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The Evolution of Emission Trading Systems: A Quantitative Assessment of the Effectiveness of EU ETS2

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To my family,
whose silent light has shown me the way,
even when I couldn't see it.

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Introduction

Climate change is one of the most urgent challenges nowadays. Among the multitude of policy responses, the Emission Trading System (ETS) stands out as the most prominent and pioneering market-based mechanism for abating and reducing the Greenhouse Gas (GHG) emissions. ETS allows companies, through economic incentives, to innovate and foster cleaner technologies. Building on this general framework, among the most widely implemented and influential systems is the European Union Emission Trading System (EU-ETS). This European mechanism, as an innovative example, has steered significant emission diminution in the European Union and has served as benchmark for the similar initiatives all over the world. The system will be enhanced with the implementation of the EU ETS2 in 2027, which includes two more sectors than the first system created: the building construction and the transport sectors. This enforcement aims to improve market stability and enhance the effectiveness of emission monitoring, depicting a crucial evolution of the European Union's climate strategy.

This thesis explores empirically how the introduction of the EU ETS2 will impact carbon pricing and, consequently, assess whether these changes in carbon pricing will effectively result in a reduction of GHG emissions.

To achieve this, the research first examines the ETS generally, detailing the evolution, core principles and the mechanisms that drive it. Afterward, the focus shifts to a more detailed analysis of the EU ETS and the upcoming transition to the EU ETS2 with a particular emphasis on the legal and policy framework underpinning these changes.

The structure of this thesis is intended to take the reader from Emission Trading Systems (ETS) overview to a deep analysis of the European Union ETS and its change into EU ETS2. Chapter 1 sets forth the foundation. It explores the global scene and how that scene prompted development by ETS. It examines the main global climate agreements which include the Kyoto Protocol and the Paris Agreement and then explains the rationale for adopting market-based mechanisms for reducing emission. The chapter then introduces the fundamental principles of ETS, also it traces their evolution with explaining the key operational features and allocation methods.

Chapter 2 focuses in on the EU ETS and also it describes its own legislative framework and compliance structure as well as institutional functioning. The analysis then turns to the EU ETS2, which is the upcoming expansion of the system. It outlines the sectors that it will newly include, the innovations that it introduces, along with the policy objectives it seeks to achieve. This chapter offers background for your comprehension of how the reform should reshape the relationship between economic activity and environmental protection within the European Union.

Chapter 3 presents the methodological framework of the study. It outlines both of the main hypotheses while also introducing the research design including describing each of the data sources with the econometric techniques adopted for it: the effect of EU ETS2 on carbon prices, and its impact on emission reductions. Their inclusion is justified in detail This discussion offers justification for its inclusion within the empirical models.

Chapter 4 is the topic for empirical analysis. That methodology estimates potential EU ETS2 outcomes after the prior chapter defines it. It does so through scenario-based forecasting as well as linear regression models. The results offer quantitative insights into the policy reform's likely market and environmental consequences.

The thesis aims to contribute with evidence to a comprehensive understanding of EU ETS2 comprehension plus its expected effects plus reflect more broadly on emissions trading's role and evolution when fighting climate change.

Chapter 1:
Overview of Emission Trading Systems (ETS)

1.1 International Context: Kyoto Protocol, Paris Agreement, and the Rationale for ETS

The evolution of global climate governance reflects the Kyoto Protocol as well as the Paris Agreement, two milestones within international climate treaties. The Kyoto Protocol, which parties adopted during 1997 within the third Conference under the United Nations Framework Convention on Climate Change (UNFCCC), effectively began in 2005. It was the first enforceable international agreement with imposed Greenhouse Gas (GHG) emission reduction targets. It only imposed them on developed nations however (Annex I Countries) (Philibert, 2004; Böhringer, 2003). Construction adhered to Common but Differentiated Responsibilities' (CBDR) principle. This tenet asserts developed nations historically were most responsible regarding climate change's development, so they assumed mitigation's main obligation. Under this treaty, the nations included in Annex I were required for achieving an effective reduction, also this reduction was an average of 5.2% below the 1990 levels during the first commitment period between 2008 and 2012. Japan committed to 6%, the European Union to an 8% reduction, also Russia agreed for remaining at 1990 levels (Philibert, 2004; Böhringer, 2003). China as well as India, emerging economies, were not subject to legally binding targets, conversely, countries not included in Annex I were encouraged to take voluntary actions for the reduction of GHG emissions (Philibert, 2004; UNFCCC, 1997). This protocol introduced a market-based approach, a meaningful innovation of sorts. Because the protocol offered flexibility and cost-effectiveness, countries could then meet targets. With this system, Annex I countries were enabled for trading emission allowances effectively creating a global carbon market that is known as the International Emission Trading System (IET). Through this system, countries struggling to meet their targets were permitted to buy surplus allowances. Energy use became more efficient because this mechanism incentivized nations toward research and cleaner technologies (Philibert, 2004; Böhm, 2000; UNFCCC, 1997). The Clean Development Mechanism (CDM) came from this global treaty. It also introduced Certified Emission Reductions or CERs as market-based mechanisms for the market. The CDM enabled developed countries for the reduction of emissions via projects located in developing countries as they carried out some work in exchange for CERs to then meet

Kyoto targets. These projects which had been intended for support of sustainable development while also adopting policies regarding climate change mitigation (UNFCCC, 1997; Philibert, 2004), included initiatives in renewable energy along with reforestation and industries for improved energy efficiency. Joint Implementation was implemented within the Kyoto Protocol and it allowed Annex I countries for the financing of emission-reducing projects. These investments, in contrast to CDM, were made only in industrialized nations, most particularly in Central and Eastern Europe. Developed economies were intended to transfer technology using this cooperation mechanism (Philibert, 2004; UNFCCC, 1997). It fostered an industrial modernization in a very cost-effective manner. JI and CDM encountered difficulties such as excessive complexity within verification procedures and high transaction costs, and transparency and integrity concerns (Böhringer, 2003). These mechanisms founded carbon markets as they influenced the development of Emission Trading Systems (ETS) worldwide. When applied directly to the European Union Emission Trading System (EU ETS), those are lessons learned from the Kyoto Protocol's cap-and-trade system, which is the most advanced and the largest ETS globally (Böhringer, 2003; Böhm, 2000). The Kyoto protocol faced important challenges, however. These challenges included the United States' withdrawal from the agreement in 2001 as well as the weak compliance that is present given several Annex I countries failed to meet their targets, which revealed loopholes also monitoring mechanisms that were inadequate (Philibert, 2004; Böhringer, 2003). Because it recognized both these weaknesses and also the need for a more adaptable climate framework, the international community developed a new approach for global climate governance, resulting in the negotiation as well as adoption of the Paris Agreement (Böhringer, 2003; Philibert, 2004). In December 2015 at COP21, the Paris Agreement adoption introduced a new climate governance model; it shifted from the legally binding, top-down Kyoto approach to a universal, voluntary framework for all countries (Chatjuthamard et al., 2024; UNFCCC, 2015). The Paris Agreement has an aim that is mainly to limit global warming to well below 2°C. They also do strive for the goal to keep global warming under 1.5°C (Chang et al., 2024; UNFCCC, 2015; Alatrash et al. 2025). The agreement makes it possible to emphasize climate resilience. Low-carbon development obtains financial flows and support is secured. The Nationally Determined Contributions (NDCs) represent a key mechanism, which requires each country to set emission reduction targets and update them every five years to improve ambition (Chatjuthamard et al., 2024; Chang et al., 2024; UNFCCC, 2015). Flexibility is promoted by this bottom-up approach, and broad participation is allowed but rules are not legally enforced (Chang et al., 2024; UNFCCC, 2015). The ETS has expanded, as mentioned earlier, because of the Paris Agreement and the Kyoto Protocol. That precedent created carbon trading's groundwork. It did this via market-based mechanisms like IET, CDM, and JI. Launched since 2005, the European Union Emission Trading System (EU ETS) exists. Kyoto's emission trading principles were directly modeled after it (Böhringer, 2003; Böhm, 2000). Many other nations like Canada, China, and South Korea then made national ETS programs because of Kyoto's cap-and-trade example (Chatjuthamard et al., 2024; Böhringer, 2003). The Paris Agreement did further allow for countries to use market mechanisms in order to achieve their NDCs. A new international carbon market framework was introduced in Article 6 and it improves transparency while also preventing double counting of emission reductions (UNFCCC, 2015; Chang et al., 2024). Countries can trade emission reductions, so this provision enables bilateral cooperation. Carbon markets do actively contribute in fact to sustainable development, and this ensures that there are positive outcomes (Chatjuthamard et al., 2024; Chang et al., 2024).

1.2. General Definition and Evolution of ETS

As explained partially in the previous paragraph an Emission Trading System (ETS) is a market-based mechanism used to control pollution by providing economic incentives useful to reach targets of emission reduction. Generally, it functions on the principle of Cap-and-Trade where e regulatory authority established a maximum to the emission allowed, known as Cap, and allocates emission allowances for free or through auction to the entities covered by the system (Singh et al., 2024). The primary unit used is *one Tonne of Co2 equal weight.* At the end of each period of compliance all the participants have to return or submit the emissions allotted which are then removed from their account. (Chen et al. 2020). Entities that are capable to emit below the allowances they have can sell their permits to other entities which exceed their limit, this is called the *trade part.* Thereby, this mechanism offers incentives to reduce pollution and improve emission reduction. (Singh et al., 2024)

The concept of ETS was proposed at the beginnig as an alternative to the direct regulatory approaches taken before. These regulatory approaches were not the most suitable choice because of the rigid emission limits imposed without taking in consideration the cost-efficient flexibility needed by the companies. Over time, the ETS has proven its effectiveness evolving into a key policy tool used worldwide to fight climate change by ensuring the occurrence of emission reduction where they present themselves as the most cost-effective. (Singh et al., 2024). Furthermore, ETS mechanisms allow for long-term planning by lowering in a progressive way the cap aligning with the global climate goals settled by the Paris Agreement, which aims to achieve net-zero emissions by 2050. The efficacy of the ETS mechanism relies into its ability to embed environmental and economic objectives, giving to firms the incentives to innovate and invest in cleaner technology in a way that allows them to do not need to buy additional permits to pollute first and then maybe reduce their emission to reach levels that enables them to sell the allowances in excess. (Singh et al., 2024). The historical development of the ETS find their roots in the early experiments with market-based environmental policies. The first large-scale ETS was the United States Acid Rain Program founded in the 1990s to limit the sulfur dioxide emissions from power plants (Martinsson et al., 2024). The success of this mechanism established the basis for the implementation of the European Emission Trading system in 2005, which still the most developed and largest ETS in the world (Kollenberg & Taschini, 2016). Beyond the European Union, other countries have established their own Emission trading System model. For example, Sweden implemented a carbon tax in 1991, then participate to the EU ETS. Concerning that, the Swedish system provided valuable empirical data on the impact of carbon pricing on emissions. These data reveal that higher carbon prices can drive significant reductions in emission nonetheless maintaining economic growth. (Martinsson et al., 2024). Analogously, California introduced a Cap-and-Trade program in 2013, which became a model for subnational carbon trading policies. However, studies have demonstrated that companies could shift production in states that have not regulation about emissions, leading to spillover effects which highlights the need for careful and well-designed ETS (Bartram et al., 2022).

