and Oil Price emerge as determinants in the market structure, highlighting the importance of the energy mix in the California market. As extensively documented in the extant literature, the energy production structure emerges as a focal point in the California Cap-and-Trade market. Jeitschko et al. (2024)[148]

Conversely, the Interest Rate variable indicates a potential correlation between the cost of capital for companies and the demand for permits in the market. This aspect illuminates the influence that monetary policy can exert on companies' demand for carbon allowances.

Moreover, it is imperative to acknowledge the pivotal role of Export in the Cover metric. This component signifies the capacity for foreign demand to exert a direct influence on the price of allowances for Californian companies.

The Frequency metric also identifies four distinctive variables. Two of these variables were previously identified in the aforementioned metric, thereby confirming their structural soundness with regard to frequency of use by the model. These variables are named Export and Natural Gas Price.

Subsequently, we proceed to highlight two additional variables that the model frequently employs in the multiple decision trees. Inflation Rate and IPI.

The former, which has minimal impact on predictive error, is frequently employed by the model. This suggests that it provides useful information on specific subsets of dataset.

Despite the lower utilisation of the last variable mentioned, IPI, a relationship is demonstrated between production activity levels and the primary allocation of permits, albeit a tenuous one.

[148] **Jeitschko, T. D., Kim, S. J., & Pal, P. (2024).** Curbing price fluctuations in cap-and-trade auctions under changing demand expectations. Energy Economics, 139, 107804. https://doi.org/10.1016/j.eneco.2024.107804

In summary, the Californian Cap-and-Trade market also has a defined and compact forecasting structure. Variables such as M2 and Retail Sales, which emerged in the European context, continue to play a pivotal role in predicting the price of carbon allowances in California.

However, it is observed that greater weights are attributed to energy and financial variables in this specific market, reflecting a relationship between the Californian market, energy dynamics and the country's monetary conditions.

The market's information structure can thus be characterised as efficient and not very dispersed, an aspect related to what is observed in the structure of feature activation within the market.

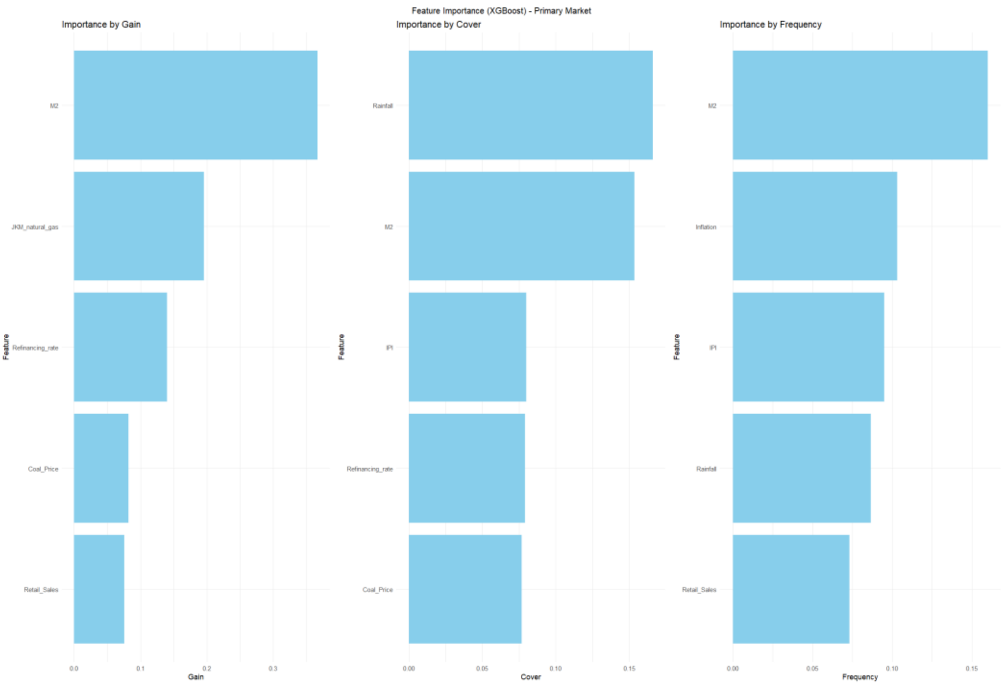
In conclusion, it can be posited that the market as analysed through this model has reached an appropriate maturity. This is in contrast to the findings observed in the earlier GAM model and the studies by Lyu and Scholtens (2023)[149] thus necessitating further studies to investigate the results found.

- *XGBoost K-ETS Results*

The third case analysed with the XGBoost model is the Korean Emissions Trading System (K-ETS). The results from both market segments are presented in an effort to identify potential high-order interactions among the explanatory variables.

— *K-ETS Primary Market*

[149] **Lyu, C., & Scholtens, B. (2023).** Integration of the international carbon market: A time-varying analysis. Renewable and Sustainable Energy Reviews, 191, 114102. https://doi.org/10.1016/j.rser.2023.114102



Graph 25: Feature importance K-ETS Primary Market results. Source: Internally Elaborated

The market analysis of the K-ETS demonstrates that the variable M2 is the predominant component across all metrics evaluated. Its substantial dominance in terms of Gain suggests that system liquidity has a direct and significant impact on the model's predictive ability in reducing forecast error. Concurrently, the substantial presence of M2 in the other two metrics underscores its foundational and pervasive role in the model's decision-making processes.

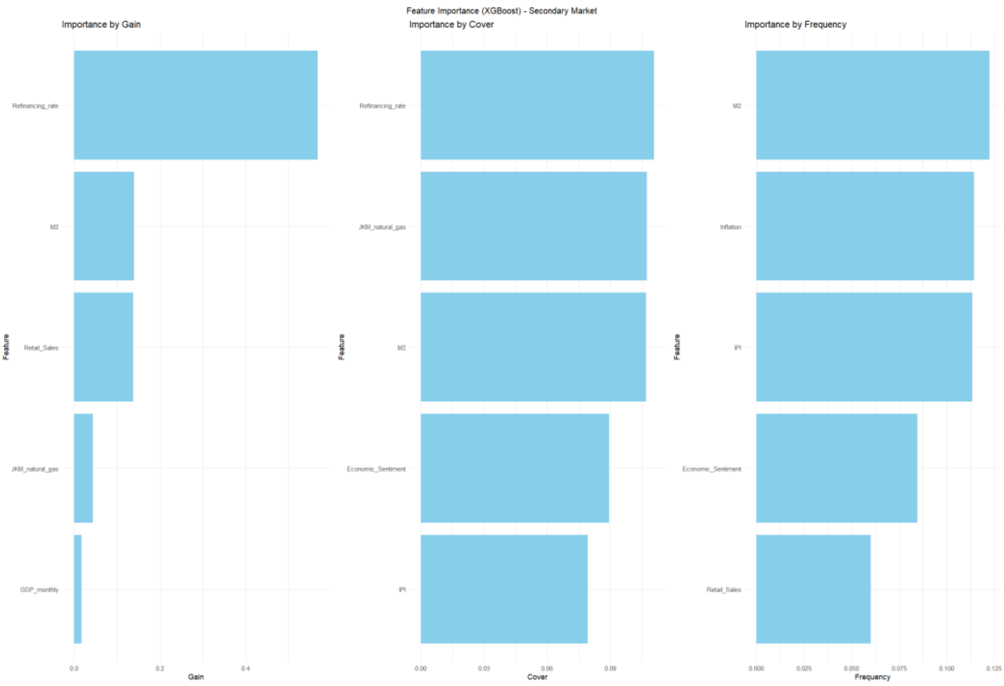
The second variable considered in the Gain metric is the Natural Gas Price. This observation indicates a correlation between energy markets and the dynamics of the Emissions Trading Scheme (ETS), emphasising the latter's reliance on external energy supplies.

The remaining variables incorporated within the metrics are as follows: Interest Rate, Coal Price, and Retail Sales. While these variables may be considered subordinate to the initial ones, they nevertheless contribute significantly to share price formation in the primary market of K-ETS.

An analysis of the Cover metric reveals that the Rainfall variable exhibits superior performance in comparison to M2, thereby occupying the preeminent position in the ranking. This outcome underscores the incorporation of climatic and environmental variables into the model, thereby signifying a robust correlation between the Korean market and energy demand in relation to climatic phenomena. In addition to the Rainfall variable, the ranking also highlights IPI, Interest Rate and Coal Price, confirming a mixed role of macroeconomic and energy variables within the model construction.

In concluding the analysis of the Frequency metric, further to the variable M2, we encounter the variables Inflation Rate, IPI, Rainfall and Retail Sales. It is noteworthy that the last of these (Retail Sales) is also a significant driver in terms of Gain; however, the others do not appear to be of particular importance in the metric. This observation suggests that these variables may serve a secondary filtering role, contributing to the refinement of model-specific decisions.

— *K-ETS Secondary Market*



Graph 26: Feature importance K-ETS Secondary Market results. Source: Internally Elaborated

A thorough analysis of the K-ETS secondary market reveals that it is characterised by distinct characteristics that contrast with those of the primary market.

In this particular instance, the variable that exerts the most considerable influence on the Gain ranking is the Interest Rate. This finding suggests that the cost of credit plays a pivotal role in the prediction of prices in the secondary market. Its significance extends beyond the primary metric, manifesting as the predominant feature in the Cover metric. This underscores its pivotal role in delineating decisions across ensemble branches. The results suggest that the cost of capital has a significant impact on the behaviour of firms with respect to the purchase and management of carbon allowances.

Nevertheless, the variable M2 also retains a high structural importance in this context. It is evident in the upper ranks of all three measures and continues to provide us with information on the extent to which the overall liquidity in the monetary system is a driver of price formation.

In consideration of another pivotal metric within the model, the Natural Gas Price, it is evident that it is a crucial element in the model. It is notable that this feature is present in both the Gain and Cover metrics. This lends support to the assertion that the Natural Gas Price in Asia is a determining factor in reducing prediction error and in model segmentation.

Finally, the Frequency metric incorporates variables such as: Inflation Rate, IPI, Economic Sentiment and Retail Sales; enables the assertion that, even in the absence of elevated values in the Gain metric, the model leverages the weak but persistent interactions of these variables frequently on subsets of the dataset.

The results demonstrate a heightened awareness of the K-ETS secondary market with respect to financial, economic conditions and the international macroeconomic environment. This market exhibits a more distributed information segmentation, characterised by reduced concentration relative to that observed in the primary market.

A comparative analysis of the two markets (primary and secondary) of the K-ETS reveals significant disparities between them.

The primary market is distinguished by a more intricate and less concentrated information structure, with economic variables such as M2, Retail Sales and Energy Prices (Coal Price and Natural Gas Price) playing a dominant role. Nevertheless, analysis of all three metrics reveals a persistence of the same variables, suggesting a trend towards market concentration.

In contrast, the secondary market is characterised by greater articulation, with a large number of variables playing a crucial role in price determination. This enhanced level of detail can be ascribed to the dynamic nature of the secondary market, which is not constrained by legal obligations or predetermined auction procedures.

Consequently, it can be deduced that the primary market for K-ETS exhibits a more linear characteristics, driven by a combination of macroeconomic and energy factors. The secondary market, as previously mentioned, is characterised by greater dynamism and multidimensionality.

- *XGBoost Comparison Between Markets*

This paper sets out the findings of research which utilised the XGBoost model in the three ETS markets examined (EU-ETS, CA CaT and K-ETS). The model allowed for an in-depth understanding of the complex dynamics underlying carbon allowance price formation. This outcome can be ascribed to the model's capacity to detect non-linear relationships, interactions between variables and heterogeneous information structures.

The analysis conducted revealed both common features and divergences within and across markets.

The analysis of the three-importance metrics (Gain, Cover and Frequency) made it possible to distinguish three distinct types of informativeness in the three markets.

- *CA CaT:*

The market is distinguished by its cohesion, with a pronounced concentration of the information structure on a limited number of key variables, including M2, Retail Sales and GDP. The presence and dominance of these three variables across the three metrics considered suggests that the model learns from the main driver. This is probably related to institutional stability, lower data noise and regulatory consistency. This hypothesis is further corroborated by the substantial number of boosting rounds (143) and the low Root Mean Square Error (RMSE) in Cross-Validation (0.0486).

- *EU-ETS:*

The market analysis reveals an intermediate configuration between the three markets considered. A predominance of macroeconomic variables (M2, Unemployment Rate and Retail Sales) is observed alongside environmental, energy and production-related variables (Rainfall, Temperature, Coal Price and IPI). In contrast to the California Cap-and-Trade market, this specific market demonstrates a multiplicity of variables in the Frequency and Cover rankings. This finding indicates that the model takes into account a multitude of variables based on institutional, energy and environmental factors, with the objective of predicting the price of carbon allowances. The dispersion of information may be consistent with the regulatory complexity of the European context, combined with the structural differences present in countries and, consequently, in companies operating in the market.

- *K-ETS:*

The market that exhibits the highest degree of heterogeneity. Furthermore, distinctions can be discerned within the market itself, thereby distinguishing between the primary and secondary markets. In the primary market, the predominant information variables are M2 and the Natural Gas Price, with weak but pertinent variables also incorporated into the metrics (Frequency): Inflation Rate, Rainfall and IPI.

In contrast, the secondary market exhibits a distinct and more intricate profile, with the variable Inflation Rate being predominant in all metrics. The Cross-Validation of the model further highlights the distinct characteristics of these markets. In the secondary market, the model aligns with the results observed for the EU-ETS market.

It is evident, upon consideration of the data collected on the markets, that further study of the variables is necessary:

- *M2:*

The results obtained from the markets provide compelling evidence to support this hypothesis, with this variable emerging as the most significant, occupying a predominant position in all rankings and reaching a value between 30% and 40% in the ranking based on the Gain metric. This finding suggests the presence of a link between price dynamics within ETS markets and aggregate liquidity. This finding indicates that a monetary expansion driven by an increase in demand for goods, and consequently an increase in demand for carbon allowances, can have a substantial impact on market dynamics.

- *Energetic variables (Coal Price, Natural Gas Price e Oil Price):*

The variables under consideration assume disparate roles within the three markets under review. Gas and Oil prices exhibit structural relevance in the Californian market (high Cover), indicating a reliance of the production sector on energetic production. In contrast, natural gas exerts a marginal influence within the European market, while Coal Price assumes a leading role, particularly with respect to its frequency of utilisation within the model. Finally, in the K-ETS model, Natural Gas Price emerges as a central element in the primary and secondary markets, suggesting a significant dependence of the Asian market on Natural Gas.

- *Economic Sentiment and Weather Variables (Rainfall e Temperature):*

Within the context of the California Cap-and-Trade market, these variables assume a secondary role. Nevertheless, these variables manifest more frequently in the other two markets (EU-ETS and K-ETS), particularly in volatile conditions or within the ranges defined by the data.

In conclusion, the model demonstrated its capacity to discern common patterns within the examined markets, while concurrently exhibiting its aptitude for differentiating significant structural disparities between them. In comparison, more mature markets, such as the EU-ETS and the California Cap-and-Trade, exhibited more compact information structures with fewer factors contributing to the understanding of their internal performance. In contrast, the K-ETS market, still in a state of consolidation, exhibits a higher degree of heterogeneity, characterised by more fragmented architectures and complex internal dynamics.

In this study, we underscore the value of the model under consideration as a useful tool for identifying the distinction between strong predictive contributions and weak but structural signals. This is a significant contribution to the broadening of knowledge about the functioning of emissions permit markets. Additionally, the model is instrumental in analysing the mechanisms through which macroeconomic, energy and environmental variables are reflected in the pricing of emission allowances.

4.5Volatility Analysis

Having concluded the analysis on price formation using the models (OLS, GAM and XGBoost) previously mentioned, the subsequent section will concentrate on the results of the analysis on the factors that influence volatility in the ETS markets.

In order to conduct the analysis, the GARCH-X model was employed, as outlined in Section 3.6.1.3 of the methodology, which necessitates the presence of stationary variables. This requirement necessitated the implementation of the model in block 1, where the variables are transformed to ensure their stationarity.

A comprehensive analysis of price volatility in emission markets is imperative for a comprehensive understanding of market efficiency and maturity.

Nevertheless, the ETS market displays a considerable degree of intricacy, influenced by a multitude of heterogeneous factors, as evidenced by the price analysis. In consideration of this intricacy, it was ascertained that the implementation of models would constitute a judicious approach. This for elucidating the temporal dynamics of the conditional variance. For the purposes of this paper, it was determined that the GARCH-X model would be employed. This model is characterized by its incorporation of exogenous variables into the process.

The aforementioned approach was instrumental in surmounting the limitations imposed by GARCH models and associated extensions. A notable drawback of these models is their failure to account for certain variables, thereby diminishing the capacity to dynamically ascribe sources of risk within the study.

So, the present study will adopt the GARCH-X model. Subsequent selective approaches, founded upon information criteria (AIC and BIC), will be conducted for the purpose of analysing whether an enhancement is achieved through parsimonious selection of variables.

As will be demonstrated subsequently, the efficacy of this approach exhibits considerable variance across markets. This finding signifies a challenge in employing the model to analyse volatility through the lens of the variables examined in this study. For this reason, the ensuing analysis should be regarded as purely exploratory. The paper's subsequent sections will explicate the limitations of the GARCH-X model and the reason why this analysis should be considered only exploratory.

4.5.1 GARCH-X General Results

As previously stated, the initial model examined was a GARCH-X, which incorporated all extant exogenous variables concurrently. However, the model did not produce satisfactory results in any of the markets considered. The instability in the estimates, as indicated by insignificant coefficients and unreliable performance, was primarily attributed to the limited sample size.

Consequently, the employment of the Akaike Information Criterion Approach (AIC) and Bayesian Information Criterion Approach (BIC) was necessary. This decision has facilitated the identification of more robust and interpretable combinations.

- *GARCH-X EU-ETS results*

The analysis conducted on the EU-ETS market produced results of considerable interest. Notably, the two variable selection criteria identified the same combination (M2 and Coal Price) in both the primary and secondary markets.

This convergence, which is not guaranteed under all circumstances, as the BIC criterion typically imposes a penalty compared to the AIC criterion, is justified by the relatively limited number of observations (132). This restriction, while limiting the diversity between models, has favoured convergence towards an unambiguous solution.

Secondly, the GARCH-X model in the M2 and Coal Price variables appears to offer an optimal balance between model fit and parsimony. This enhancement is of particular significance, although no statistically significant impact on the M2 variable is observed.

Despite the lack of statistical significance of variable M2, Coal Price has been identified as a significant secondary market element (with a p-value < 0.001), indicating a substantial impact on the volatility of emission allowances.

The role of Coal Price, therefore, is pivotal in the analysis of market volatility, thus corroborating the assumptions of Salvagnin et al. (2024)[150]. The authors of the study in question highlight the significance of Coal Prices as a crucial indicator in contexts of energy stress.

It was determined through the application of statistical analysis that the dummy variables for exogenous events (EU-ETS shocks and shock temperature) were not statistically significant.

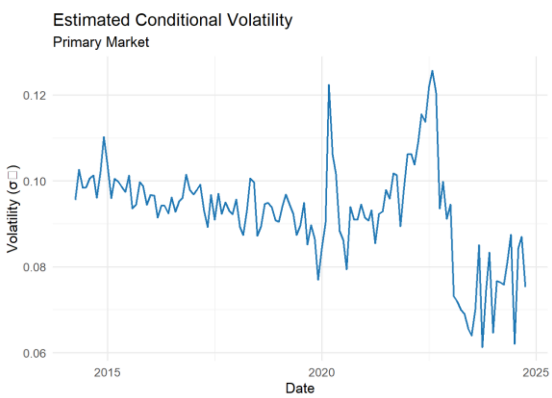
The outcomes of the model are exhibited in Table 23:

— *EU-ETS Primary and Secondary Market*

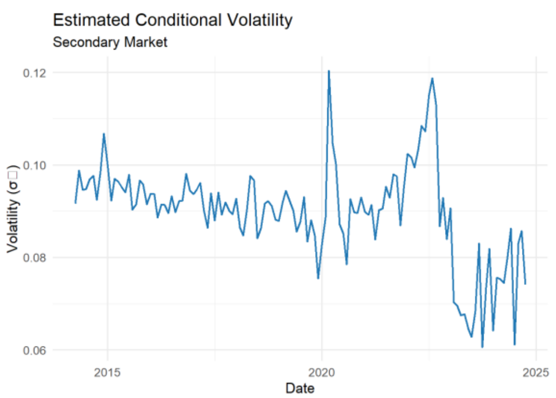
Driver	***Estimate Primary***	***p-value Primary***	***Estimate Secondary***	***p-value Secondary***
μ	0.017	0.039	0.017	0.024
ω	0.000	0.998	0.000	0.998
α	0.000	0.999	0.000	0.999
β	0.994	0.001	0.995	0.001
M2	0.000	0.957	0.000	0.957
Coal Price	0.000	0.227	0.000	0.001
Dummy Temperature Shocks	0.000	1.000	0.000	1.000
Dummy EU-ETS Shocks	0.000	0.999	0.000	0.999

Table 23: GARCH-X EU-ETS Primary and Secondary Market results

Graphs 27 and 28 illustrate the dynamic fluctuations in the conditional volatility observed across the respective primary and secondary markets.



Graph 27: Estimated Conditional Volatility EU-ETS Primary Market. Source: Internally Elaborated



Graph 28: Estimated Conditional Volatility EU-ETS Secondary Market. Source: Internally Elaborated

[150] **Salvagnin, C., Glielmo, A., De Giuli, M. E., & Mira, A. (2024).** Investigating the price determinants of the European Emission Trading System: a non-parametric approach. Quantitative Finance, 24(10), 1529–1544. https://doi.org/10.1080/14697688.2024.2407895

A thorough examination of the graphs reveals the presence of heterogeneous volatility within the two markets, and a strong similarity.

Volatility peaks, which are associated with periods of market instability, can be attributed to market shocks resulting from extraordinary factors. Of these, two peaks have been identified as being of particular significance:

1) The global health crisis linked to the pandemic from Covid 19: March 2020
2) The outbreak of war in Ukraine and its escalation: from February 2022

The impact of these two events on perceptions of systemic risk was significant, and their effect on price formation mechanisms and volatility was immediate.

The analysis of Wang et al. (2025)[151] and of Lyu and Scholtens (2023)[152] demonstrates the instrumental role of these two events in causing the sudden increase in the volatility of carbon allowance markets.

In conclusion, a two-diagnostic-test protocol was deemed appropriate to validate the model.

1) The Ljung-Box test was applied to standardised squared residuals. The objective of this investigation is to verify the absence of any residual autocorrelation patterns. The outcomes of the aforementioned test, as illustrated in Table 24 below, demonstrate the absence of significant residual autocorrelation, with a p-value > 0.05, which corresponds to the minimum threshold of statistical significance.

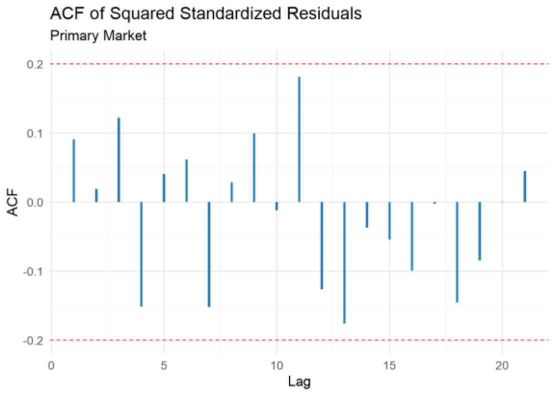
Market	***p-value***
Primary	0.3147
Secondary	0.6499

Table 24: Test Ljung-Box EU-ETS Primary and Secondary Market results

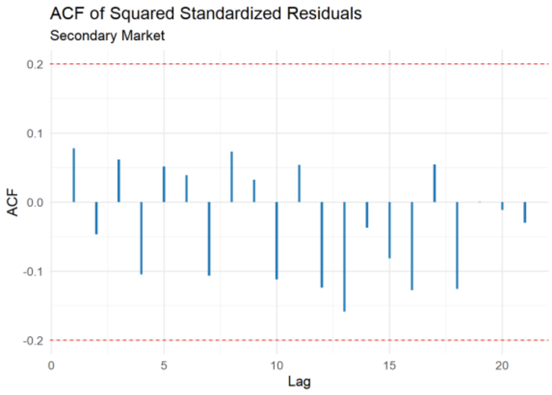
2) The following test is a graphical analysis of the autocorrelation of the standardised squared residuals (ACF). The objective of this procedure is to corroborate the conclusions of the aforementioned test by means of a graphical analysis of the

[151] **Wang, X., Jin, W., Xu, B., & Wang,K. (2025).** Volatility in carbon futures amid uncertainties: Considering geopolitical and economic policy factors. Journal of Futures Markets. https://doi.org/10.1002/fut.22565
[152] **Lyu, C., & Scholtens, B. (2023).** Integration of the international carbon market: A time-varying analysis. Renewable and Sustainable Energy Reviews, 191, 114102. https://doi.org/10.1016/j.rser.2023.114102

autocorrelation in the initial 21 lags. The results presented in Graphs 29 and 30 indicate an adequate fit of the model to the volatility structure.