The design of an ETS, as we will see in the other part of this Thesis, involves different key choices, including the type of cap, the allocation method and the flexibility mechanism such as banking and borrowing of allowances (Singh et al., 2024).

The evolution of these mechanisms has been shaped by technological advancements and financial downturns such as economics crises. For example, the 2008 financial crises led to a decline in emission because of the reduced industrial activity causing an oversupply of allowances in the EU ETS and a prolonged period of low carbon prices (Kollenberg & Taschini, 2016).

1.3. Allocation Mechanisms: Methods and Processes

The effectiveness of the ETS relies not only on the cap imposed but also on the method and the process to allocate the emissions among the participants of the mechanism. Once the cap is set, the focus shifts from that to the methodology used to allocate these permits as this could impact directly on the market dynamics, firms' behavior and overall system efficiency (Burtraw & McCormack, 2017; Aid & Biagini, 2021). The incentives for emission reduction, the competitiveness of firms and the determinant of the cost-effectiveness of the systems are all features shaped by the allocation mechanism (Sun et al., 2014). These mechanisms represent trade-off between efficiency, fairness but also the need to mitigate negative economic impacts derived from production and not only from that, but such also as market distortion and carbon leakage. (Jiang et al., 2016; Dimos et al., 2023). The topic related to the allocation method is crucial because empirical studies contradict classical theory which stated that under ideal market conditions the initial method used to primary allocation should not influence the efficiency related to emission reductions (Montgomery, 1972). The empirical studies which we are referring to, have demonstrated that the allocation of emission allowances affect both market efficiency and firms' strategic behavior. For example, firms receiving more allowances than needed tend to trade less actively, leading to a market liquidity reduction (Sun et al., 2014). Different policies priorities are reflected into the vary allocation methods. *Free allocation mechanism*, for example, aim to mitigate the financial load on industries during the primary stages of an ETS, while *auction-based systems* prioritize features such as transparency and economic efficiency (Burtraw & McCormack, 2017). Recently, there are different approaches, as *output-based allocation* and *consignment auctions*, which try to balance production incentives and market stability with efficiency (Lin & Lu, 2023). Furthermore, the need for more adaptable and equitable systems have led to responses specifically dynamic and cooperative mechanisms (Gutiérrez et al., 2021). These kinds of mechanism function adapting and adjusting allocations on real time economic indicators and corporate conduct, aiming to improve the market fairness while enable implementation of environmental outcomes Aid & Biagini, 2021). The different allocation methods are explained in the next sections.

1.3.1 Free Allocation Mechanism

The method of *free allocation*, also known as *Grandfathering*, is a fundamental and core approach used in emission trading systems (ETS) to allocate emission permits. In this method, the allowances are distributed to a firm at no cost, based on their historical emission or production levels. Firm with higher emissions in the past receive more permits, creating an allocation system that reflects the historical contribution to pollution. (Jin et al., 2020). This process involves three primary mechanisms, the first one is the historical benchmarking where allocations are determined on a firm's historical emission based on a specific baseline period (Sun et al., 2014). The second one is the proportional allocation, based on this principle the companies that emitting more in the past receive a higher share of allowances. This could be beneficial because could provide continuity but on the other side it could disadvantage the newer, cleaner firms. The third is the fixed cap, a total emission cap is fixed to limit overall emissions, the number of permits remains capped to ensure environmental target are met though permits are allocated for free (Gutiérrez et al., 2017). Free allocation offers predictability and stability as firms can anticipate their share of permits based on historical data. These characteristics simplify compliance planning and helps companies manage regulatory risks effectively (Burtraw & McCormack, 2017). This system is widely accepted at a political level since it minimizes the primary financial impact on high-emitting industries, reducing potential opposition and facilitating policy implementation (Grimm & Ilieva, 2013). Despite that, it also carries risks, among them we can identify the risk of distorting market dynamics by favoring with historically high emissions, which could create barriers for new entrants and disincentivize early actions to reduce emissions (Sun et al., 2014). Furthermore, this allocation method could incentivize firms to aver report the emission during the benchmark period trying to secure more allowances in future allocation rounds (Jin et al., 2020).

1.3.2 Auctioning of Allowances

The auctioning of allowances in the emission trading systems (ETS) is used as a critical mechanism to allocate carbon emission rights efficiently among firms. These kind of mechanism for emission allowances has emerged as an alternative to the Grandfathering method. Unlike the Grandfathering method, this is a market-driven mechanism in which firms competitively bid for emission allowances through different type of auctions, ensuring that emission rights are allocated to those that value them most (Chen et al., 2020; Lin & Lu, 2023). Auctioning allocates emission permits through competitive bidding, allowing firms to purchase them based on their willingness to pay (Chen et al., 2020). Different type of auctions influenced in different ways the market behavior and efficiency. For instance, the English clock auction is able to enhance their efficiency when a large number of participants are involved, due to that they can reduce the possibility of collusion (Cong & Wei, 2012). Despite this, speculative behavior in secondary markets can erode the effectiveness of primary auctions, this could lead to misallocation of allowances and reduced revenues for the auctioning authorities (Khezr, 2024). The frequency of the auction also plays a crucial role, frequent auctions function as stabilizer for the market prices, while the infrequent auctions may encourage speculative bubbles (Grimm & Ilieva, 2013). In the typical auction system, called Pay-as-Bid, firms submit bids for the amount of allowances they are interested in at their willing to pay prices. The firm with the highest bids receives allowances and so forth until the permits are exhausted (Lin & Lu, 2023). There are different auction formats used in the ETS worldwide. The Uniform Price Auction is a format in which all winning bidders pay the same price which is typically determined by the highest rejected bid or the lowest accepted bid. This method promotes fairness and transparency ensuring that all successful bidders pay the same amount or their allowances. Another system is the English Clock Auction. Mentioned before, this format is functioning with a rising price mechanism. The auctioneer gradually increases the price until the demand matches the available supply. In this way, firms withdraw from the auction when the price exceeds their willingness to pay. The auction is concluded when the supply and demand are balanced at a clearing price (Cong & Wei, 2012). A different form of auction is the Dutch one, that in contrast with the English clock one, begin with a high price which decrease until a bidder accepts the current price. This type of auction is efficient for quick transactions and also can be effective when there is the need to allocate large quantities of allowances in a short period (Lin & Lu, 2023).

1.3.3 Output-Based Allocation (OBA)

Output-Based Allocation distributes emission permits based on firms' actual production output, thus linking directly the economic performance with the allocation (Lin & Lu, 2023). This kind of mechanism fosters the production efficiency while it preserves the competitiveness. This is valid, particularly, for energy-intensive industries that would otherwise face high compliance costs (Böhringer & Lange, 2005). Unlike the Free Allocation mechanism, here the permits are distributed proportionally to the output not relating to the historical emission. The functioning process begin with the production of a benchmark. Firms report their output level and allowances are allocated on a predefined emission benchmark relate to the production volume. (Jin et al., 2020). Then the allocation is adjusted over time in accordance with the changes in the firm's production output, ensuring fairness and competitiveness for high-output industries (Böhringer & Lange, 2005). Thanks to this mechanism firms are incentivized to product in a more efficient way without increasing emission results in surplus allowances that can be sold (Jin et al., 2020). OBA has been notably effective in the context of China's National Emission Trading System, where it ensures that the efforts in emission reduction are spread across various sectors, preserving macroeconomic stability (Jin et al., 2020). Nevertheless, OBA can present drawbacks, it can incentivize increased production output potentially offsetting gains derived from emission reduction (Böhringer & Lange, 2005). Uniform linear allocation mechanisms, which derive from OBA, have demonstrated Pareto efficiency under Cournot competition when firms differ only in their abatement abilities (Lin & Lu, 2023).

1.3.4 Consignment Auctions

Consignment auctions represent a hybrid approach that integrates aspect of free allocation with market-based auctions to distribute emission allowances. Under this system, firms primarily receive allowances for free based on historical data or benchmarks (Burtraw & McCormack, 2017). However, instead of holding these permits, they are required to deliver a portion or sometimes all of them to an auction. This auction allows firms to either buy back the permits they need or allow other market participants to bid on them. The revenues generated from these sales is turned to the original holders in proportion to the allowances they consigned, ensuring the process remains revenue-neutral (Burtraw & McCormack, 2017). This mechanism offers several advantages, one of these is the fact that requiring firms to submit allowances to the auction the market becomes more liquid with a larger volume of permits available to be traded. This enhanced the market stability and transparency also making clear the price discovery, as the auction-clearing price reflects real market demand (Wang & Duan, 2022). In addition, firms can make better informed decisions regarding emission reduction strategies, as the cost of compliance becomes clearer through market-based signals. Moreover, consignment auctions also address fairness issues that are often associated with free allocation. By mandating participation in the auction process, all firms, regardless of their initial allocation, are subject to the same competitive conditions. This prevents larger firms from hoarding allowances and ensures that new market entrants have equal access to emissions permits (Burtraw & McCormack, 2017). Additionally, the transparent nature of this mechanism encourage investment in cleaner technologies. Firms have stronger incentives to innovate and reduce emissions when the price of emission allowances reflect in accurate way the market conditions (Wang & Duan, 2022). Despite these advantages, consignment auctions require careful market structuring and regulation. The auction structure must prevent market manipulation while ensuring compliance from participating firms (Burtraw & McCormack, 2017). Additionally, this mechanism is often seen as a transitional approach, particularly effective for markets in the early stages of implementing ETS, such as China's national emissions trading program (Wang & Duan, 2022).

1.3.5 Dynamic and Cooperative Allocation Mechanisms

Dynamic allocation mechanisms adjust emissions permit allocations in response to macroeconomics and environmental factors such as time market fluctuations, economic shocks and environmental targets (Aïd & Biagini, 2021). Moreover, variational models make regulators able to adapt allocation strategies to changing market conditions, ensuring the reduction of emission consistent with policy goals. In addition, cooperative allocation strategies, which have their roots in the game theory, are focused on the distribution in an equitable way among firms with different level of production technologies (Gutiérrez et al., 2017). These strategies often adopt bankruptcy rules and fairness-based methods to ensure that emissions rights are allocated minimizing competitive distortions while promoting overall system stability. The process involves firms cooperating to allocate emission permits based on mutually agreed upon benchmarks. The permits, as said before, are distributed firstly among firms using rules like the Constrained equal awards (CEA) (Gutiérrez et al., 2017).

1.4. Challenges and Benefits of ETS Implementation

Emission trading systems (ETS) as seen in the previous paragraphs and discussed in the following chapters are markets-based mechanism widely used to reduce greenhouse gas (GHG) emissions. However, their effectiveness is often undermined by various structural, economic, legal and political challenges. They often meet numerous obstacles on their path, undermining their optimal function.