Graph 29: Test ACF EU-ETS Primary Market results. Source: Internally Elaborated



Graph 30: Test ACF EU-ETS Secondary Market results. Source: Internally Elaborated

The analysis conducted on the EU-ETS market demonstrates that the GARCH-X models, when applied with information criteria, provide a reliable representation of market volatility.

The model in question facilitates the accurate identification of the main exogenous factors and the capture of variations in conditional volatility, while also enabling the identification of moments of greatest instability. This finding appears to corroborate the hypothesis that these markets are influenced by macroeconomic and geopolitical factors.

The methodological approach adopted proves to be crucial not only for delineating the time structure of market volatility, but also for identifying the sources of risk affecting the EU-ETS market.

- *GARCH-X CA CaT results*

The analysis of the California Cap-and-Trade market, performed using the Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) penalisation criteria, led to the identification of the two most significant variables within the GARCH-X model. Within this particular instance, the variables have been identified to be as follows: Unemployment and Rainfall.

A similar observation was made in the EU-ETS market, where convergence of variables from the two criteria (AIC and BIC) was demonstrated. This phenomenon can be attributed to the same mechanisms outlined above.

The findings of the investigation substantiate the elevated statistical significance of the variables Rainfall (p-value < 0.001) and Unemployment Rate (p-value < 0.001). This finding indicates a substantial correlation between emission allowances, macroeconomic and environmental variables within the Californian market. This correlation suggests the possibility that these factors may influence the perception of internal market risk. The relationship evidenced by local climatic factors has been previously studied in other models, as evidenced by the studies of Eslahi and Mazza (2023)[153]. The authors state that in periods marked by climatic events, especially extreme ones, there is a relationship with the volatility of carbon allowances. However, it is important to note that this study was conducted within the European market, given the paucity of specific studies on the market in question.

At the same time, the existing literature has not yet explored the relationship between the unemployment variable in depth, except in an indirect manner. For example, Chevallier (2011)[154], study states that "carbon prices tend to respond negatively to an exogenous recessionary shock in global economic indicators". This indicates a price fluctuation linked to economic instability.

Table 25 shows the coefficients estimated by the GARCH-X model with the criteria (AIC and BIC).

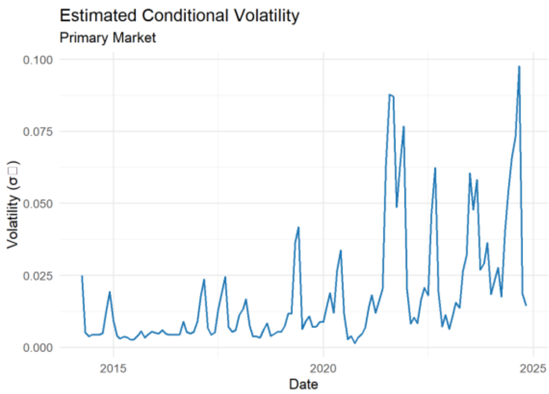
— *CA CaT Primary Market*

Driver	***Estimate Primary***	***p-value Primary***
μ	0.003	0.000
ω	0.000	0.000
α	1.000	0.000
β	0.016	0.326
Unemployment Rate	0.000	0.000
Rainfall	0.000	0.000
Dummy Temperature Shocks	0.000	0.388
Dummy USA Shocks	0.000	0.265

Table 25: GARCH-X CA CaT Market results

[153] **Eslahi, M., & Mazza, P. (2023).** Can weather variables and electricity demand predict carbon emissions allowances prices? Evidence from the first three phases of the EU ETS. *Ecological Economics*, *214*, 107985. https://doi.org/10.1016/j.ecolecon.2023.107985
[154] **Chevallier, J. (2011).** Carbon Price Drivers: An Updated Literature Review. SSRN Electronic Journal. https://doi.org/10.2139/ssrn.1811963

Graph 31 below shows the value of the estimated conditional volatility:



Graph 31: Estimated Conditional Volatility CA CaT Market. Source: Internally Elaborated

The graph illustrates the considerable heterogeneity that has been observed in the California Cap-and-Trade market over time. This heterogeneity has notably worsened since 2019.

The highest observed peaks are concentrated in the final period of the graph, which extends from 2020 to 2024. These peaks could be attributed to a combination of factors including:

- The tightening of regulation at the state level has resulted in increased costs for allowances. In addition, the market has undergone four phase changes, transitioning from phase 2 (2015-2017) to phase 3 (2018-2020) to phase 4 (2021-2023) to phase 5 (2024-2026). Each phase has resulted in a tightening of the regulations concerning the emission of carbon allowances[155].
- Fluctuations related to commodity prices due to what the Covid-19 pandemic has had on companies Lyu and Scholtens (2023)[156].
- The political evolution and double transition in the final years of the US presidency. It is widely acknowledged that the presidency of Joseph Biden resulted in a heightened emphasis on environmental policies, leading to an increase in allowance prices. However, with the return of Trump to the presidency, a reduction in these prices could be observed. Indeed, as has been recently observed, President Trump's return to the highest office in the US has

[155] **USA - California Cap-and-Trade Program. (n.d.).** International Carbon Action Partnership. https://icapcarbonaction.com/en/ets/usa-california-cap-and-trade-program
[156] **Lyu, C., & Scholtens, B. (2023)**. Integration of the international carbon market: A time-varying analysis. Renewable and Sustainable Energy Reviews, 191, 114102. https://doi.org/10.1016/j.rser.2023.114102

led to a renewed call for the exit from the Paris Agreement, as was previously initiated during his administration in 2019[157].

In contrast to the European market, it is important to acknowledge that the Californian CaT market functions in a distinct manner characterised by autonomy and decentralisation. The market's response to shocks is distinct, frequently influenced by political considerations rather than global macroeconomic and geopolitical factors.

Also, in the case of the California Cap-and-Trade market, the robustness of the model became clear in the two tests mentioned above (Ljung-Box Test and ACF Test).

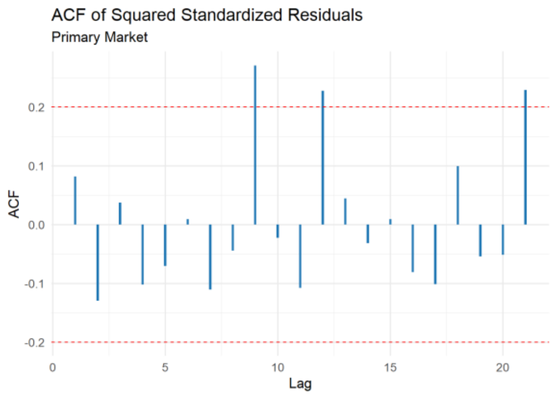
1) Test ljung-Box: The analysis yielded favourable results, as demonstrated in Table 26. The value obtained is above the minimum p-value threshold of 0.05, suggesting the absence of significant autocorrelation in the residuals.

Market	***p-value***
Primary	0.060

Table 26: Test Ljung-Box CA CaT Market results

2) Test ACF: The evaluation, as demonstrated in graph 32 below, corroborates the adequacy of the present model while simultaneously emphasising the potential for enhancement. This assertion is grounded in the discernment of anomalies within the graph itself:
    - It is important to acknowledge that certain peaks (lags 9, 12 and 21) marginally exceed the established confidence band, which is set at ±0.2. This finding indicates that a proportion of the conditional variance may not be fully explained by the model.

[157] **European Parliament. (2025, February 10).** *US withdrawal from WHO and the Paris Agreement: Debate in plenary*. https://www.europarl.europa.eu/news/en/agenda/briefing/2025-02-10/3/us-withdrawal-from-who-and-the-paris-agreement-debate-in-plenary



Graph 32: Test ACF CA CaT Market results. Source: Internally Elaborated

The analysis conducted on the California Cap-and-Trade market revealed that its inherent volatility is influenced by local environmental and macroeconomic factors, such as Rainfall and Unemployment, rather than geopolitical shocks of international interest. Consequently, the market's risk profile appears to be shaped by the prevailing regional economic and environmental conditions.

The graph depicting the estimated conditional volatility analysis offers further elucidation into the accentuated manifestation of this phenomenon, particularly in recent years, a phenomenon attributable to the evolution of state environmental policies and post-pandemic uncertainties. This finding serves to further substantiate the market's structural peculiarity, which, functioning independently from global policies, renders it more susceptible to policy decisions and local idiosyncratic factors.

The model check produced encouraging results, although slight indications of residual autocorrelation were identified. This finding suggests that, in general, the model is robust and effective in representing market dynamics.

- *GARCH-X K-ETS results*

The analysis of the K-ETS market yielded results that were consistent with the trends observed in the two markets previously examined (EU-ETS and CA CaT). In a manner consistent with the observations made in the aforementioned two markets, this market also exhibits a convergence of results with regard to the selection criteria (AIC and BIC) of the most effective variables for the GARCH-X model.

However, in contrast to the EU-ETS market, significant variations in the selection of variables for the primary and secondary markets within the K-ETS are evident.

In the primary market, the selected variables include: Unemployment Rate and GDP. Conversely, the secondary market is characterised by the consideration of Export and Oil Price as the selected variables.

These selected variables were found to be highly significant (p-value < 0.001), indicating a strong link between volatility, Unemployment Rate and GDP. These findings imply that the Korean primary market is predominantly influenced by internal dynamics pertaining to the real economy.

The present study corroborates the conclusions reached in the work of Joo et al. (2023)[158] on the subject of the K-ETS market. The aforementioned authors observe that this particular market is characterised by domestic political dependence, and that strong public interventions in the market amplify domestic variables. This, in turn, lends the findings of this study a degree of credibility.

Table 27 below illustrates the results of the primary market mentioned above.

— *K-ETS Primary Market*

Driver	***Estimate Primary***	***p-value Primary***
μ	0.048	0.000
ω	0.000	0.073
α	0.000	0.999
β	0.004	0.000
Unemployment Rate	0.035	0.000
GDP	0.014	0.000
Dummy Temperature Shocks	0.000	1.000
Dummy Korea Shocks	0.000	1.000

Table 27: GARCH-X K-ETS Primary Market results

In the context of the secondary market, the variable Brent oil is noteworthy due to its statistical significance, with a value of (p-value < 0.001). However, the variable Export, although included in the model, does not reach acceptable levels of significance, with a (p-value > 0.05). These findings imply that Oil Price is capable of explaining market volatility, while Export appears to play a less leading role in the explanation.

158 **Joo, J., Paavola, J., & Van Alstine, J. (2023).** The divergence of South Korea's Emissions Trading Scheme (ETS) from the EU ETS: An institutional complementarity view. Politics &Amp Policy, 51(6), 1155–1173. https://doi.org/10.1111/polp.12566

In contrast to the dynamics observed in the primary market, the secondary market appears to be less influenced by the same market forces. Instead, the strong dependence of companies on external factors, primarily energy, means that the market is influenced much more by external factors, in the primary market mitigated by policy.

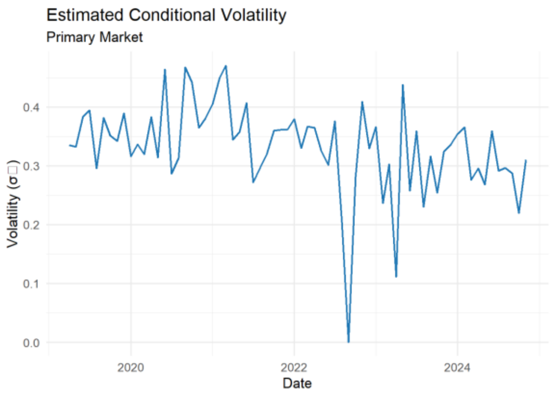
The results of the secondary market are illustrated in Table 28 below:

— *K-ETS Secondary Market*

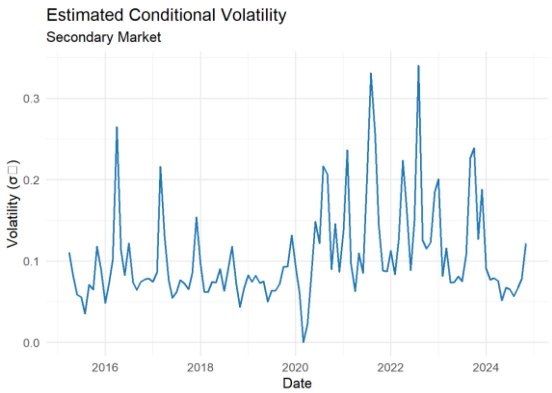
Driver	***Estimate Primary***	***p-value Primary***
μ	-0.007	0.000
ω	0.003	0.000
α	0.831	0.000
β	0.058	0.000
Export	0.000	0.507
Oil Price	0.000	0.000
Dummy Temperature Shocks	0.000	0.996
Dummy Korea Shocks	0.000	0.996

Table 28: GARCH-X K-ETS Secondary Market results

Graphs 33 and 34 below show the estimated conditional volatility for the two markets:



Graph 33: Estimated Conditional Volatility K-ETS Primary Market. Source: Internally Elaborated



Graph 34: Estimated Conditional Volatility K-ETS Secondary Market. Source: Internally Elaborated

- *Primary Market*

The examination of Graph 33, pertaining to the primary market, unveils a tendency towards elevated and persistent volatility, typified by substantial fluctuations and less stable dynamics.

A salient aspect of the analysis pertains to the examination of the positive and negative peaks within the market. The analysis indicates that at specific junctures within the market, volatility surges beyond 0.4 per cent, signifying substantial shocks that are likely associated with regulatory shifts within the market itself or with events occurring within the country.

The precipitous decline observed in 2022, succeeded by a swift resurgence, may be ascribed to a precipitous regulatory shift within the market or an overshooting phenomenon (comprised of an overreaction by the market in the short term, succeeded by a swift readjustment towards a long-term equilibrium)[159].

The numerous peaks and the significant decline in 2022 can be located in the explanations provided in the aforementioned work of Joo et al. (2023)[160] who observed sudden regulatory changes desired by the central government and the limited autonomy of internal market participants. These substantial regulatory changes and alterations in the rules governing allocation may have precipitated the observed phenomena.

In contrast to the prevailing trend in the European market, there is no indication of a long-term normalisation of volatility in this market, which suggests the possibility of a further phase of consolidation.

- Secondary Market

As demonstrated in Graoh 34 on the secondary market, there is a heterogeneity in the temporal dynamics of the variance, with numerous peaks throughout the entire period.

Of particular pertinence are the years from 2020 onwards, which appear to signal enduring consequences of the pandemic caused by the virus known as SARS-CoV-2, also known as the Coronavirus, and the subsequent geopolitical tensions between the Russian Federation and Ukraine, as well as the domestic crises within the latter.

The increase in volatility is attributable to shocks resulting from the pandemic and geopolitical events. This conclusion is supported by the research of Lyu and Scholtens

[159] *Overshooting - **Dizionari simone online. (n.d.).*** https://dizionari.simone.it/6/overshooting

[160] **Joo, J., Paavola, J., & Van Alstine, J. (2023).** The divergence of South Korea's Emissions Trading Scheme (ETS) from the EU ETS: An institutional complementarity view. Politics &Amp Policy, 51(6), 1155–1173. https://doi.org/10.1111/polp.12566

(2023)[161], who demonstrated that the European market experienced heightened price instability.

In conclusion, the analysis of the K-ETS secondary market reveals a particular sensitivity to external shocks, accompanied by a remarkable ability to return to a stable state within a brief period of time. This outcome serves to further substantiate the market's less than fully consolidated nature, a factor that persists in exerting its influence on the market's dynamics.

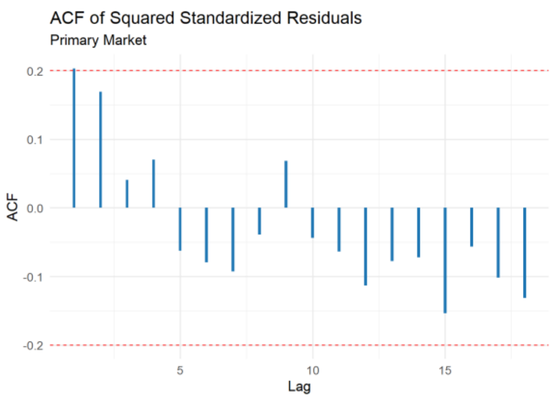
To confirm the above observations, two specific tests were conducted: the Ljung-Box Test and the ACF Test.

1) Test di Ljung-Box: The results presented in Table 29 demonstrate that there is no evidence of autocorrelation. Moreover, the p-values for the two markets are higher than the critical threshold of 0.05, thereby indicating a significant level of confidence.

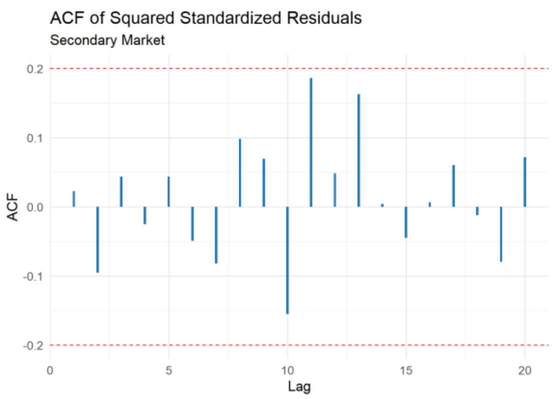
Market	***p-value***
Primary	0.6674
Secondary	0.6465

Table 29: Test Ljung-Box K-ETS Primary and Secondary Market results

2) Test ACF: This second test also demonstrated that there were no issues with the data. Graphs 35 and 36 illustrate that.



Graph 35: Test ACF K-ETS Primary Market results. Source: Internally Elaborated



Graph 36: Test ACF K-ETS Secondary Market results. Source: Internally Elaborated

[161] **Lyu, C., & Scholtens, B. (2023).** Integration of the international carbon market: A time-varying analysis. Renewable and Sustainable Energy Reviews, 191, 114102. https://doi.org/10.1016/j.rser.2023.114102

The concluded analysis of the K-ETS market revealed several peculiarities compared to the previously examined markets. A further comparative analysis with the results of the EU-ETS market revealed a significant difference in the factors considered by the AIC and BIC criteria. This finding indicates that the primary and secondary markets exhibit a market-specific structure, influenced by distinct variables.

The primary market is influenced by domestic macroeconomic factors, such as the Gross Domestic Product (GDP) and the Unemployment Rate. This suggests a significant link to the domestic real economy.

The secondary market, conversely, underlines the pivotal function of the Oil Price as a pivotal variable, reflecting an interconnection with the global energy market that determines its influence.

In terms of the estimated conditional volatility of the respective markets, it can be posited that there exists a difference with respect to the shocks to which they are subject. The primary market demonstrates a heightened sensitivity, manifesting elevated volatility peaks. However, both markets appear to indicate signs of instability, which may be attributable to ongoing consolidation phases.

- *GARCH-X Comparison Between Markets*

The utilisation of the GARCH-X model, complemented by the implementation of selection criteria (AIC and BIC), facilitated the extraction of variables, thus enabling an analysis of conditional volatility across the three ETS markets (EU-ETS, CA CaT and K-ETS). This analysis revealed distinct dynamics and offered relevant insights into aspects such as maturity, risk factors and adaptability.

The application of the AIC (Akaike Information Criterion) and BIC (Bayesian Information Criterion) selection criteria resulted in equivalent outcomes with regard to the selected variables, as demonstrated in the market (EU-ETS and CA CaT). This outcome is primarily attributed to the constrained nature of the observations included in the sample. The limited number of observations restricts the complexity of the parametric model and promotes the stability of the observations. Consequently, this resulted in the development of stable and statistically robust models.

Table 30 below provides a synoptic overview of the results of the analyses conducted.

Market	*Type*	*Variable 1*	*Sign.*	*Variable 2*	*Sign.*
EU-ETS	Primary	M2	X	Coal Price	√
	Secondary	M2	X	Coal Price	√
CA CaT	Primary	Rainfall	√	Unemployment	√
K-ETS	Primary	GDP	√	Unemployment	√
	Secondary	Oil Price	√	Export	X

Table 30: Selected variables from the XGBoost model

The analysis of the results indicates a discrepancy between the variables subjected to selection and the statistically significant variables. The findings of this study consequently entail the following conclusions:

- *EU-ETS:*

It has been demonstrated that the significance of the coal price is indicative of the importance of energy factors in the study of price volatility in the carbon allowance market.

- *CA CaT:*

The findings reveal that both variables exhibit statistical significance, underscoring the pivotal role that local economy variables play as determinates.

- *K-ETS:*

In the primary market, both of the above-mentioned variables are shown to be significant and related to the domestic economic situation, thereby highlighting the market's dependence on internal factors. Conversely, in the secondary market, the Oil Price variable stands out as the sole significant factor, thereby suggesting that, in contrast to the primary market, the Korean secondary market is influenced by external factors.

Conditional volatility analysis enables the discrimination of divergent market situations and maturities:

- *EU-ETS:*

The European market has been observed to be the most mature and least influenced by internal shocks. Nevertheless, it is evident that external factors have exerted a substantial influence on market volatility, as evidenced by the events of the global pandemic (Covid-19) and the ongoing Russo-Ukrainian war.

- *CA CaT:*

The analysis of the market reveals that the level of its volatility has increased over time. In addition, the market is becoming less dependent on external events and more influenced by domestic political shocks.

- *K-ETS:*

Of the three markets examined, this is the least developed. It is distinguished by markedly elevated volatility in contrast to the other two markets, exhibiting pronounced reactivity while concurrently exhibiting excessive instability, primarily attributable to endogenous factors.

The conclusion of this study leads to three primary observations:

- Market maturity exerts a direct influence on the stability of volatility within the market. It is evident that markets that have attained a higher level of consolidation demonstrate a propensity to exhibit more stable volatility over an extended timeframe.
- The drivers examined in this study vary significantly across the markets investigated and are influenced by a range of factors including geographical characteristics, institutional structures, and market maturity.
- Shocks, defined as events external to the market, are found to have a crucial role in the formation of volatility. Nevertheless, the capacity to adapt to such shocks exhibits considerable variation and is contingent on the market's inherent capacity to absorb them.

In summary, the analysis of volatility using a GARCH-X model yielded significant findings. These results include an in-depth understanding of the volatility trend itself, as well as the identification of the variables that determine its fluctuations. Furthermore, the analysis enabled the delineation of the potential risk dynamics that are unique to each market.

Nevertheless, as indicated by the findings of the analysis, the EU-ETS market is the only market for which comprehensive conclusions can be drawn. It should be noted that this conclusion is primarily a function of two key factors. Firstly, the available sample appears to be sufficient for the purposes of this particular study. Secondly, the variance formation has been found to be adequately stable. The third element to consider is that the experimental tests carried out appear to be largely within the established limits.

4.6Conclusion

The empirical analysis conducted within this chapter highlighted the structural complexity of the ETS markets considered and the importance of using a stratified methodological approach to study the determinants that influence these markets. The utilization of heterogeneous models has enabled the identification of distinct patterns and characteristics inherent to the formation of prices and market volatility in each ETS market.

Among the models examined, the XGBoost model demonstrated superior performance in analysing price determinants, exhibiting its ability to capture complex interactions through its variable handling capabilities. This finding notably surpasses the limitations observed in previous studies conducted on these markets.