Overallocation of allowances

This issue has been observed in different ETS worldwide and it severely impact on market stability, environmental effectiveness and the economic rationale behind emission trading (Singh, Ritchie, & Chen, 2024). Overallocation of allowances occurs when the numbers of permits issued exceed the emission levels. This factor could lead to an oversupply that drives carbon prices decreasing and undermine the financial incentive for industries to reduce their emission through cleaner technologies. Specifically, when allowances are allocated based on forecast of the probable emissions, but the actual emission are lower due to different factors, the market become flooded with excess of permits (Schmalensee & Stavins, 2017). An ETS is effective when the principle of scarcity is satisfied, when there is ample quantity of allowances companies can avoid developing long-term decarbonization measures purchasing surplus allowances at a cheap price. In addition, overallocation creates market instability and make investors uncertain. The fluctuations and so the unpredictability of carbon prices makes industries reluctant because they cannot justify spending on carbon reduction technologies if allowance prices are too low to yield a return on investment. Moreover, the lack of confidence in the carbon market can lead to reduced participation, further limiting the system's efficiency in driving emissions reductions (Singh et al., 2024).

Another problem due to overallocation is the lack of effectiveness of the interaction between ETS and complementary climate policies. Many jurisdictions implement additional emission reduction measure, this measures indirectly could lead to a decrease demand for ETS allowances. When these policies are not integrated effectively, they can contribute to the accumulation of surplus allowances, exacerbating the issue of weak carbon prices (Schmalensee & Stavins, 2017). Instead of making the ETS stronger these interventions can unintentionally diminish the role of carbon pricing as a key driver of emission reduction (Singh et al., 2024).

There are some mitigation strategies that have been implemented and introduced in ETS program worldwide. One of them is the Market Stability Reserve (MSR) which absorb excess of allowances preventing prices from falling too low (Schmalensee & Stavins, 2017). Another strategy is the transition from a free allocation mechanism to an auction-based one, assuring the allocation is based on the market demand. Moreover, stringent criteria on emission caps can prevent an oversupply, solving the problem at its root. Lowering emission ceiling ensures allowances to remain scarce (Singh et al., 2024). Additionally, some ETS programs have adopted periodic adjustments to the number of available allowances based on real emissions data to prevent long-term accumulation of surpluses (Shen, 2015).

Lack of Banking Provisions

Lack of banking provision is one of the other challenges ETS can face. Banks allow companies to save unused emission allowances for the future, in this way they provide flexibility in compliance but also preventing the fluctuations of carbon prices (Singh, Ritchie, & Chen, 2024). However, when it doesn't happen, companies are then required to use or sell their permits before the end of the compliance period and this factor can lead to market distortions and price volatility (Schmalensee & Stavins, 2017). An example of this phenomenon can be found in the Phase I of EU ETS (2005-2007). Indeed, during this phase the banking of allowances during different period was not allowed, so any surplus of allowances at the end of the phase became worthless. This led companies to rush sell permits causing a dramatic drop of prices. This experience has demonstrated that without banking, companies can feel a lack of incentives in emission reduction, leading to inefficiencies in the ETS. (Schmalensee & Stavins, 2017). To avoid the occurrence of this event, policymakers should ensure that allowances can be carried forward cross multiple compliance periods. By implementing robust banking system, ETS programs can encourage investments in emission reductions, follow then by all the benefits they bring with them (Singh et al., 2024).

Carbon Leakage

In the design of an ETS one of the many concerns can be the Carbon Leakage. This phenomenon concerns the relocation of production from countries with strong environmental regulations to countries with weaker ones to avoid costs derived from the compliance to the stringent requirement of regulations. This relocation undermines the effort in the reduction of global emissions and also can have severe economic consequences for regulated countries. Carbon leakage is particularly problematic in the industries that are energy-intensive and trade-exposed (EITE), such as steel, cement, and chemicals, which may shift operations to jurisdictions without stringent carbon pricing. To address this, some ETS programs have introduced a free allocation of permits for sectors with high-risk related to carbon leakage but obviously this approach has raised concerns about the market efficiency and fairness (Singh et al., 2024). Also, Carbon Border adjustment Mechanisms (CBAMs) are emerging as strategies to fight the carbon leakage by charging a carbon price on imports from countries with lower environmental standards. This mechanism ensures that foreign producers face same carbon costs as domestic industries. In this way the fairness between domestic and foreign is re-established and the relocation is discouraged. (Singh et al., 2024). Some studies suggest that this type of risk as large-scale has been lower in regions equipped with well-designed ETS policies. Obviously, there are challenges posed by policy uncertainty which affects long-term mitigation strategies (Shen, 2015). International cooperation plays a key role in reducing disparities among different countries and different carbon prices regimes (Singh et al., 2024).

Limited Market Coverage and Scope

Limited coverage and scope are another challenge faced by the ETS because it restricts the overall impact on the emission reduction. Many ETS programs focus initially on specific industries to test the system and the design before implementing themselves. The sectors initially taken in consideration are heavy manufacturing and power generation while excluding other high emitting sectors such as transportation, agriculture and residential heating. The efficacy of ETS relies on its sectoral coverage. The sectors exclusion leads to uneven carbon pricing where there are only few industries bearing the financial burden of emission reduction while other still largely unaffected (Singh, Ritchie, & Chen, 2024). This phenomenon can be identified in the EU ETS, the initial focus was on energy-intensive industries and power generation while other sectors were only gradually considered for inclusion (Schmalensee & Stavins, 2017). As a result, the emissions derived from the transport sector continue to rise despite the reductions in covered industries, due to that the effectiveness of the overall system. Also, the California's Cap-and-Trade Program initially focused on industrial emission but later expanded to include fuels and transportation, recognizing that a more substantial coverage is necessary to achieve deeper emission cuts (Singh et al., 2024). Nonetheless, expanding the coverage is also difficult because of different obstacles, including political opposition, industry resistance and regulatory complexities. The high-emitting industries often try to resist against their inclusion in the ETS system, arguing that carbon prices will increase costs and reduce competitiveness (Schmalensee & Stavins, 2017). For example, the agricultural sector has been largely excluded by ETS programs due to the difficulties detected into the measurement of emissions (Singh et al., 2024). To try to solve this problem the policymakers must work toward expanding coverage to additional high-emitting sectors. However, this expansion, as outlined earlier, entails several critical challenges. Indeed, to do this they must address regulatory barriers, improve emission measurement techniques and implementing phased transitions for new industries entering ETS framework. Moreover, the introduction of flexible compliance mechanism such as sector-specific benchmarks and transition periods can help industries to adapt carbon pricing without causing economic disruptions (Singh et al., 2024).

Market Liquidity and Trading Challenges

A well-functioning ETS relies on frequent and active trading of emissions allowances to ensure that prices reflect the true cost of carbon emissions. A lack of liquidity can lead to difficulties in buying and selling allowances at a stable price, resulting in market distortions that undermine the effectiveness of trading system. This issue has been particularly evident in China's pilot ETS programs, where low trading volumes have led to erratic price movements. Several factors contribute to liquidity challenges, one of them is the limitation to the participation, which occurs when the number of active buyers and sellers remain too low to sustain a stable market. This phenomenon happens often in the new ETS programs where the market confidence is not yet built. Also the weak trading activity is part of the cause of the problem. Market fragmentation is one key factor, cross border training is in fact limited because multiples ETS systems operate independently. A fragmented market restricts the pool of participants and prevents economies of scale, leading to low trading volumes and price volatility. The lack of liquidity can also lead to market manipulation, where a small number of players influenced all the other ones. This can create market distortion and reduce the fairness of the trading system, undermining its credibility and effectiveness (Shen, 2015). To address the liquidity problem, policymakers must implement different strategies aiming to increase the active participation and ensure a steady flow of allowances in the market. One effective approach is the integration of regional ETS into national or international one, which can create a more liquid trading environment expanded the pool of participants (Shen, 2015).

Despite all the challenges the ETSs face, they bring also many benefits.

Cost-Effective Emissions Reductions

ETS enables emission reductions to be achieved at the lowest possible cost by allowing entities with lower abatement costs to sell their excess allowances to those with higher abatement costs. This process enables regulated entities to comply their emission targets while minimizing the financial burden. ETS allows businesses to select the most economical method of compliance, in this way they enhanced both efficiency and flexibility. This flexibility aims to improve energy efficiency, shift to low-carbon fuels, investment in emission reduction technologies or purchase allowances from entities that have exceeded their reduction targets. These mechanisms ensure that emission targets are achieved but at the lowest possible cost for the economy (Singh et al., 2024). The most cost-effective abatement opportunities are utilized first due to the fact that the price of carbon fluctuates based on supply and demand. By contrast the carbon taxation presents difficulties in determining the appropriate price level and may lead to an ineffective incentive to lowest-cost reductions (Singh et al., 2024). Traditional regulatory approaches impose uniform emission targets, which can be inefficient because they fail to account for differences in abatement cost across industries. Some examples, such as the U.S and the EU ones, have shown that providing regulated entities with a choice in how to meet their targets lead to a more cost-effective compliance. The US sulfur dioxide (SO_2) trading program resulted in estimated cost saving of 15% to 90% compared to conventional regulatory approaches. The program has not only achieved its environmental goals but did so at a significantly lower economics cost, demonstrating the superior efficiency of market-based mechanisms like ETS (Schmalensee & Stavins, 2017).

Incentivizing Innovation and Long-Term Planning

ETS are designed not only to reduce emission-cost effectively but also to stimulate regulated entities to invest in cleaner technologies. The integration of climate considerations into their decision-making process and financial strategies is fundamental and it's stimulated by the creation of a carbon price signal (Hoffman, 2007). The shift from carbon-intensive processes to investment in low-carbon assets is one of the key objectives of the ETS. The improvement of energy efficiency and the transition to renewable energy sources are encourage by the cap-and-trade mechanism which creates financial incentives for firms (Neuhoff, 2011). Moreover, carbon pricing has a strong role in fostering innovation through its signal. A predictable carbon price makes firms encouraged in developing new low-carbon technologies and processes, ensuring they remain competitive in a future with stricter environmental regulation (Rogge et al., 2010). Empirical evidence suggest that firms facing a shortage of allowances are more likely to innovate to environmental friendly technologies than those with surplus. Indeed, this evidence support the view that ETS functions as catalyst for technological progress, particularly when allowances are scarce and carbon price expectations are satisfied (Calel & Dechezleprêtre, 2012). Furthermore, a well-designed ETS provides to companies a framework for long-term strategic planning by offering a predictable carbon price, allowing firms to incorporate carbon costs into their investment decisions avoiding stranded assets and positioning themselves for a low-carbon future (Hervé-Mignucci, 2011).