Conversely, the GARCH-X model, employed for volatility analysis, exposed a significant concern, despite its capacity to discern specific factors within the markets. This finding underscores the need for cautious interpretation of the model's conclusions, given its limited sample size and the numerous variables it considers. It suggests that the model may have produced misleading results due to its inability to accurately account for the complex interactions present in the market data. The unique market in which we can affirm the solid results of the same is the EU ETS market, as from the tests carried out it seems to be the only stable one among the three markets considered.

The subsequent Table 31 offer a succinct synopsis for each market. This will facilitate comprehension of:

- Model with best performance
- Key Variables (Price, Volatility)
- Limitation for the Market

Markets	***Primary/ Secondary***	***Best Model***	***Key Determinants (Price)***	***Key Determinants (Volatility)***	***Limitation***
EU-ETS	Primary	XGBoost	M2, Retail Sales, Coal Price, Inflation	Coal Price	Relationships are mostly non-linear; climate variables are less relevant than might be expected in some models.
	Secondary	XGBoost	M2, Retail Sales, Temperature, Inflation	Coal Price	Relationships are mostly non-linear; climate variables are less relevant than might be expected in some models.
CA CaT	Primary	XGBoost	M2, Retail Sales, Natural Gas Price, Oil Price	Unemployment, Rainfall	OLS model insufficiently accurate; GAM with few explicit variables; tendency towards political and energy factors
K-ETS	Primary	XGBoost	M2, Natural Gas Price, Rainfall, Infaltion	Unemployment, GDP	Limited sample; OLS model insufficiently accurate; relationship with Unemployment

					variable counterintuitive; market structure highly unstable and related to political rather than market decisions.
	Secondary	XGBoost	Interest Rate, Natural Gas Price, M2, Inflation	Oil Price	OLS model slightly explanatory; low significance of variables

Table 31: Summary of the Analysis

5. Findings

The chapter will focus on the examination of the results that emerged from the econometric analysis, which are explicated in Chapters 3 (Methodology) and 4 (Empirical Analysis).

The objective is to elaborate on the results obtained from the analyses conducted on price, using the OLS, GAM, and XGBoost models, and volatility, using the GARCH-X model. This methodological approach aspires to underscore the theoretical and practical ramifications of such analyses, emphasizing the factors that exert influence on ETS markets. The analysis will focus on the three markets examined within this paper: EU-ETS, CA CaT, and K-ETS.

In addition to the aforementioned, the theoretical ramifications of the findings and the challenges, both market-related and analytical, identified will be emphasized.

The analysis will be concluded with the presentation of potential future policy and regulatory interventions to improve the current state, as well as insights for future research to overcome the limitations of the paper itself.

5.1 Price Determinants: Linear Approach, Non-Linear Approach, Machine Learning Approach

In order to facilitate a comprehensive discussion, this section will present a thorough account of the results obtained from the analyses conducted. The objective is to provide readers with a timely reference for the subsequent section.

The analysis of the price on carbon allowances in ETS (Emissions Trading Scheme) markets was conducted using three econometric models.

Initially, a linear regression model (OLS model) was considered. However, as the analysis progressed, a more flexible model, namely the Generalized Additive Model (GAM), was employed to identify non-linear relationships. Finally, a Machine Learning model (XGBoost) was employed due to its theoretical ability to accommodate more intricate and potentially non-stationary relationships.

It is important to acknowledge that OLS and GAM models necessitate the utilization of stationary variables; in the absence of such variables, the results obtained might be distorted.

In contrast, the XGBoost model has been found to be capable of handling non-stationary variables, thus presenting an advantageous alternative in such contexts. This distinctive attribute of the model ensures the provision of substantial results devoid of bias, thereby ensuring exceptional accuracy and reliability in predictions, even in the presence of non-stationary variables.

5.1.1 OLS Model (Block 1, Stationary Variables)

The Ordinary Least Squares (OLS) model is a linear regression model. The inclusion of the OLS model in this study is intended to facilitate the comprehension of the linear relationships between the independent variables and the dependent variable, which is the focus of this research.

The ensuing discussion will present a concise summary of the results obtained.

- *EU-ETS Market*

In the context of the EU-ETS market, the model exhibited moderate explanatory capability, as evidenced by the value of the metric R^2_adj., which was found to be approximately 36% in both markets. The analysis identified statistically significant variables, including the interest rate (refinancing rate of the European Central Bank) with a positive sign, Retail Sales (also with a positive sign), and two climate variables (Dummy Variable Temperature with a positive sign and Temperature with a negative sign). This finding underscores the substantial impact of macroeconomic and climatic factors on the European market. Conclusively, the model reveals a strong similarity between the primary and secondary markets within the EU ETS market, suggesting a uniform response to the same determinants.

- *CA CaT Market*

In the context of the California Cap-and-Trade market, the model demonstrated limited explanatory power, with the metric R^2_adj.^2 exhibiting negative values. Notwithstanding this limitation, the model identified a single significant driver: the Dummy Variable Temperature (with positive sign). This outcome underscores the limitations of linear regression models in accurately reflecting the intricate price dynamics within California's carbon trading market. This is evidenced by the considerable divergence between the legislative framework, regulatory mechanisms, and hedging practices observed in California compared to those implemented in European market.

- *K-ETS*

In the Korean market, there was considerable variation in the model implementation among the markets incorporated within the K-ETS. Specifically, the primary market exhibited a markedly constrained explanatory capacity, as evidenced by the negative value of the evaluation criterion R^2adj. In contrast, the secondary market exhibited a positive explanatory capacity of the model, albeit with evident limitations; the value of R^2 remained below 18%. Variables that proved to be statistically significant included coal price (with a positive sign, only for the secondary market) and unemployment (with a positive sign for both markets). However, the sign of the unemployment rate variable presents a counterintuitive outcome. The findings suggest that an increase in unemployment results in an increase in demand, which, in turn, leads to an increase in output. This is in direct contradiction with conventional economic theories, which posit that an increase in unemployment serves as an indicator of economic reduction. Nevertheless, this positive indication might be ascribed to the remarkably stringent regulatory framework that currently prevails in the Korean market. This restrictive environment potentially exerts a deterrent influence on the demand for carbon allowances, regardless of economic variability.

5.1.2 GAM Model (Block 1, Stationary Variables)

In the course of conducting a thorough analysis, it became imperative to expand the scope of relationships assessed by the OLS model. The complex structure of ETS markets, in conjunction with the potential nonlinear relationships among variables, necessitated the implementation of a non-linear modelling approach. In light of these complexities, the adoption of a modelling approach, such as the Generalized Additive Model (GAM), emerged as imperative. This approach confers a greater degree of flexibility, thereby enabling the revelation of nonlinear relationships between variables.

The ensuing section will present the results of the model.

- *EU-ETS*

An examination of the EU-ETS market, as substantiated by the OLS model, unveils a striking similarity between the two markets, with variables, significance levels, and signs demonstrating remarkable congruence. The constructed model yielded significant results, with the majority of the variables demonstrating a close linear correlation with the designated dependent variable. This observation is substantiated by the statistical significance indicators, as depicted in Tables 16 and 17, where the value of (EDF) is less than 2 for the majority of variables. However, two variables, namely natural gas price and economic sentiment, exhibited values of EDF greater than 2. Of particular note is the shape of the graph generated by the smooth function for the first variable, which is similar to a "V," suggesting that when gas prices are high or low, the variable positively influences the market, leading to an increase in the price of carbon allowances. The second variable examined: Economic Sentiment, for which, as demonstrated in Graphs 4 and 5, growth is apparent only for above-average values, while for lower values the effect is nearly negligible.

- *CA CaT*

In the context of the California market, the application of the model revealed the emergence of two variables related to energy factors, identified as Coal Price and Oil Price. The aforementioned variables demonstrate a non-linear relationship with the designated independent variable, as evidenced in Table 18, where a value of EDF > 2 is observed. A further examination of these variables discloses a U-shaped pattern, with the former displaying a higher level of pronounced compared to the latter. These findings imply that energy prices, both above and below the average benchmark, exert a non-linear effect on the cost of allowances within the CA CaT market.

- *K-ETS*

An analysis of the Korean market revealed common elements present within the two markets that coexist there. Of particular note is the observation that the Interest Rate demonstrates a non-linear relationship with the dependent variable, exhibiting a "U"-shaped pattern in both markets. The second relevant variable is the Unemployment Rate, which shows a nearly linear relationship with the dependent variable and an increasing monotonic trend. This observation signifies that, within the framework of the Generalized Additive Model (GAM), the cost of allowances exhibits a proportional increase in alignment with rising unemployment. The secondary market analysis yielded two additional variables. The first of these is M2, which demonstrates a nearly linear relationship, albeit with low significance (p-value < 0.1). Secondly, the variable "Coal Price" exhibited a significant oscillatory pattern, as evidenced by an (EDF) greater than 6. This finding is particularly noteworthy due to its implications for market dynamics. These findings collectively substantiate the market's tendency towards transitional phases and its sensitivity to a multitude of variables.

5.1.3 XGBoost Model (Block 2, Non-Stationary Variables)

The final stage of this research involved implementing a Machine Learning model (XGBoost) to complete the analysis. This methodological approach enabled the examination of the variables in their original form, obviating the necessity for specific transformations by the model, given its capacity to process these variables autonomously. The R2 values resulting from this model in nearly all markets are notably elevated, with most exceeding 90%, with the exception of the K-ETS secondary market, which stands at 77%. Nevertheless, the considerable significance of these values necessitates the validation of the model's robustness. To that end, a 5-Fold Cross-Validation was conducted. The validation process yielded favourable outcomes, affirming the model's capacity to effectively fit the observed data and to generalize the derived results. This capacity is a pivotal element in the broader context of this analytical framework.

The subsequent section will provide a comprehensive overview of the study's outcomes.

- *EU-ETS*

Analyses conducted within the EU-ETS market demonstrate the pre-eminence of macroeconomic factors, encompassing M2, retail sales, and unemployment, on the model's capacity to reduce error for each tree (Gain metric). In addition to these economic variables, variables pertaining to energy and climate (coal price and temperature, respectively) were also identified as contributing significantly to the model. However, these latter variables are not incorporated into the Gain metric. This finding indicates that they are operational in the model with greater frequency and across a broader range of factors (Cover and Frequency metrics) for the purpose of drawing conclusions, but do not contribute meaningfully to the enhancement of the model itself.

- *CA CaT*

An analysis of the California market reveals discrepancies in comparison to the trends observed in the European market. While the M2 index remains a pivotal factor, the incorporation of supplementary metrics serves to refine the model's forecasting accuracy (Gain metrics). In addition to the aforementioned variable, the model incorporates supplementary macroeconomic variables, including retail sales (Retail Sales), gross domestic product (GDP), and interest rates (Interest Rate). Furthermore, the model incorporates metrics pertaining to the energy sector, including Natural Gas Price and Oil Price. While these may be of lesser relevance when it comes to the Gain metric, they play a foundational role in the overall structure of the system, significantly contributing to its efficiency as measured by metrics Cover and Frequency.

- *K-ETS*

The analysis of the Korean market reveals a substantial disparity between the domestic markets, a discrepancy that was also observed in the OLS model. In the Korean primary market, the element that demonstrates greater prevalence is oriented as in the other markets examined, namely M2. Additionally, the model incorporates supplementary macroeconomic parameters, such as the Interest Rate and the Retail Sales. A notable departure from the analysis of other markets is the heightened significance observed in energy-related variables, specifically the prices of natural gas and coal in the Gain Metric. Notably, precipitation emerges as a crucial climatic factor, frequently incorporated in the model at a high frequency. In contrast to the findings in the primary market, the secondary market is predominantly characterized by the predominance of the Interest Rate variable. It is also notable that, with the exception of the Natural Gas Price variable, which is found throughout the model and in the reduction of errors for each tree (Gain and Cover metrics), no additional macroeconomic or other variables were identified.

5.2 Volatility Determinants: GARCH-X Model

In order to obtain a comprehensive understanding of Emission Trading System (ETS) markets, it is essential to incorporate volatility analysis as a critical component of the analysis. A superficial analysis of price dynamics, which does not account for the inherent variability and uncertainty in returns, provides a limited comprehension of the intricacies and fluctuations that typify these markets. Volatility, defined as a comprehensive examination of fluctuations in terms of frequency and magnitude, is instrumental in anticipating potential risks in both the near and long term. As discussed in the preceding sections and elaborated in this chapter, it is imperative to recognize that this analysis is exploratory in nature, necessitating a cautious interpretation of its findings

5.2.1 GARCH-X Model (Block 1, Stationary Variables)

As previously discussed in Chapters 3 and 4, which address methodology and analysis, it is important to note that the study of volatility was conducted through returns analysis, using the GARCH-X model. The GARCH-X model has the ability to incorporate the variables themselves into the model. To select variables, the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC) were utilized.