Revenue Generation for Climate and Social Programs

Another benefit bring by ETS is the generation of substantial revenues for governments. The funds can be reinvested strategically in climate mitigation and in other kind of initiatives supporting the transition towards a low carbon economy (Singh et al., 2024). ETS generates revenues primarily form auctioning systems where, as explained in previous paragraph, companies bid for emission allowances. Unlike free allocation methods, auctioning ensures that polluters pay a price to emit. Furthermore, through this mechanism ETS creates both economic an economic incentive ad a source of funds for governments (Neuhoff et al., 2011). In addition, some ETS frameworks also set aside a portion of allowances for targeted funds like the Innovation fund, to support innovation in low-carbon technologies, and the Modernization Fund to support the modernization of energy systems (Laing et al., 2013). In the Regional Greenhouse Gas Initiative (RGGI) in the U.S, the 25% of allowances must be sell through auctions and the proceeds used to fund energy efficiency and renewable energy projects (Sijm et al., 2006). For example, the California Cap-and-trade program has reinvested its auction proceeds to support initiatives as public transit expansion, energy-efficient building and clean vehicles subsidies. Indeed, this demonstrates the potential of ETS to facilitate a broader green transition (Burtraw et al., 2015). In addition to all the initiatives presented before, the revenues of ETS are also used to finance social equity program such as the Just Transition fund, which helps communities dependent on fossil fuels industries transition to sustainable economic activities by funding job retraining programs and infrastructure development (Singh et al., 2024).

Supporting Market Stability and International Cooperation

Market stability results occur and international entities can cooperate with ETS implementation. ETS eases a worldwide standard way to lower emissions through connecting carbon markets in regions plus using price control systems (Flachsland et al., 2009). ETS program uses strategies such as price floors, ceilings, and market stability reserves (MSR) to smooth out extreme price fluctuations and ensure investments are stable (Schultz & Swieringa, 2014). As an example, the EU ETS Market Stability reserve (MSR) is a strategy that prevents extreme price drops because it adjusts permit supply in response to market conditions (Mizrach, 2012). Furthermore, the integration of different ETSs improves the efficiency of the market. Compliance costs are also reduced. The EU ETS, California's Cap-and-Trade System, and the New Zealand ETS have demonstrated cross-border carbon trading benefits because linked markets allow entities access internationally to lower-cost abatement opportunities (Ranson & Stavins, 2016). The ETS has an important role: align regional climate policies with global commitments like the Paris Agreement. ETS incentivizes decarbonization efforts via setting clear carbon price signals also eases international negotiations on carbon market cooperation (Carbone et al., 2009). The national ETS of China is at present the world's largest carbon market that exists. It has been designed to integrate with international systems as this marks a major step in the direction of a globally linked carbon market (Nogrady, 2021).

Chapter 2:

The EU ETS and the Transition to EU ETS2

This chapter analyzes the creation of the European Emission Trading System. After analyzing the ETS in general, we aim to discuss how European Union has implemented this kind of mechanism, so how they have designed their system. Indeed, we will discover all the features of the EU ETS starting from the beginning and proceeding with the development of the different phases which represent the evolution of this system, leading it to the system that we know nowadays. After the analysis of the EU ETS, we will discuss how the situation evolved leading to the creation and the development of the EU ETS 2, highlighting also in this case all the features that characterize this mechanism.

2.1 The EU ETS: Functioning, Compliance, and Monitoring Mechanisms

The European Union Emission Trading System formally came about at the time when Directive 2003/87/EC established the cap-and-trade system within the European Union. The Directive, adopted October 13, 2003, intended to provide a cost-effective and economically efficient mechanism for GHG reduction in the EU. Because it set binding emission reduction targets in developed countries, the Kyoto protocol established the groundwork for the EU ETS. For the EU's climate policy, the European trading system was designed as a foundation ensuring compliance with the international standards. It also fostered some economic growth since it provided for industries incentives to reduce emission in a way that was cost-effective and flexible. The directive's main goal involved creating the market-based system to lower GHG affordably. Limits upon emissions were progressively tightened also. To ensure integrity and harmonize national policies across Member States, the Monitoring, Reporting and Verification system was implemented. This implementation has also created certain flexibility mechanisms which included the possibility for the EU ETS to be linked in order to work with other emission trading systems (Directive 2003/87/EC, 2003). As one of the most established carbon markets worldwide, the EU ETS is in fact the first carbon market. It is one of those with the largest trading volume, too. Since its launch in 2005, it has served as a model for carbon markets worldwide. Also, it features tough rules and a solid monitoring, reporting, and verification (MRV) system, and that guarantees abidance through firm control and punishments.

2.1.1 Legislative Framework

The Directive 2003/87/EC presents different Articles under which the EU ETS was created. The Article 1 established that the EU ETS is legally binding system, ensuring the regulation of GHG emissions across multiple sectors in the European Union. The system was applied initially to power generation, industrial production, and heat production, and was later expanded to include additional sectors such as aviation. The Directive mandated that Member States implement national allocation plans, summarize under the acronym NAPs, detailing how allowances would be distributed. However the first phase. Between 2005 and 2007 revealed issues related to over allocation and windfall of profits for certain industries leading to subsequent reforms that prioritize the auction system for allocation rather than the free allocation method. Additionally, the Article 9 introduced a linear reduction factor, ensuring the decreasing of the cap on emissions over time, align the system with the objectives posed by international agreements. This reduction factor was increased to 2.2% annually from 2021 to accelerate the pace of decarbonization. Since its foundation the EU ETS has gone through different updates aimed at enhancing its effectiveness. The Directive 2009/29/EC revised the system to align with the EU's 2020 climate goals, introducing harmonized allocation rules and expanding the scope of the coverage of emissions. In addition, the Directive 2018/410 further strengthened the ETS, increasing the annual cap reduction and introducing the Market Stability Reserve (MSR) to prevent excessive price fluctuations. (Directive 2003/87/EC, 2003).

2.1.2 Key Components and Operational Structure

At the core within EU ETS is its emission cap, one of the components of the cap-and-trade mechanism on which the ETS is based, as said before. Covered installations are limited with respect to the volume of greenhouse gases that they are allowed to emit. This total limit is something the cap determines. This cap is reduced annually as progressive emission reductions drive to ensure the alignment to the EU's climate targets. Emissions faced limits from the European Union. About 40% of the EU's total CO2 emissions falls under this cap (Grubb, 2012). Emission reductions drive the cap's reduction annually. By 2024, the cap was reduced via 90 million allowances. This reduction aligns alongside the EU's strengthened climate objectives. Therefore, the 2024 total cap is 1,386 million tonnes CO_2 equivalent ($MtCO_2e$). Because it is guided by such an increased linear reduction factor that is raised from 2.2% to 4.3% for 2024 until 2027, this trajectory will be 4.4% from 2028 onwards (European Commission, 2024). The EU ETS covers power generation as well as heat production. These sectors emit a large part of all of the emissions, and the EU ETS also includes energy-intensive industries such as steel, cement, chemicals, and so forth. The aviation sector is finally included, most specifically the intra-European flights were integrated within the system back in 2012. In addition, the system, as it was seen before in Chapter 1, can link up to other emission trading systems such as those located in Switzerland and potentially future global markets. (Sitarz et al., 2024). The operational structure for this system starts from allowances allocation, referred to as European Union Allowances (EUAs), each letting the holder emit one tonne of CO_2 equivalent. In the early phases (2005-2012), National Allocation Plans (NAPs) were the means through which allowances were allocated, mainly on a free basis. For some industries, windfall profits, in the power sector particularly, and over-allocation occurred because this allocation mechanism was just not optimal. Electricity prices were higher because energy companies passed allowance costs along to consumers without incentivized emissions reductions (Convery, 2009). To address these issues, the system has shifted toward auctioning part of the allocation because that made it the primary method. At this time, auctioning is now the default mechanism that is for the power sector. Some free allowances still go to energy-intensive industries and aviation, so this reduces carbon leakage risk, a concept explained earlier (Bekkhus & Van Hecke, 2008). The EU Auctioning Platform manages the auctioning process, as well as ensuring market transparency plus equal access to allowances. Funding that is provided for low-carbon technologies also funds energy transition projects all across the EU plus climate and energy, benefiting from revenues generated from these auctions (Sitarz et al., 2024). In regard to the trading mechanism and also market dynamics, the EU ETS has a flexible design, and this feature lets companies trade allowances at times when they need to do so. The EU Emission Trading System (EU ETS) works as a hybrid within an Over-the-Counter (OTC) and a regulated financial market. It is incorporating different characteristics from both of the systems. Oversight via the European Commission (EC) is the first similarity found between the EU ETS and regulated financial markets because it establishes compliance rules, administers the allowances cap, and ensures market stability. This structure mirrors what is the role of financial regulatory bodies. Stock and commodity exchanges are under the supervision of the U.S. Securities and Exchange

Commission (SEC) and the European Securities and Markets Authority (ESMA) (Jones, 2010). In addition, just as in commodity markets, centralized auctions determine the allowance prices, and this ensures transparency plus discovery of prices through platforms that include the European Energy Exchange (EEX) (Jones, 2010). Since Phase III (2013-2020), the EU ETS shifted from free allocation to auctioning for it aligned with market-based allocation models that financial systems use (Jones, 2010). Carbon emissions transform into tradable financial assets such as EU Allowance (EUA) futures, reflecting similarities to how securities and commodities trade in financial markets (Mansanet-Bataller & Pardo, 2008). Obviously, the EU ETS presents several features of OTC markets, with transaction flexibility as well as compliance mechanisms particularly. Most of the transactions occur by way of exchanges. In this manner companies can trade allowances bilaterally plus deals happen outside platforms centralized. This flexibility suits Over The Counter trading since deals get negotiated directly between counterparties not on a public exchange (Grubb et al., 2012). The EU ETS includes within it Certified Emission Reductions (CERs). These serve as carbon credits that companies may use for compliance. Similar to OTC derivatives, this mechanism enables firms to tailor risk management solutions for their specific needs (Grubb et al., 2012). The EU ETS is affected by price volatility, a challenge influenced by oversupply of allowances with external economic factors such as the 2008 financial crisis. Commodity markets show such volatility, price swings occur since supply and demand are imbalanced (Jones, 2010). Participants can hedge against price fluctuations or speculate on future carbon prices via trading carbon derivatives like EU allowance futures and options. This feature aligns the EU ETS within the derivatives markets that exist. In OTC trading, Mansanet-Bataller and Pardo covered this (2008). Participants can purchase Kyoto Credits in secondary markets because the Clean Development Mechanism (CDM) and the Joint Implementation (JI) mechanism link the Kyoto Protocol to the EU ETS. This cross-border market interaction reflects OTC commodity trading characteristics furthermore (Mansanet-Bataller & Pardo, 2008). For EU ETS companies, it is important to ensure emissions stay within the limits of their allocated allowances. At each compliance period's end, companies must surrender allowances equivalent to their emissions. Meaningful punishments await them if they do not act. For each excess tonne of CO_2 emitted, a fine of 100€ is a strong financial deterrent. Long-term accountability relies on the obligation to compensate for the shortfall in the next compliance period (Bekkhus & Van Hecke, 2008).

2.1.3 Monitoring, Reporting, and Verification (MRV)

MRV refers to a structured approach that enables organizations, regulators and policymakers to track emissions and ensure that climate commitments are being met. This process is fundamental for carbon markets, compliance schemes and voluntarily reporting initiatives (European Commission, 2024). The credibility of emission reduction commitments is based on a robust MRV which ensures that emission data are collected, reported and verified in a way that meets international standards allowing in this way the comparison of data among different jurisdiction also in different time (European Commission, 2024). In addition, it plays a key role in establishing baselines for emission reduction commitments tracking progress towards the net-zero goals and providing reliable data for climate finance mechanism. Moreover, accurate and standardized MRV systems are essential for governments, business and international organizations to ensure that emission reductions are achieved efficiently and equitably (European Commission, 2025).

The first part is monitoring, establishing a monitoring plan allows that methodologies are detailed for tracking emissions, ensuring accuracy and completeness. The monitoring plan should be approved by the relevant authority and also updated whenever there are significant operational changes that could affect emission. In some cases entities are requested to determine the most appropriate monitoring approach (European Commission, 2024-2025). This plan must cover:

- the identification of emission sources
- selection of appropriate monitoring methodologies
- procedures for data collection and management
- implementation of quality control measures to minimize uncertainties
- the inclusion of tiered approaches based on the complexity and scale of emissions sources (European Commission, 2024).

Moreover, the monitoring technologies must be in line with regulatory guidelines ensuring that emissions are measured accurately. In the EU ETS there two primary approaches to emission monitoring, direct management and calculation-based approach. Respectively, the first uses instruments to measure emissions at the source, such as continuous emission monitoring systems (CEMS). The second uses activity data and emission factors to estimate emissions, which is often used when direct measurement is not feasible (European Commission, 2024-2025). Despite this, in some cases alternative methodologies may be allowed if standards ones create disproportion in costs or are technically unfeasible. Additionally, new monitoring technologies such as remote sensing, satellite imaging and machine learning algorithms are being integrated into modern MRV systems to enhance accuracy (European Commission, 2025). For this purpose reliable data collection and management systems are fundamental. These systems should be able to:

- Store emissions data securely
- Track changes and updates to reported data
- Ensure transparency and accessibility for verification purposes
- Utilize blockchain or cloud-based systems for enhanced security and traceability (European Commission, 2024).

Following the monitoring part, there is the reporting one. Regulated entities under the EU ETS must submit annual reports based on verified data. The reports in this case should include:

- Activity data and calculation factors.
- Assumptions used in determining emissions.
- Measures taken to ensure data consistency and accuracy.
- Sector-specific reporting requirements based on industry guidelines (European Commission, 2024).

To facilitate the consistency across different entities and jurisdictions, the data must be reported in standardized format often aligned with United Nations Framework Convention on Climate Change (UNFCCC) guidelines (European Commission, 2024). Standardized reporting ensures the comparability among data, the reduction of administrative burdens and Integration with climate finance reporting and international carbon crediting mechanisms (European Commission, 2024). To maintain the compliance, the entities under this mechanism must respect deadlines settled by authorities and delay in submit the reports can result in penalties, including fines or revocation of operating licenses. In addition, some jurisdiction also impose progressive penalties, increasing the severity of enforcement actions for repeat offenders (European Commission, 2024, 2025). The last part of MRV is the mandatory verification. This verification must be a third-part verification, it ensures the credibility and accuracy of reported emissions data. The verification process involved different step. The first one is the risk assessment, which aims to identify the potential errors or misreporting in emissions data. The second step is the data validation, through these cross-checking reported figures against monitored data. The third is the check of compliance which ensures conformity with the regulatory requirements and the last step is the site inspection, where physical audits are conducting if necessary (European Commission, 2024-2025). As previously mentioned, the emerging of new technologies made monitoring techniques requires that monitoring techniques must become updated to improve their efficiency and accuracy reducing in this way uncertainties. Some developments in this field include the use of satellite monitoring for large-scale emission tracking, the use of artificial intelligence to detect anomalies in the data analysis, blockchain technology to ensure the integrity of the data and as last the expansion of remote senses capabilities for real-time monitoring. Ultimately, strengthening compliance mechanisms through stricter penalties, enhanced international cooperation, increased voluntary participation, and the establishment of transparency frameworks will ensure that MRV systems remain robust, credible, and effective in supporting global climate action (European Commission, 2025).

2.2. The Evolution of the EU ETS

The EU ETS emerged after the failure of the introduction of carbon tax in Europe. In 1992, the European Commission proposed a European wide carbon and energy tax aimed at reducing CO_2 emissions. However, the initiative faced strong resistance from member states, in particular they were concerned about the economic impact of carbon taxation on the energy-intensive industries. The Kyoto Protocol provided a crucial turning point by embracing market-based mechanisms, including emission trading system, as tool for achieving emissions reductions. Recognizing the potential benefits of cap and trade over carbon taxation the EU Commission shifted its focus toward establishing a European emission trading system (Convery, 2009). By the early 2000s, the UK and Denmark had introduced their emission trading schemes, raising concerns that Europe could end up with multiple, uncoordinated systems that would complicate cross-border business operations (Laing et al., 2013). The adoption of a unique system for all Europe, relying also on the features described in the previous paragraph, helped the unification of the regulation of emission, in this way regulatory inconsistencies are prevented and a level playing field is ensured for the regulated entities (Zaklan et al., 2021).

2.2.1 Phases of Implementation and Key Reforms

The evolution of EU ETS has evolved through a number of different phases that have refined its mechanism in a way to improve its effectiveness and efficiency (Directive 2003/87/EC, 2003). From 2005-2007, the first phase did act as a pilot phase, and the basis of the emission system was laid. The system accounted for half of the EU's total CO2 emission, also it covered approximately 11,500 industrial installations within high-emission sectors such as power generation and steel (European Commission, 2016). NAPs chiefly gave allowances without charge using grandfathering dependent on past emissions. The first chapter explains this system in Directive 2003/87/EC, 2003. Difficulties with respect to the allocation method led to more of an oversupply in this phase. Even with this issue here, the phase posed the MRV mechanism. It set the stage toward the future improvements (European Commission, 2016). The second phase, from 2008 to 2012, aligned itself with the Kyoto Protocol's first commitment period, as it allocated more strictly as well as integrated international carbon offset mechanisms. Even though the scope was still the same, the system in some Member States was expanded to include additional gases such as nitrous oxide (European Commission, 2016). Even though most allowances are located freely, stricter caps are targeted at emissions reducing by 6.5% compared to 2005 levels (Directive 2009/29/EC, 2009). Companies are able to now use offset credits coming from the Clean Development Mechanism (CDM) and Joint Implementation (JI) projects in order to meet a part of what their obligations are, and this links the EU ETS with global carbon markets (European Commission, 2015). The financial crisis that happened in 2008 impacted the system in an important way; the surplus derived from the decline of the industrial activities led to an excess of allowances. Due to this, a surplus existed that made carbon prices drop, also this highlights a need for structural mechanisms in order to prevent imbalances later (European Commission, 2016). The third phase, 2013-2020 brought structural reforms; the system was centralized during this phase; and the NAPs was eliminated in favor of a single EU-wide cap. Designed to decrease annually by 1.74%, the total emissions cap targeted a 21% emissions reduction by 2020 versus 2005 levels (European Commission, 2015). Allocation relied mainly on auctioning also the power sector had to buy 100% of allowances plus the industrial sector moved from 20% in 2013 to 70% by 2020 (Directive 2009/29/EC, 2009). However, free allocation was maintained for sectors at risk of carbon leakage, yet they based it now on performance benchmarks to reward efficiency and incentivize the one with lower emissions per output unit (European Commission, 2016). The system expanded into some new sectors. Aviation was indeed one of these sectors.

In this phase, the Commission innovated by introducing the Market Stability Reserve (MSR). For fighting price volatility and stopping allowances from amassing, the MSR was designed to adjust the allowance supply (European Commission, 2015). By phase 3's end, EU ETS sectors' emissions dropped nearly 35% compared to 2005 levels (European Commission, 2016). The last phase is actually the fourth phase (2021-2030), aligning the EU ETS with the European Green Deal plus reinforcing its role for achievement of climate neutrality by 2050. Emissions see an increased linear reduction factor each year from 1.74% to 2.2%, setting a trajectory reducing emission by 43% from 2005 levels by 2030 (Directive (EU) 2018/410, 2018). Until 2023, the MSR intake rate is doubled temporally to 24%, solving emission allowances effectively. This ensures a faster reduction in excess permits (European Commission, 2021). The “Fit for 55” package introduced several new reforms, including an extension of the EU ETS to the maritime sector and also the creation of the EU ETS 2 for the road transport and buildings sector. The EU ETS 2 along with the extension collectively account for nearly 40% of the EU’s greenhouse gas emissions (European Commission, 2021). This system in the next paragraph will be discussed. Still, this stage brought forth two aid systems. The Innovation Fund as well as the Modernization Fund were among them. It aimed toward financing energy transitions and low-carbon technologies in lower income Member States (Directive (EU) 2018/410, 2018). Phase 4 is still continuing, and the measures which were adopted are expected to ensure the EU meets its 2030 targets for decarbonization. Climate neutrality will be fully achieved through these measures by 2050 (Directive (EU) 2018/410, 2018).

2.2.2 Market Stability Reserve and Carbon Border Adjustment Mechanism

The evolution of the EU ETS during the years has led to the creation of two important systems that are fundamental for the implementation of the European emission trading system. These mechanisms are the Market Stability Reserve and the Carbon Border Adjustment Mechanism, they help the EU ETS system strengthening the carbon market's efficiency while mitigating the competitive disadvantages for European industries (Borghesi et al., 2023; Kardish et al., 2021).