The ensuing section presents a thorough exposition of the outcomes that emerged in the course of this study:

- *EU-ETS*

The examination of the variables employed the model to ascertain the statistical significance and relevance of market variables. The results obtained from the analysis indicate that, subsequent to the imposition of penalties, the Coal Price variable is the only variable that is statistically significant and relevant for both markets. Furthermore, a comprehensive examination of the graph analysis derived from the estimated conditional volatility indicates a general trend of stability in the market until the early 2020s. However, the confluence of the pandemic and the ensuing Russo-Ukrainian conflict led to a substantial surge in market volatility. This mark is highlighted by notable spikes in both positive and negative directions. Finally, the latter period is distinguished by a moderate return to stability, albeit current levels remain below those recorded prior to the pandemic.

- *CA CaT*

A comprehensive analysis of the California market reveals that Unemployment Rate and Rainfall emerge as significant variables. This evidence suggests that the volatility of the CA CaT market is influenced by both economic and environmental factors. An examination of the conditional volatility graph reveals that the market exhibited heightened volatility, particularly in the post-2021. The underlying causes of this phenomenon are multifaceted and may include both market-specific factors, such as the transition from phase 2 to phase 5, and external factors influenced by national policies, which appear to have a substantial impact on market stability.

- *K-ETS*

As previously observed in the models for the analysis of price determinants, in the volatility analysis the K-ETS market also manifests a different dynamic between its primary and secondary markets. Within the primary market, the predominant influence stems from domestic economic factors, such as the Unemployment Rate and the Gross Domestic Product (GDP). Conversely, in the secondary market, the predominant role is played by the energy variable, such as Oil Price. The conditional volatility graph analysis reveals that despite the high volatility observed in both markets, the secondary market exhibits significant spikes attributable to external factors; in the primary market, these spikes are often mitigated by policy interventions, highlighting the potential for regulatory influence on price volatility.

5.3 Interpretation of Results and Links to the Literature

The results of the study largely corroborate the findings from the extant literature on the subject, while concurrently offering supplementary insights that may serve to inform future research in the domain of Emission Trading System (ETS) markets. The ensuing discussion will elaborate on the salient points that emerged from the analyses.

- *Macroeconomic variables*

A close examination of the macroeconomic variables reveals that they exert divergent impacts across the three markets.

Within the European context, initial analyses indicated that the variables interest rate and retail sales exhibited a linear relationship. Subsequent analyses encompass additional variables exhibiting various relationship patterns, including quasi-linear (Inflation), non-linear (Economic Sentiment), and complex (M2) relationships. This finding aligns with the observations made by Chevallier (2011), who underscored the growing interconnection between macroeconomic and financial signals within the EU-ETS market. Within the CA CaT market, the variable-dependent relationship appears to be predominantly nonlinear, a conclusion that is further substantiated by this study's findings. From the analysis, it is evident that variables only become significant in the machine learning model, in which the presence of internal macroeconomic variables is predominant (such as M2, Retail Sales and Refinancing Rate).

Finally, in the context of the Korean market specifically, a distinction must be made between these two markets. In the first market, the variable detected as linear by the models is unemployment (which is highlighted with a positive sign and confirmed by its increasing monotonic form in the generalized additive model [GAM]). Nonlinear variables that were identified as significant included Interest Rate, M2, and Inflation Rate. In the secondary market, similar relationships are evident with the same variables considered. However, these relationships manifest through different models. Notably, the GAM model in this market successfully articulates what the XGBoost model only suggests in the primary market.

- *Energetic Variables*

An analysis of energy variables reveals a distribution that appears to be significant across all markets. However, notable variations are also apparent among these variables.

The analysis revealed that the Coal Price variable exhibited distinct patterns, although it was present in all three markets under consideration. However, it did not seem to have an impact on the primary market in K-ETS. In all other cases, the type of relationship resulting from this variable is found to be a nonlinear relationship with a U- or S-shaped curve, as seen in the graphs created by the GAM model. This variation in the curves can be attributed to the differential impact of the carbon price on the allowance price, resulting in a gradual shift in some cases and fluctuations that only concern deviation from the average price, or continuous changes related to changes in the price itself.

In contrast, the Natural Gas Price has emerged as a significant predictor in the EU-ETS and K-ETS markets, albeit with distinct characteristics. A notable distinction between these two markets is that, although both the OLS and GAM models could identify the former's presence in EU-ETS, they were unsuccessful in detecting it in the K-ETS market. In essence, this dynamic becomes discernible solely through the employment of the XGBoost model, unveiling a nuanced relationship within the context of the Korean market and the aforementioned variable.

The final variable under consideration is the Oil Price. This variable is exclusively relevant for the CA CaT market and exhibits a nonlinear U-shaped relationship. This finding lends further credence to the notion that this market demonstrates a profound reliance on oil price fluctuations, given its pivotal role as a crucial input for the constituent enterprises.

- *Climate Variables*

Climate-related variables have been demonstrated to be of significant importance across all markets. Initially, we will examine the variable with the greatest impact across all markets: Temperature. This variable's behaviour has been found to follow a nearly linear and monotonically decreasing trend. The consequence of this phenomenon is a decline in allowance costs as temperatures rise, as has been previously documented. This decline can be attributed to a reduced reliance on heating, leading to a decrease in firm pollution levels.

The Rainfall variable also emerges as significant, particularly in complex relationships highlighted by the XGBoost model. The Rainfall variable is evident in all markets, with the exception of the CA CaT market, which appears to be unresponsive to its presence.

The dummy variable Temperature demonstrates significance as well. However, it does so to a lesser extent than the previously mentioned two. Its presence suggests that the market could be vulnerable to strong climatic swings, which might occasionally lead to price increases.

5.4Comparisons

This section will involve a comparative analysis of the markets that have been examined and of the models that have been considered in this study.

5.4.1 Market Comparisons

The analysis revealed several similarities and divergences among the Emission Trading System (ETS) markets considered (EU-ETS, CA CaT and K-ETS). A close examination of these markets reveals a multifaceted interconnectedness across diverse macroeconomic, energy, and climate variables. However, each market exhibits a unique response to these variables, necessitating a highly customized and articulated approach. The price and volatility dynamics in each market are influenced by a range of factors, including maturity, geographical and geopolitical location, and prevailing regulatory frameworks.

Furthermore, the utilization of disparate methodologies, including OLS, GAM, XGBoost, and GARCH-X, has led to the identification of heterogeneous relationships among the independent variables (drivers) and the dependent variable (Log_Price, returns).

As delineated in the subsequent segment, the markets are defined by the subsequent characteristics:

- *EU-ETS*

The most mature market of those analysed is characterized by the presence of often nonlinear dynamics, as well as a multiplicity of variables. This combination of factors contributes to its complexity, while simultaneously ensuring its stability. Indeed, as evidenced by volatility, the market maintains a high degree of stability, with the exception of significant external shocks that are not predictable and lead to substantial fluctuations in all markets, not solely limited to carbon allowances.

- *CA CaT*

The intermediate market among the three examined markets appears to be more influenced by domestic policies, as well as by factors that are intrinsically linked to the very nature of the nation of which it is a part. The intricate nature of these patterns renders them challenging to capture through linear relationships, underscoring the necessity for more sophisticated and adaptable analytical frameworks to comprehensively grasp their complexity.

- *K-ETS*

The least mature market of the three is evidenced by the substantial difference between its internal markets (primary and secondary), which respond to extremely divergent logics. The primary market exhibits a strong resemblance to the CA CaT market, primarily due to its significant reliance on domestic policies established by the nation (e.g., the structure of the unemployment variable with its atypical form). Conversely, the secondary market's responses align more with those observed in the EU-ETS market, reflecting its sensitivity to external market forces and its autonomy from domestic policy influence, underscoring its response to market-driven logics. Furthermore, the maturity of the market is discernible by the substantial fluctuations in volatility, which significantly influence prices through wide-ranging variations that are challenging to predict.

5.4.2 Model Comparison

A collaborative endeavour among OLS, GAM, XGBoost, and GARCH-X models facilitated a profound examination of ETS markets from multiple perspectives, with the opportunity to highlight the strengths and weaknesses of each model.

The OLS model demonstrated limitations in its explanatory capacity, despite its noteworthy interpretative capability, particularly in complex contexts (CA, CA-T, and K-ETS markets), where linear relationships proved inadequate. In contrast, GAM has emerged as a model with superior performance in bridging this gap. Its application has revealed nonlinear patterns between variables, thereby enabling a more flexible interpretation of the dynamics present in these contexts. However, the GAM model remains sensitive to the technical choice of splines and knot, necessitating caution in interpretation.

In comparison, the XGBoost model has demonstrated its aptitude for accurate prediction, exhibiting a notably high R2 in all the markets examined. The XGBoost model has also demonstrated a remarkable capacity to effectively handle nonlinear variables and discern complex relationships, rendering it a highly efficacious tool in contexts such as ETS markets, where a high degree of interactive relationships between factors exists.

The GARCH-X model was found to be a valuable tool for analysing market volatility. However, its application was hindered by several factors, including limited datasets, unstable markets, and a high number of variables. These limitations led to the model's inability to provide reliable and conclusive results. Notably, the EU-ETS market was the only one where the GARCH-X model yielded substantial results, as substantiated by diagnostic tests. In the CA CaT and K-ETS markets, as previously mentioned, the validity of the estimates is weaker due to the complexity of the dynamics highlighted. Consequently, this type of analysis is considered to be primarily explanatory.

In summary, the utilization of a distinct set of models facilitated a more profound comprehension of the interrelationship between variables within the markets, while concurrently enabling the adaptation of analytical instruments to the unique characteristics inherent in each market.

5.5 Answer to the Research Questions

The results that are presented within this chapter have been found to be consistent with the objectives delineated in the introduction of this thesis. The analysis identified the drivers that influenced carbon allowance prices and volatility. The comparison of the EU-ETS, CA CaT, and K-ET markets revealed how the structure, regulation, and maturity of the markets affect their sensitivity to the different variables considered.

The employment of an integrated approach encompassing classical econometric models (OLS), flexible econometric models (GAM), machine learning (XGBoost), and volatility models (GARCH-X), enabled the optimal identification of relationships between variables as dictated by market necessities.

Consequently, it can be concluded that the methodological strategy employed was adequate to accomplish the intended objective: to furnish a comprehensive and comparative examination of the functioning of ETS markets, thereby contributing to scientific understanding and establishing a foundation for firms and policymakers.

Given the aforementioned assertions and the findings of the data analysis, it is now feasible to formulate precise and comprehensive responses to the initially posed research inquiries.

1) *Which drivers affect price in ETS markets?*

Empirical evidence collected thus far shows that macroeconomic, energy and climate factors exert a highly heterogeneous influence on carbon allowance prices within markets. Market fluctuations are determined by factors such as maturity, individual market structure, geographic needs, and political considerations.

In the context of the EU-ETS market, the market response to the examined factors is predominantly influenced by macroeconomic parameters (e.g., interest rate, retail sales, and M2) as well as energy parameters (e.g., coal price and natural gas price). These factors have been found to be statistically significant in the analysed models. The market relationships under scrutiny are characterized by a predominance of nonlinearity, a hallmark of a sophisticated and developed system.

The CA CaT market is found to be predominantly influenced by energy factors, such as coal and oil prices. In contrast, macroeconomic variables emerge as significant only in complex models. In this regard, the observed nonlinear relationships suggest a degree of market maturity, though it must be noted that a direct comparison with that of the European market is not feasible. Further analysis reveals a pronounced dependence of the market itself on sectoral factors, particularly energy supply.