The Carbon Border Adjustment Mechanism (CBAM) is a key policy initiative developed by the policymakers of European Union to address principally the problem of carbon leakage[1] while strengthening its climate commitments. It was introduced as a part of the European Green Deal, it is designed to complement the EU ETS by ensuring the same carbon price between the imported good and the ones imposed on the European producers. Indeed, extending the carbon cost to imported goods, the EU aims to prevent distortions in competition while incentivizing foreign producers to adopt lower-carbon production processes (Ambec, 2022). The CBAM is structured to function parallelly with the EU ETS, replacing in a gradual way the system of free allocation of allowances that was initially to protect domestic industries from competitiveness risks. Unlike the free allowances method which provide implicit subsidies to EU producers , the CBAM adheres more closely to the polluter-pays principle by ensuring that all producers, within the and outside the EU, face similar carbon pricing constraints (Meadows, Yordi, & Vis, 2023). The mechanism was phased in over a transition period, during which importers were required to report the integrated emissions of their products before the imposition of financial obligations. The industries characterized by high carbon intensity and significant trade exposure were the one initially covered, including e.g iron and steel, cement, aluminum, fertilizers, electricity, and hydrogen (Kardish et al., 2021). Importers are required to purchase the CBAM certificates whose price are determined by the prevailing EU ETS auction price. The cost of these certificates is calculated basing on direct emissions from production with measures for indirect emissions in ceratin sectors such as cement and fertilizer. Additionally, a deduction of carbon prices already paid in the country of production is possible when the firm provides evidence that these costs are verified by an

[1] Described and discussed in the first chapter

accredited third party (Ambec, 2022). The mechanism established, also, default values for emissions in cases where verifiable data from exporters is unavailable. In fact, these values are used to prevent circumvention by ensuring that importers cannot underreport the carbon intensity of their products (Meadows, Yordi, & Vis, 2023). From 2026, the CBAM charges will be incrementally introduced with an expected fully implementation by 2034. During this transition, the free allocation of allowances under the EU ETS will be phased out, ensuring that the CBAM fully replaces previous leakage protection measures. Due to that, the disruptive economic impacts are less likely, allowing industries sufficient time to adjust accordingly (Kardish et al., 2021). Despite its ambitious goals, the CBAM has generated considerable debate regarding its legal, economic and geopolitical implications. The compatibility with the World Trade Organization (WTO) rules is one of the primary concerns, some critics argue that this kind of mechanism could be discriminatory in the trade measure, potentially violating, in this way, the principle of non-discrimination and equal treatment (Meadows, Yordi, & Vis, 2023). To reduce these concerns, the European Union has stated that domestic as well as foreign producers will be treated in an equal manner by this mechanism. Adjustments for the Least Developed Countries (LDCs) or allocating revenues to support their climate transition has been proposed toward improving the equity and fairness (Kardish et al., 2021). The CBAM has real economic implications for all of EU industries. International trade relations are affected also in large ways. This expected mechanism will cause greater production costs for European industries that depend on imported raw materials including builders, chemical producers, and automotive manufacturers. Therefore, higher consumer prices within the EU, raising concerns about economic competitiveness (Ambec, 2022). Moreover, CBAM faced strong opposition from major trading partners such as China and Russia, that argue policy unfairly penalizes developing economies. These countries state that CBAM in effect imposed the unilateral carbon tax, rather than a climate policy measure aimed at global emission reductions (Kardish et al., 2021). In response to this criticism some countries, including Canada and Japan, have considered developing their own carbon border mechanisms which could led to harmonized global carbon pricing frameworks (Meadows, Yordi, & Vis, 2023). An additional challenge concerns the methodology for measuring embedded emission. In fact, CBAM requires that importers report their emissions at a specified product level, creates administrative burdens and potential verification difficulties. Despite the certification auditing system proposed by the EU, there are concerns about the manipulation of emission data from exporting countries outside the European union or resource filling a practice that involves the use of low carbon production for EU products while continuing high carbon production elsewhere (Kardish et al., 2021). For these reason, several policy recommendations have been proposed. Firstly, the EU will work closely to the WTO and ensure that CBAM aligns with international trade rules and does not trigger legal disputes (Ambec, 2022). Another strategy is to engage major trading partners to encourage the adoption of national carbon pricing mechanism, reducing the need for carbon adjustments as previously discussed in this paragraph. Indeed, the EU has provided exemption for the countries implementing comparable carbon pricing schemes, providing incentives for global carbon pricing convergence (Meadows, Yordi, & Vis, 2023). After this analysis of the CBAM, it's clear that it represents landmark policy initiative aimed at aligning international trade with climate objectives. While it faces important challenges, it could serve as a model for other jurisdiction and drives broader global efforts towards decarbonization and climate accountability.

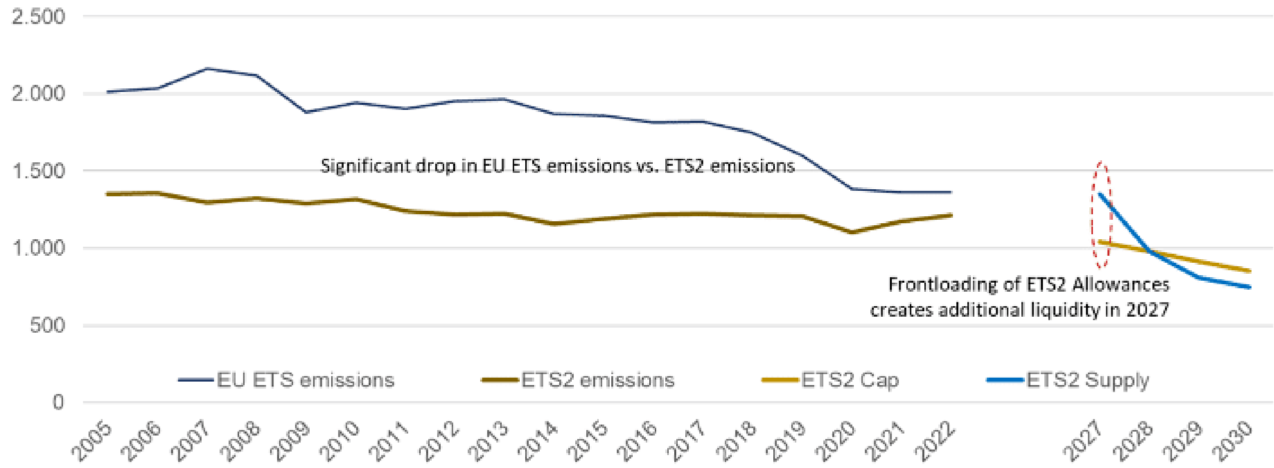
The Market Stability Reserve (MSR) is a fundamental reform of the European Union Emission Trading System, designed to address the persistent surplus of allowances that has undermined the efficiency of this system. The MSR was introduced in the 2019 and it was developed in response to structural problems that emerged due to the overallocation of emission allowances, the financial crisis of 2008 and the policy overlpas with renewable energy and energy efficiency measures (Borghesi et al., 2023). The MSR aims to stabilize the market conditions, preventing excess in price volatility and ensure that the EU ETS remains an effective tool for emission reduction (Mauer, Okullo, & Pahle, 2020). The core function of the MSR is to regulate automatically the volume of allowances available in the EU carbon market. The mechanism is triggered based on the total number of allowances in circulation (TNAC). If this measure exceeds 833 million allowances, the MSR withdraws 24% of the surplus allowances from the market annually and place them in its reserve. Conversely, if the TNAC falls below 400 million allowances, the MSR releases 100 million allowances back into circulation over a 12-month period (European Union, 2015). This process is used to correct imbalances and ensuring in this way the alignment of supply and demand, mitigating the risk of persistently low carbon prices, which could reduce the incentives for emission reduction (Borghesi et al., 2023). One of the key policy revision associated to this mechanism was the reform put in place in the 2018 which introduced an additional feature which is the cancellation of excess allowances. Prior to this, the allowances placed in the reserve of MSR were expected to eventually return to the market, meaning that the long-term cap on emission remained unchanged. However, this 2018 amendment established that allowances that exceed the volume auctioned in the previous year are permanently canceled from circulation (Perino & Willner, 2016). This transformation effectively made the EU ETS cap dynamic, linking the overall supply of allowance to market participants' banking behavior and expectations about future scarcity (Quemin & Trotignon, 2021). Despite its intended role in stabilizing the carbon market, the MSR, as the CBAM, has experienced extensive debate regarding its effectiveness and potential unintended consequences. One of the primary concerns, in this case, is the fact that the MSR may exacerbate fluctuations in carbon prices. Research indicates that the MSR can increase price volatility due to three main factors. The first, it shortens the allowance of banking period reducing the firms' ability to smooth compliance costs. The second, its activation is delayed, meaning that it responds with a lag to demand shocks. The third, its fixed outtake rate does not fully compensate for sudden increases in demand (Mauer, Okullo, & Pahle, 2020). Some studies suggest that this design flaw could lead to price surges, with projections indicating that the allowance price could increase by as much as 2400% by 2030 under certain market conditions (Borghesi et al., 2023). Another issue is the interaction between the MSR and overlapping climate policies, particularly national coal phaseouts and renewable energy subsidies. The waterbed effect was partially mitigated by the amendment in 2018, where reductions in emissions from one policy lead to an equivalent increase in emissions elsewhere due to the fixed cap on allowances (Perino, 2018). Some studies indicate that if a large-scale decarbonization policy is announced well in advance, market participants may reduce current emissions, which turn in lowers the TNAC and limits the future MSR cancellations. This could result in a perverse outcome where an ambitious climate policy today leads to higher emissions in the long term, undermining its intended impact (Perino et al., 2022). Then, the 2023 revision of the MSR, part of the broader "Fit for 55" legislative package, introduced additional adjustments to address some of these concerns. The reform extended the higher intake rate of 24% until 2030 rather than allowing it to decline to 12% after 2023, as originally planned. Moreover, it introduced a 100% marginal intake rate for TNAC levels between 833 and 1,096 million allowances, reducing threshold effects and improving the predictability of the mechanism (European Union, 2023). However, these measures do not address all outstanding issues, particularly the asymmetric nature of uncertainty for policymakers and market participants alike (Quemin & Pahle, 2023). From an economic perspective, the MSR has had a significant implication for investment in low-carbon technologies. It has increased the incentives for renewable energy deployment and industrial decarbonization projects. However, the unpredictability of allowance supply and price levels has complicated long-term investment planning, particularly for energy-intensive industries that rely on stable carbon pricing for capital allocation decisions (Borghesi et al., 2023). Future evolution of the MSR is a key area of research and policy debate concerns. Some scholars advocate for replacing the MSR's volume-based triggers with a price-based mechanism, which could provide greater predictability and reduce price volatility (Perino & Willner, 2017). Others suggest integrating the MSR with other ETS reforms, such as sectoral expansions and linking with international carbon markets, to enhance market stability while maintaining stringent emissions reduction targets (Borghesi et al., 2023).

2.3 The Introduction of EU ETS2

After examining the functioning and the features of the EU Emission Trading System, we now turn our attention to its newly introduced counterpart, EU ETS 2, which represents a significant expansion of the European carbon pricing framework. From the establishment of the EU ETS in 2005, it became evident that the sectors included in the system, power sector and energy intensive industries, have diminished their GHG emissions and that additional measures were necessary for the sectors not originally included in the system. Among these sectors, emerged the building and road transport ones, which have remained the largest sources of emission in the EU. In fact, these two sectors alone contribute to approximately 40% of the total energy-related CO2 emissions (Rickels et al., 2023). To address this regulatory gap, the EU ETS 2 has been designed as a separate cap-and-trade system that will become operational in the 2027, providing market-based incentives for emission reductions in these sectors while ensuring a cost-effective transition toward climate neutrality (Günther et al., 2024).

Figure 1. Historical and Projected Emissions under EU ETS and ETS2, Including ETS2 Cap and Supply

Historical emissions under EU ETS and projected emissions under EU ETS2, with cap and supply projections up to 2030. The graph illustrates the emission gap between the two systems and highlights the planned frontloading of ETS2 allowances in 2027 to support market liquidity.



Source: Florence School of Regulation (2024)

The sectors not covered by the EU ETS has been governed traditionally by the Effort Sharing Regulation (ESR). This regulation includes buildings, transports agriculture and small industries. Under it each of the EU Member State is assigned bunding national reduction targets, which they are required to meet through domestic policy measures. However, progress in reducing emissions in these sectors has been inconsistent because of the different national policies and the lack of a common carbon price (Pahle et al., 2024). The EU ETS 2 was introduced as "Fit for 55" package as explained before it is a set of policies from the Green Deal, aiming to achieve E's goal of reducing emission by at least 55% by 2030 compared to the 1990 levels (European Commission, 2024). The incorporation of the road transport and building into the carbon pricing system is a measure of the EU to create a more consistent policy framework that aligns with its long-term commitment for climate neutrality objectives. The system complements existing regulations while encouraging investment in cleaner technologies and energy efficiency measures. After saying that is important to specify that the EU ETS 2 will not replace the ESR but rather function as an additional instrument to support emission reduction in these sectors (Held et al., 2022). The EU ETS adopts an upstream approach, placing the compliance obligation on fuel suppliers rather than to end consumers. So, this implies that companies supplying fossil fuels for the sectors of road transports and building heating must purchase emission allowances to cover emission associated with their products (European Commission, 2024). The purpose lie in the internalization of the cost of carbon into fuel prices, thereby incentivizing consumers and businesses to shift toward lower-carbon alternatives (Görlach et al., 2022). Given the political sensitivity of fuel price, the EU ETS 2 incorporates a sort of Market Stability Reserve which include the multiple safeguards against excessive price increases. At the beginning an intervention of 45€ per tonne of CO2 has been set, with an allowances release mechanism that prevents extreme price surges in the early years of the system (Rickels et al., 2023). However, projections suggest that actual market prices could fluctuate between €71 and €261 per ton by 2030, depending on the strength of complementary energy efficiency policies and market conditions (Günther et al., 2024). In addition, a gradual reduction in emission allowances through a linear reduction factor will be featured by EU ETS 2 (Pahle et al., 2024). This declining cap is expected to accelerate the transition away from fossil fuel dependence in the covered sectors (Held et al., 2022). The implementation of this new system is raising important question about the coexistence with national carbon pricing policies, particularly in countries that have already established a domestic mechanism. For example, Germany's Brennstoffemissionshandelsgesetz (BEHG), a national emissions trading system for fuels, was introduced in 2021 and already imposes a carbon price on transport and heating fuels (Nysten, 2024). This has led to debates over wheter EU ETS2 will harmonize with or override existing national pricing frameworks. Legal analyses indicate that Member States will retain the ability to implement additional carbon pricing instruments, provided that do not interfere with the functioning of the EU ETS 2 (Görlach et al., 2022). This means that countries can maintain higher national carbon prices, allowing them to exceed the EU-mandated carbon price floor if they choose to adopt more ambitious climate policies, However, adjustment or phasing out of certain national schemes may be possible after the introduction of the EU ETS 2 depending on their alignment with the new system. The EU ETS is expected to deliver significant efficiency gains, although not to the extent of a fully integrated emission trading system covering all sectors. However, different studies utilizing computable general equilibrium model suggest that the introduction of this new system will generate approximately one quarter of the efficiency gains that a unified carbon pricing system could achieve (Rickels et al., 2023). In fact, while this represents a meaningful improvement it also highlights the potential benefit deriving from an eventual integration of EU ETS and EU ETS 2to form a single EU-wide carbon market (Günther et al., 2024). The distributional effects of EU ETS2 are expected to vary across the different Member States. Indeed, countries in the Southern and Easter Europe are likely to benefit from selling allowances to higher-income countries where abatement cost are lower (Held et al., 2022). However, there are still concerns about the social impact of the higher carbon prices on low-income households, particularly in regions where alternative heating and transport options are less accessible (Pahle et al., 2024). To address this potential issue the European Union has introduced a Social Climate Fund which will use a portion of the revenues generated from the allowances auctions to support vulnerable households and businesses affected by the incrementation of fuel costs (European Commission, 2024). This mechanism is designed to mitigate the risk of energy poverty while ensuring that low-income populations are not disproportionately burdened by the transition to a low-carbon economy (Nysten, 2024).

2.3.1 Differences Between EU ETS and EU ETS2

EU ETS and EU ETS2 are two pillars of the climate-neutral economy strategy in the European Union. While both systems share foundational cap-and trade principle the differences between that are numerous and substantial. One of the key differences concerns, obviously the sectoral coverage. regulates emissions from large industrial installations, power generation, and, since 2012, intra-EU aviation and, more recently, maritime transport (European Commission, 2003). These are centralized, high-emitting sources that are relatively easy to monitor. In contrast, the EU ETS2 is designed to extend the carbon price to the so-called diffuse sector, in specific road transport and buildings, as well as some industrial activities. These sectors were before governed by the Effort Sharing regulation (ESR) which set national targets, integrating them into a market-based system marks a major policy shift (Held et al., 2022). Looking also at the regulation, it is also fundamentally different. ETS 1 is a downstream system, where monitoring and compliance responsibilities fall directly on the entities that emit GHG: power plants, steel mills, refineries (European Commission, 2003). ETS 2 by contrast is upstream: it places obligations on fuel suppliers, who must acquire and surrender emissions allowances based on the carbon content of the fuels they release for consumption. This disconnected the regulated entities, that are the suppliers, from the end emitters, that are the consumers. Avoiding the need to monitor millions of households and vehicle owners this system allows to increase the administrative efficiency (European Commission, 2024). As a result of these features the monitoring and reporting systems differs among EU ETS and EU ETS2. In the EU ETS, the emissions are measured directly by the plants, often the CEMS[2] are used or process-based calculations (European Commission, 2023). ETS2 requires monitoring of the type and volume of fuels placed on the market, with special attention to the scope factor that defines what portion of the fuel is used in the covered sectors as opposed to exempt uses (European Commission, 2024). Proper *scope factor* [3] calculations are essential to avoid double-counting emissions between EU ETS and EU ETS2. Another difference can be found in the allocation mechanism. EU ETS, as explained in the recent paragraphs, employs a mix of free allocation, mainly to protect energy-intensive, trade-exposed sectors, and auctioning. Although free allocation is being gradually reduced, it still plays a significant role in the allocation method. Unlikely, the EU ETS2 as anticipated will rely only on auctioning, no free allowances will be provided. So, all the suppliers must purchase the necessary permits, reinforcing the carbon price signal. However, this choice raised concerned about social equity and potential financial burden on low-income consumers (Held et al., 2022). Also, to stabilize the possible issues deriving from fluctuations on carbon price, the EU ETS2 has intrinsically a price control mechanism. Indeed, a price ceiling of €45/tCO2 will apply during the initial years. Then if market prices exceed this level for two consecutive months, up to 40 million additional allowances will be released (Günther et al., 2024). ETS2 also includes mechanisms for addressing rapid price increases and may eventually introduce a price floor to stabilize investments in low-carbon solutions (Held et al., 2022). The EU ETS, unlikely, has tried to bring stabilization with the Market Stability reserve, addressing the problem of surplus of allowances and limiting price volatility (Borghesi et al., 2023). Finally, the two systems have different roles, EU ETS is a mature, central tool of the European Union climate policy targeting industrial and energy-related emissions and sending long-term investment signals. EU ETS2 is intended as a complementary measure which works alongside different regulations that are sector-specific (e.g., the Energy Efficiency Directive, CO2 standards for vehicles) and the Effort Sharing Regulation (ESR). Indeed, ESR has a sort of

[2] continuous emissions monitoring systems

[3] The *scope factor* is the proportion of fuels released for consumption by a regulated entity that are actually used in sectors covered by the EU ETS2 (such as buildings and road transport), as opposed to exempt sectors (e.g., ETS1 installations, agriculture, or military uses). It is a key element in calculating reportable emissions, ensuring accurate attribution and avoiding double counting between ETS1 and ETS2 (European Commission, 2024).

function as warning indicator because if the prices rise sharply this may could be a signal of insufficient progresses in related policies and prompt corrective action (Held et al., 2022).

2.3.2 Expansion to New Sectors and Policy Objectives

The expansion of carbon pricing to new sectors under the EU ETS2 reflects not only an increase in coverage of sectors but also an evolution in the role of emission trading as a policy tool. The inclusion of road transport and building, previously governed by the Effort Sharing Regulation (ESR), represents a shift towards the harmonization of the climate objectives across the EU with a common price signal (Günther et al., 2024). This expansion addresses the need to unlock emissions reductions in sectors where technological and behavioural changes are highly decentralized and where abatement costs are more heterogeneous compared to industry or power generation (OECD, 2020). Buildings and transport sectors together represent over half of the European Union's final energy consumption, yet until now, they lacked a coherent EU-wide pricing mechanism aligned with climate targets. From the sectors previously mentioned are projected to reach, in quantitative terms, approximately 800 millions of tons of CO2 by 2030 under the strong European Parliament scenario[4] The rationale to target this sectors is both environmental and economic. Firstly, the marginal abatement costs in buildings and transport are potentially comparable to or even lower than those in EU ETS sectors, especially when energy efficiency policies are effectively implemented (Günther et al., 2024). Secondly, the gap among private and social costs can be reduced with the introduction of a carbon price, internalizing externalities such as local air pollution particularly in the case of transport (OECD, 2020). For example, the emission factor used for duels in transport is around 74 tCO2 per terajoule, while for residential heating is approximately 56 tCO2 per terajoule (Held et al., 2022). The sector covered are extremely important for the households and policy scenarios suggest that without enough effort prices could rise significantly up to €261/tCO_2 by 2030 (Günther et al., 2024). This because households and small businesses as end users of heating and mobility fuels, will face increased costs unless revenues are recycled effectively (Flues & Van Dender, 2017).

[4] The "Strong EP scenario" refers to a policy projection aligned with the European Parliament's high climate ambition, assuming enhanced energy efficiency, accelerated deployment of renewables, and stricter complementary measures across ETS2-covered sectors (Günther et al., 2024).

On average the total spend for low-income households in the EU is 1.1% of their total consumption on ETS2-related energy goods while high-income households spend approximately 0.4% (Held et al., 2022). In addition, there are country-level differences, for example, average per capita emissions in ETS2 sectors are 1,534 kg CO_2/year in France, 1,727 kg CO_2/year in Italy, and 2,525 kg CO_2/year in Ireland (Held et al., 2022). The EU ETS2 embodies a shift in the logic of climate policy creating a price-based signals that influence a wide basket of choices from energy use in homes to transport mode selection. The approach that this system promotes is a decentralized one, where millions of market participants respond to common economic signals rather than detailed administrative mandates (OECD, 2020). The inclusion of the sectors of road transports and buildings under the EU ETS2 will lead to broaden the carbon pricing base, in this way market reduction will be reduced and also long-term signals for the development of low-carbon solutions such as electric vehicles, heat pumps, and energy-efficient building materials will be sent (Günther et al., 2024). This transition also aligns carbon pricing with broader ESG (Environmental, Social, and Governance) investment trends that prioritize climate-aligned portfolios (OECD, 2020). Significantly, the implementation of this systems can act as a catalyst for the integration of national policies into a more coherent and less fragmented EU framework. . In many cases, price-based instruments have the advantage of fostering innovation while remaining neutral about the specific technologies or behaviours that achieve emissions reductions (OECD, 2020). This avoids the knowledge problem faced by regulators and leverages the informational advantages of market participants.