In conclusion an analysis of the K-ETS market reveals significant disparities between primary and secondary market dynamics. In the primary market, macroeconomic variables such as the Unemployment Rate, as well as the Interest Rate, are found to be significant factors. However, the patter deviate from what would be considered normal for Unemployment Rate. These anomalous patterns suggest the presence of considerable influence from public policies, which serve to alter the standard behaviours of these variables. In contrast, the secondary market exhibits an absence of this influence. This observation can be attributed to the enhanced responsiveness observed in the secondary market to prevailing market factors and the preeminent role played by energy-related variables within the respective models. These characteristics contribute to a structural resemblance between the Korean secondary market and the European market. Consequently, it can be concluded that the Korean market is currently in a phase of development and stabilization, contrasting with the trends observed in previous markets.

To sum up, an in-depth review of the relevant analyses indicates the presence of a highly intricate and complex condition. This condition involves relationships that exhibit considerable variation across markets, as well as within certain marketplaces. It must be acknowledged that the intricacies and diversities of markets preclude the capacity for a conclusive resolution to the interrogative posed by the research. Nevertheless, it can be concluded that markets possess distinctive characteristics and do not adhere to uniform logics. To provide a satisfactory answer to the research question, a focused analysis of a particular market is imperative, as this will allow for the discernment of the factors influencing that market's operation.

2) *Which drivers affect volatility in ETS market?*

As previously mentioned, the analysis of the GARCH-X model on volatility should be regarded as exploratory due to the aforementioned reasons. Nonetheless, valuable insights can be obtained from this analysis.

In the context of markets, the observed variability appears to be influenced by distinct, unique factors for each market, analogous to the observations made regarding prices.

The analysis conducted within the context of the EU-ETS Market reveals that volatility is stable and correlated with the variable (Coal Price). This finding is noteworthy, particularly in the context of significant, unpredictable shocks, such as the Coronavirus pandemic (Covid-19) and the war between Russia and Ukraine. These shocks have led to pronounced spikes in prices, but the long-term volatility has remained within appropriate bounds, suggesting a fundamental stability of the market.

In contrast, the CA CaT market exhibits higher levels of volatility and more sustained trends compared to the previous market. The volatility exhibited is influenced by a combination of macroeconomic factors, such as the Unemployment Rate, and climatic variables, including Rainfall. This evidence indicates that, within the context of the California market, fluctuations in allowance values are more influenced by political factors and local conditions than by exogenous variables, which play a more significant role in the global market.

Finally, pronounced and unstable volatility is observed in both the primary and secondary markets of the K-ETS market. Nevertheless, the predominant variables exhibit distinct characteristics across these two market settings. In the primary market, a significant correlation emerges with domestic macroeconomic variables (i.e., unemployment rate and GDP). In contrast, energy variables (e.g., oil price) prevail in the secondary market.

This finding suggests the existence of a fundamental difference between the two markets. Specifically, the primary market appears to be more susceptible to political influences, while the secondary market exhibits greater responsiveness to broader economic factors.

Consequently, even in this particular instance, it proves unfeasible to reach a consensus answer regarding the matter raised in the research question. Despite conducting a preliminary investigation, a similar observation was made concerning the determinants of price. The markets exhibited notable determinants variations in their volatility. To formulate a comprehensive response to the research question, a case study approach is recommended, focusing on a specific market to elucidate the underlying factors influencing its volatility.

3) *What situations are present in the markets?*

As indicated by the analyses conducted in this paper, there is considerable differentiation in the response of macroeconomic, energy, and climate variables within the three ETS markets.

The EU-ETS market is characterized as the most advanced and dynamic environment, with a high level of differentiation in its response patterns. This assertion finds corroboration in the analysis of a sophisticated and sensitive structure, demonstrating responsiveness to an extensive array of factors influencing the examined models. While macroeconomic variables (M2, interest rates, and retail sales) persist as the predominant influence, the incorporation of energy-related variables (coal and natural gas prices) serves to augment the intricacy of the market, which is shaped by a multitude of factors. In light of these multifaceted dynamics, it is imperative to acknowledge the intricate nonlinear and complex relationships underlying the market. In conclusion, the relatively stable volatility lends further confirmation to the initial hypothesis, thereby indicating that the market has matured and is demonstrating resilience.

A notable feature of the CA CaT market is its relatively uncomplicated configuration, which stands in contrast to the intricate structures observed in the EU-ETS. A distinctive characteristic of this market is its pronounced orientation toward linkages, or interrelationships, among variables. It should be noted that the relationships governing these variables are predominantly non-linear. Furthermore, these variables, which fall within the sphere of energy and climate drivers (Oil Price, Coal Price, and Rainfall), give the market reduced sensitivity to conventional macroeconomic variables. A more thorough investigation unveils the presence of interconnected relationships between these variables and the dependent variable. This type of relationships are characterized by a high degree of complexity that surpasses that observed in more elementary models. The existence of high and persistent volatility underscores the need for the further evolution and maturation of the market, which are accompanied by the manifestation of structural vulnerabilities.

The K-ETS market thus manifests a duality, existing between the primary and secondary markets. In the primary market, the internal macroeconomic variables include the Unemployment Rate and GDP, while in the secondary market, the external and market-specific factors, such as Oil Price and Interest Rate, become the focal point. Furthermore, evidence suggests comparable volatility between the two markets, characterized by significant segmentation and numerous positive and negative spikes. The aforementioned characteristics are indicative of a market in an early stage of development and characterized by high instability.

In summary, it can be concluded with a high degree of confidence that there is no specific and universal set of drivers that can explain how volatility move in all three ETS markets. The findings of the analysis substantiate the autonomy of each market, driven by its own set of variables that function in distinct and non-overlapping ways. This finding lends further support to the hypothesis that these markets necessitate analysis employing flexible methodologies capable of adapting to the unique characteristics of each market. This necessity for adaptation should not be confined to analysis; it should also extend to the management of the markets themselves, taking into account factors such as maturity, institutional frameworks, and the political, economic, and cultural contexts in which they are situated.

5.6 Implications for the Literature and Policymakers

5.6.1 Implication for the Literature

The results of this study constitute a substantial addition to the extant literature on Emission Trading System (ETS) markets, particularly with regard to the analysis of the determinants of price and volatility. The methodological approach employed, and the empirical analyses conducted in this study corroborate the findings of preceding studies and meaningfully advance the theoretical framework and methodological approach previously delineated.

Firstly, the study corroborates the significance of macroeconomic, energy, and climate factors in the pricing of emission allowances in ETS markets, as emphasized in earlier studies conducted by Chevallier (2011)[162] and Alberola, E., Chevallier, J., & Chèze, B. (2009)[163]. In particular, these studies indicated that allowance pricing is influenced by macroeconomic factors, such as industrial returns, as well as by energy factors, such as energy shocks. This influence is particularly evident during the first stage of the EU-ETS market. Further studies have corroborated this finding, particularly in the aftermath of the 2016 Paris Agreement. For instance, the research by Li et al. (2021)[164] demonstrated that the allowance price has become increasingly responsive to its own determinants. This finding aligns with the results reported in this study, which highlighted the nonlinear and dynamic characteristics of the variables under consideration. The findings of this research are of paramount importance in the identification of the explanatory variables and the selection of the most suitable methodology for the investigation.

This finding suggests that future academic research should prioritize the adoption of models capable of capturing and elucidating the nonlinear dynamics observed in this paper. This phenomenon underscores the limitations of employing rigid linear models in delineating the behaviours of markets that evolve within regulatory and economic environments characterized by continuous evolution.

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[162] **Chevallier, J. (2011).** *Carbon price drivers: An updated literature review*. HAL. https://halshs.archives-ouvertes.fr/halshs-00586513
[163] **Alberola, E., Chevallier, J., & Chèze, B. (2009).** Emissions compliances and carbon prices under the EU ETS: A country-specific analysis of industrial sectors. *Journal of Policy Modeling*, 31(3), 446–462. https://doi.org/10.1016/j.jpolmod.2008.12.004
[164] **Li, P., Zhang, H., Yuan, Y., & Hao, A. (2021).** Time-Varying Impacts of Carbon Price Drivers in the EU ETS: A TVP-VAR Analysis. *Frontiers in Environmental Science*, 9, 651791. https://doi.org/10.3389/fenvs.2021.651791

Secondly, the present study introduces an element of innovation within the extant literature by extending the study of markets and, consequently, the empirical analysis, to the simultaneous comparison of three markets (EU-ETS, California Cap-and-Trade, and Korea-ETS). Previous academic production has primarily focussed on the EU-ETS market or Chinese regional markets, while research related to the other markets is limited and there is an absence of evidence of a specific study conducted to this end. Addressing these shortcomings, the present study adopts a consistent econometric approach and utilizes four distinct econometric models (OLS, GAM, XGBoost, and GARCH-X) to examine each market. By integrating heterogeneous markets with a range of models, this study has made significant contributions to our understanding of market behaviour. It has facilitated a more nuanced examination of the role individual variables play in price and volatility formation, while also elucidating structural differences in market responses to these variables.

This finding suggests that academics conducting research on ETS markets should undertake more extensive studies. Consequently, the paradigm of research should undergo a shift from the analysis of individual, isolated case studies to a more systematic, comprehensive, and integrated examination of market dynamics. This shift aims to provide a more extensive and comparable perspective on market operations and outcomes.

Thirdly, the present study offers a valuable contribution to the existing body of knowledge by offering a comprehensive clarification of the role played by maturity, institutional structure, and regulatory structure in explaining the relationships present among the variables. The EU-ETS market is characterized by intricate yet interpretable relationships, which aligns with prior studies by Hintermann (2010)[165] and Daskalakis et al. (2009)[166]. In contrast, the California market exhibits a preponderance of energy-related factors, such as the coal and oil prices. This outcome aligns with Jeitschko et al.'s (2024)[167] findings, underscoring the importance of incorporating energy dynamics into market analysis. Finally, the Korean market reveals a dichotomy between the primary and secondary

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165 **Hintermann, B. (2010).** Allowance price drivers in the first phase of the EU ETS. Journal of Environmental Economics and Management, 59(1), 43–56. https://doi.org/10.1016/j.jeem.2009.07.002

166 **Daskalakis, G., Psychoyios, D., & Markellos, R. N. (2009).** Modeling CO2 emission allowance prices and derivatives: Evidence from the European trading scheme. Journal of Banking & Finance, 33(7), 1230–1241. https://doi.org/10.1016/j.jbankfin.2009.01.001

167 **Jeitschko, T. D., Kim, S. J., & Pal, P. (2024).** Curbing price fluctuations in cap-and-trade auctions under changing demand expectations. Energy Economics, 139, 107804. https://doi.org/10.1016/j.eneco.2024.107804

markets, with a pronounced political conditioning, especially for the primary. This finding aligns with earlier research by Joo et al. (2023)[168] and Tan et al. (2024)[169], who underscored the pivotal role of the political landscape. This offers insights into the counterintuitive behaviour exhibited by economic variables, such as the observed positive correlation between the Unemployment Rate and the allowance price, which is contrary to conventional economic predictions.

The outcomes observed in the various markets exhibit substantial discrepancies, indicative of divergent institutional and structural characteristics. This underscores the necessity of focusing on the diverse requirements of each market when considering future literary production in order to effectively grasp its distinct characteristics. This objective is to provide a comprehensive view of the market, thereby enabling the reader to comprehend the findings of the studies conducted.

In continuation with the volatility analysis, the study underscores the efficacy of the GRACH-X model in the determinant analysis process. However, it simultaneously demonstrates the model's limitations when confronted with structural instability and insufficient data. Although prior studies, including those by Han and Kristensen (2015)[170] and Yeasin (2022)[171], have demonstrated the efficacy of incorporating exogenous regressors in conditional volatility models, the analysis demonstrates that this implementation is valid but only applicable to stable markets (EU-ETS), yielding uninterpretable estimates in markets with limited sample sizes or those that are not yet mature and stable (CA CaT and K-ETS). This underscores the necessity to adopt more robust models or utilize larger data sets to ensure the stability of the results.

In summary, the results obtained contribute to the current academic discussion and provide a framework for future studies on ETS markets, which are still undergoing continuous expansion. A notable strength of the study is the introduction of a comparison

[168] **Joo, J., Paavola, J., & Van Alstine, J. (2023).** The divergence of South Korea's Emissions Trading Scheme (ETS) from the EU ETS: An institutional complementarity view. Politics &Amp Policy, 51(6), 1155–1173. https://doi.org/10.1111/polp.12566
[169] **Tan, X., Wang, R., Choi, Y., & Lee, H. (2024).** Does Korea's carbon emissions trading scheme enhance efficiency for sustainable energy and utilities? Utilities Policy, 88, 101752. https://doi.org/10.1016/j.jup.2024.101752
[170] **Han, H., & Kristensen, D. (2015).** *Semiparametric multiplicative GARCH-X model: Adopting economic variables to explain volatility*. Working paper. Retrieved from https://creates.au.dk
[171] **Yeasin, M., Singh, K. N., Lama, A., & Paul, R. K. (2020).** *Modelling Volatility Influenced by Exogenous Factors using an Improved GARCH-X Model*. Retrieved from https://www.researchgate.net/publication/348163301_Modelling_Volatility_Influenced_by_Exogenous_Factors_using_an_Improved_GARCH-X_Model

framework, which provides valuable insights into the differential maturity of markets and their response to the variables examined.

Overall, the present study aspires to motivate scholars to employ a more diverse and homogeneous array of methodological instruments among the ETS markets that will be examined in forthcoming years. This assertion derives from a recognition of two interconnected concepts. Primarily, the necessity of conducting a meticulous analysis of markets. Moreover, the necessity of acknowledging that each market is characterized by distinct peculiarities that demand consideration in order to comprehensively capture responses to external factors.

5.6.2 Implications for Policymakers

Within this extremely complex framework, it is therefore necessary for policy-makers to take into account factors from different areas (macroeconomic, energy and climate) and to monitor them carefully, in order to be able to understand not only the mechanisms of interaction between the variables, but also the specific features of the individual contexts in which the markets for which they are making decisions are embedded.

This finding underscores the necessity for policymakers to integrate an integrated monitoring system into their work on ETS markets. The utilization of a such instrument is recommended to surmount the limitations imposed by sectoral regulation, which has exhibited a track record of inefficacy within the context of these specific markets. The implementation of an integrated system may serve as an indicator of the cross-cutting dynamics that are present within these markets.

Staying on this point, there is another factor that they need to take into account. As this study has shown, in addition to the variables that are taken into account, it is also necessary to look at what is happening outside these markets. Possible exogenous factors and/or external shocks (financial, political or climatic) can destabilize the system very quickly, with the risk of potentially affecting the functioning of the ETS market as a whole.

In light of these developments, the necessity for a framework that demonstrates adaptability to diverse market requirements has become increasingly evident. A prompt and precise reaction would serve to minimize the repercussions of unanticipated exogenous shocks.

At the same time, public decision-makers have another delicate task, that of coordination, which aims to maintain a balance between a price for allowances that is high enough to provide an incentive to reduce emissions and a price that is sustainable enough for companies to avoid undermining their profitability too much. If these two levels were to fail, in the first case the instrument would hit companies too hard and risk putting them in difficulty, and in the second case, on the contrary, it would become ineffective. In either case, the market would fail to achieve the primary goal of reducing greenhouse gas emissions.

This observation aligns with the themes previously discussed in preceding chapters. The capacity of policy actors to formulate an effective pricing mechanism is not only pivotal from an economic standpoint, but is also manifestly reflected in social and political contexts. The absence of a comprehensive system capable of achieving this objective would inevitably result in deleterious consequences within the market, thereby compromising the primary objective of reducing greenhouse gas emissions.

To summarize what has been said so far, the systematic monitoring of the factors analysed in this paper and the ability to integrate them in a systematic way will become a fundamental requirement for policy makers in order to refine existing regulation or to intervene promptly in situations of stress or ineffectiveness of previously adopted measures.

In addition, the analytical tool also becomes crucial for the industries entering this market, because by knowing how the market tends to move and what factors cause these movements, they can apply hedging policies or investment planning in an informed manner, thus securing their ultimate mission while effectively contributing to global carbon emission reductions.

In conclusion, the process of building and maintaining a stable, fair and effective ETS market is a long and challenging task that requires interdisciplinary expertise and specific governance mechanisms that balance the needs of the public and private sectors. The contribution of in-depth analyses, such as those conducted in this paper, provides theoretical feedback that is crucial for all stakeholders in practice to promote evidence-based decisions and provide insights for further market refinements.

5.6.3 Policy Recommendations

The extant findings of the present study suggest the development of recommendations for public policies that would refine the established practices of managing Emission Trading System (ETS) markets.

- The construction of an integrated regulatory system for addressing interrelated macroeconomic, energy, climate, and market relationships. This system must be designed to consider these dimensions holistically, avoiding a fragmented approach that treats these individual dimensions in an isolated manner.
- Establishment of a proactive monitoring and early warning system is imperative, leveraging the utilization of constantly updated data from various sectors to facilitate the identification of potential risks and the subsequent planning of regulatory adjustments.
- Implement a balanced and predictable allowance pricing system to ensure that companies operating in the market can plan for long-term investments while preserving their economic sustainability.
- The integration of adaptive and flexible mechanisms into market analyses for the identification of market peculiarities. This is a crucial component for the formulation of policies that are adapted to and specific to the contexts in which policymakers must make decisions.

5.7Research Limitations and Future Perspectives

As evidenced by several empirical analyses, this paper has some structural and methodological limitations, which, although they do not undermine the overall validity of the results, may provide relevant stimulus for further future academic research aimed at overcoming these limitations.

First, it should be noted that the chosen temporal frequency of the data (monthly) was determined to ensure systemic consistency between the drivers and markets considered, given the difficulty in finding more precise data, especially for macroeconomic drivers. However, the use of a higher granularity of data, such as weekly or even daily frequency, could lead to a more in-depth analysis of the effects in the short term. In this context, the use of high-frequency data could lead to a dynamic analysis of the relationship between drivers and the ETS market.

A second limitation concerns precisely the markets selected in this paper. Currently, the EU ETS, the California Cap-and-Trade and the Korea ETS are characterized by their advanced structure and maturity. However, while this ensures a meaningful comparability between heterogeneous environments in terms of structure, regulation and maturity, these markets do not include emerging markets. Emerging markets such as China, Latin American or Oceania countries were not included due to the limited data available at the time, which would not have allowed an adequate analysis. A possible extension of the analyses included in this paper could lead to a further deepening of the knowledge and understanding of the dynamics of ETS markets, allowing for the evaluation of policies adopted in contexts different from those studied.

Methodologically, the use of heterogeneous models (OLS, GAM, XGBoost, and GARCH-X) allowed for the identification of the main relationships between the variables considered in this study. However, the analysis did not explore explicit causal models such as vector autoregression (VAR) models, Bayesian approaches, or methods such as quantile regression. The use of the latter could provide further insight into the interdependencies between variables and the dynamics they manifest at different thresholds of the regressions.

In addition, a generalized additive model (GAM) robustness test was not performed, even though this would have yielded meaningful results, including the presence of U or inverse U relationships suggesting different behavioural thresholds. At this stage, sensitivities to specific alternatives in the definition of the number of splines, the location of knots, or the selection of variables were not investigated. Such checks are not considered essential for the purposes of this research; however, their analysis could help to strengthen the reliability of results in future studies.

Another limitation, related to the analysis carried out using the GARCH-X model to investigate the influence of drivers on price volatility, deserves separate consideration. The combination of monthly data frequency and a substantial number of exogenous variables considered in this study made it particularly difficult to obtain estimates that could be considered robust, particularly for the CA-T and K-ETS markets. This can be seen by examining the penalties calculated using the Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) models, which include the same variables identically in all markets considered. It should be noted, however, that the results obtained for the European market were significant. The selection of the AIC and BIC criteria resulted in a stable and parsimonious structure in this market, with two variables (M2 and coal price) identified. The Ljung-Box and ACF diagnostic tests confirmed the absence of residual autocorrelation, confirming the reliability of the model in capturing the conditional volatility. In contrast, the model provided less stable estimates in the CA, CaT and K-ETS markets, with uneven results between the primary and secondary markets, suggesting less interpretative stability and a less established structure. In light of the findings, it is noted that the present analysis should be considered exploratory only. Therefore, future studies will require more extensive and homogeneous datasets, i.e., more parsimonious and focused specifications. Such specifications can be based on an ex-ante selection of drivers according to statistical or theoretical criteria.

We conclude with evidence that, despite the limitations delineated in this section, the analysis presented provides a robust foundation for understanding the dynamics governing price and volatility within ETS markets. The aforementioned suggestions for future directions, which include increasing the frequency of data, broadening the geographic context to other markets, introducing more specific models, and robustness testing, can serve as a basis for further refinement of the proposed analysis. The ultimate goal of this refinement is to offer a more precise contribution to the definition of policy tools and strategies for companies in the context of global greenhouse gas (GHG) emission reduction.

5.8 Conclusion

The objective of the present chapter is to engage in a critical discussion of the empirical results obtained from analyses conducted on the three markets in question (EU-ETS, CA CaT, and K-ETS) through the implementation of a variety of econometric models.

The analysis revealed significant heterogeneity across markets with respect to macroeconomic, energy, and climate drivers, both in terms of allowance prices and market volatility.

The EU-ETS demonstrated a reaction to numerous drivers, accompanied by relatively stable volatility, thereby substantiating its market maturity. Conversely, the California market exhibited a pronounced sensitivity to energy and climate factors, as well as to domestic macroeconomic variables, with high and persistent market volatility, indicating that, while it is maturing, it does not yet reach the same level of development as the EU-ETS market. Finally, the Korean market exhibited significant dualism between the primary and secondary markets, along with volatility characterized by heterogeneous spikes, indicating a structure undergoing consolidation and thus remaining less mature.

The employment of models capable of encompassing diverse dynamics, including linear, nonlinear, and complex phenomena, as illustrated in this study (e.g., OLS, GAM, XGBoost, and GARCH-X) has enabled the identification of relationships heretofore unexamined within extant literature. Consequently, the analysis underscored the value of employing flexible and comparative methods to attain a comprehensive understanding of ETS markets in their operational context. Moreover, the insights derived from this study could serve as a valuable resource for both corporate entities and regulatory authorities seeking to comprehensively assess the vulnerabilities and strengths of these markets.

6. Conclusion

The objective of this paper was to identify the variables and to perform a comprehensive analysis of the factors that influence prices and volatility in Emissions Trading System (ETS) markets. To this end, three markets were selected as representatives for analysis. The EU-ETS, CA CaT, and K-ETS are notable examples of such initiatives.

A comparative empirical investigation, employing diverse econometric models (linear, nonlinear, and machine learning methods), examined data from January 2014 to October 2024 on an ongoing basis. This analysis, conducted using a variety of models, revealed that ETS markets are significantly impacted by not only macroeconomic, energy, and climate variables but also by the institutional and regulatory characteristics of these markets.

The emergent body of evidence indicates that markets exhibit distinctive characteristics and significant differences. Despite the presence of certain minimal similarities, it is evident that each individual market possesses distinct characteristics, a phenomenon that can be attributed, at least in part, to the unique socio-economic and regulatory environments that characterize each locale. The EU-ETS market is a multifaceted trading platform that is influenced by a myriad of dynamic variables, thus resulting in a complex and nuanced set of market dynamics. The aforementioned complexity is attributable to its composition, which includes the participation of more than 30 countries, thereby helping to generate a highly diversified market. The California CA CaT market demonstrates a heightened sensitivity to energy and climate variables, exhibiting greater consistency with a regional market. The K-ETS market is found to be more significantly influenced by domestic variables in comparison to the primary market. Conversely, international variables exhibit a preponderant influence over the secondary market. This aspect underscores the market's segmentation and underscores the pivotal role that policy plays in this context.

The obtained results yield two principal contributions. Primarily, they serve to enhance existing scientific literature through the introduction of theoretical frameworks, thereby addressing knowledge gaps that surfaced during the course of the literature review. The second point to consider is the practical aspect. This aspect provides regulators and firms operating in the field with explicit guidance. This guidance is intended to optimize the regulators' and firms' understanding of the diversity present in markets. This process is designed to enhance effectiveness and efficiency for the former and develop more efficient strategies for the latter.

In summary, the results obtained from this research confirm the significance of implementing diversified approaches tailored to each ETS market. These methodologies underscore the imperative of attaining precise cognisance and adept oversight of the aforementioned factors for the optimal functioning of these systems, particularly within the paradigm of international competition aimed at diminishing greenhouse gas emissions.

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TABLE OF FIGURES

TABLE OF GRAPHS

APPENDIX I: DRIVERS BIBLIOGRAPHY

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