2.4 Legal and Policy Framework of EU ETS2

The legal framework under which the EU Emission Trading System 2 was built is embedded within the evolving and multilayered climate governance architecture of the European Union. As an extension of the already work EU ETS, this new system inherits the regulatory framework that was grounded in the primary EU legislation, formed by particularly directives adopted by the European Parliament and Council, and it was shaped by delegated act implementing regulations and guidance issued by the European Commission (European Parliament and Council, 2003; European Commission, 2024). The system is further influenced by the principles and objectives of the Green Deal and international commitments that is laid in the Paris Agreement, which collectively form the normative foundation for the EU's climate neutrality goal by 2050 (European Commission, 2021; UNFCCC, 2015). The fit for 55 package which amends Directive 2003/87/EC and restructures the Union's internal market for carbon allowances to involve the some of the missing sectors which increment pullution and where under the ESR (Görlach et al., 2022). The regulatory expansion requires careful coordination among Union-level law and national implementation and international legal obligations, particularly because this system works alongside other instruments such as domestic carbon pricing in several Member States (Nysten, 2024). The design of the system is also asked to be compliant with integrity, transparency and enforceability while addressing potential legal challenges such as double regulation or distortion of competition (European Commission, 2024).

2.4.1 European Green Deal and Legislative Framework

The legal foundation of the EU ETS2 lies in a set of interlinked legal acts adopted at European Union Level which amend and expand the existing emissions trading framework established by Directive 2003/87/EC. ETS2 was introduced through Directive (EU) 2023/959, specifically amending Directive 2003/87/EC for new provisions to include the buildings and road transport sectors, thereby creating a parallel but separate cap-and-trade system within the EU ETS framework (European Parliament and Council, 2023). To enact the EU's pledges under Kyoto Protocol, Directive 2003/87/EC was first adopted. It has acted as a playground for that primary legal act establishing the emission trading system in the EU because Article 192 of the Treaty on the Functioning of the European Union (TFEU) empowers the Union so it can act in the field of environmental protection (European Parliament and Council, 2003). Coverage, scope and implementation timeline of the EU ETS2 are introduced by the 2023 amendment introducing a new chapter in the Directive. This includes also the establishment of a separate emission cap, the full auctioning of allowances and the application of the system to fuel suppliers (European Parliament and Council, 2023). To make operative these new legal provisions, the commission also adopted a set of secondary legislation. The first to be mentioned is the Regulation (EU) 2018/2066 (Monitoring and Reporting Regulation – MRR), amended to apply to ETS2 sectors with upstream-specific rules (European Commission, 2024). The second one is the Regulation (EU) 2018/2067 (Accreditation and Verification Regulation – AVR), which sets standards for third-party verification of emissions reports by regulated fuel suppliers (European Commission, 2025). At least, the are additional implementation of delegated acts which defines technical aspects such as scope factors, emission factors, reporting format and also registry requirements. Importantly, ETS2 also incorporates key principles of EU environmental law. The *polluters pays* principle (Article 191(2) TFEU), is operationalized through mandatory auctioning of allowances. In addition, the principle of subsidiarity ensuring the maintaining of discretion among Member States over how to allocate ETS2 revenues (e.g. via the Social Climate Fund), provided they comply with EU-level conditions (European Commission, 2024). The legal architercture is embedded in the Fit for 55 legislative package from the Green Deal. The coordinated reforms inside it are the The Effort Sharing Regulation (Regulation (EU) 2018/842), which continues to apply to buildings and transport, even after the implementation of ETS2, creating a dual governance framework. Then, the Energy Taxation Directive, which is being revised in parallel to align fossil fuel taxation with carbon pricing mechanisms and the Climate Action Regulation, which ensures consistency with the EU's commitment under the Paris Agreement (UNFCCC, 2015). While the ETS2 is harmonized at EU level, its enforcement relies on National Implementation measure. In summary, the EU ETS2 is grounded in a multi-layered legal framework composed by Primary Legislation, composed by the Directive 2003/87/EC as amended by Directive (EU) 2023/959, a Secondary legislation formed by Monitoring and Verification Regulations (EU 2018/2066 and 2018/2067) and delegated acts, Treaty basis, composed by Articles 191–193 and Article 192 TFEU and as least Integration with broader EU climate law consists in the Fit for 55 package, ESR, and Green Deal strategies.

2.4.2 Compliance Requirements and Enforcement

To support its regulatory integrity the EU ETS2 is underpinned by a robust compliance and enforcement regime. This regime is centered on the principles of transparency and accuracy, and also accountability. The Monitoring and Reporting Regulation (MRR), based on Regulation (EU) 2018/2066, is adapted specifically for the upstream architecture over which the EU ETS2 is built (European Commission, 2024). The regulated entities, in this context, which are the fuel distributors, are required to calculate and report the volume and carbon content of fuels released. They are required to submit the Monitoring Plan to the National Competent Authority in their Member State prior to the start of reporting obligations. This Plan must describe how emissions are calculated, including the use of default emission factors, standard densities, and calorific values, depending on fuel type (European Commission, 2024). The plan becomes legally binding once approved and must be updated in case of significant changes in methodology or operations (European Commission, 2024). The compliance cycle under the EU ETS2 is following an annual schedule, in this case fuel suppliers must monitor emissions throughout the calendar year, prepare and submit an Annual Emission Report (AER) by the end of March of the following year. In addition they must ensure third-party verification by an accredited verifier and surrender the corresponding number of allowances by May 31 (European Commission, 2024). Verification becomes mandatory starting from the 2025 reporting year and must follow the detailed procedures outlined in the AVR, including materiality thresholds, risk analysis, and sampling methodologies (European Commission, 2025). However, harmonized templates has published for MP's and AERs along with tools to assess uncertainty levels, evaluate the proportionality of costs and standardize the treatment of scope exclusions (European Commission, 2024). The application of the *scope factor* is essential to prevent double counting of emissions (European Commission, 2024). The National Competent authorities are responsible for the approval of monitoring plans, reviewing submitted reports, conducting on-site inspections, and issuing corrective decisions when data inconsistencies are found (European Commission, 2024). They are required, also, to cross-check data with the Union Registry, which tracks allowance ownership and compliance status in real time (European Commission, 2024). The penalties derived from the missing compliance are the same of the EU ETS. These penalties, as explained in chapter 2.1.2, consists in a fine of €100 per excess tonne of CO_2 emitted, and a mandatory make-up of the shortfall in the subsequent year (Held et al., 2022). Additionally, EU ETS2 allows for simplified MRV obligations for small-volume fuel suppliers or low-risk installations, provided this does not compromise the overall accuracy and transparency of the system (European Commission, 2024). Electronic reporting systems are also accommodated in a way that allows to reduce the administrative burden while ensuring full traceability and auditability (European Commission, 2024). So, the compliance and the enforcement regime of EU ETS2 reflects a high level of legal precision and operational harmonisation. It leverages existing MRV infrastructure from EU ETS but introduces specific innovations that are tailored to the characteristics of the transport and building sectors (European Commission, 2024; European Commission, 2025).

Chapter 3:
Methodology and Empirical Analysis

The foundation of this thesis bases its argument upon two main hypotheses, which estimate the expected effects of implementing the EU ETS2 on the Carbon Price as well as on the Emission reduction it will lead to. Chapters 1 and 2 serve to develop the theoretical and policy background. This background discusses the design principles of cap-and-trade systems as well as the evolution of emission trading systems as key pillars concerning European Union climate policy, grounding these hypotheses.

On Carbon Prices EU ETS2's impact is the first hypothesis's focus. This premise underlies that with the introduction of this new parallel emissions trading system, which will cover Buildings and Transportation sectors under a full auctions regime, this will modify the expectations and the sentiment to influence the European Union Allowances price dynamics. Testing this hypothesis matters since the carbon price, like the previous chapters explain, is a key signal of the system. Indeed, it guides the investment decisions as it determines the abatement costs. It influences, furthermore, the distributional effects of climate policy. Because perception of the EU ETS2 is fundamental, it should be reflected in the behaviour of market participants and their forward-looking approach if it is perceived as credible and binding. The first hypothesis that was tested therefore evaluates whether or not a structural policy change generates a measurable price response in the carbon market a key fact that is needed to understand the power and informational efficiency of the ETS framework. Then, the second hypothesis tests and investigates how the new emission trading system could reduce emissions in theory. The emissions cap-and-trade mechanism works toward a set quantity. However, its environmental effectiveness specifically in newly regulated sectors depends on just how energy demand responds plus technology uptake reacts to carbon price signals. Because of two principal reasons, empirically testing this relationship is fundamental and also important. The first is that it provides for an ex-ante valuation and assessment of the policy's likely environmental outcome. Evidence of the ex-post type is not yet available at this point. It also enables quantifying how rising EUA prices marginally abate emissions, so it guides related policy design. Particularly helpful is estimating social cost-benefit ratios and evaluating EU climate strategy's overall efficiency. These hypotheses together capture emission trading systems' dual logic. Hypothesis 1 reflects the role that it has as a market instrument affecting prices. Because it drives real-world reductions, Hypothesis

2 tests its performance as an environmental policy. The tests combined both fill a current literature gap since EU ETS2 implications remain underexplored and contribute in a timely way to the carbon pricing policy debate in the European Union.

3.1. Methodology and Data Collection

To empirically test the two hypotheses presented above, this paragraph and the following ones use a structured methodological approach, and this approach merges the econometric estimation and the forward-looking scenario analysis. Two separate models, yet methodologically consistent, articulate the empirical framework. The first model examines what determines carbon price variation, also the second simulates how carbon pricing could potentially impact upon the emissions. The first model can be estimated from harmonized time series data that is covering 2008 up to 2024. Since that captures the forward-looking effects of the EU ETS2, projections are extended to 2030. Even though all the data for all variables were only available up to 2024 for the first, the second one is estimated with data until the 2023 due unavailability of data for 2024. Each model was developed using multiple linear regression techniques selecting independent variables based on their theoretical relevance to carbon price formation or emissions behaviour. Including sector-specific energy use, climatic conditions, and also macroeconomic indicators controls for the external influence. The forecasts are constructed under three distinct scenarios which include the Business As Usual baseline, a policy scenario that incorporates the effects of the EU ETS2 implementation through changes to the EUA price with related adjustments within a low emission scenario as well as an ETS2 scenario within a high emissions scenario. This scenario-based structure seems particularly appropriate because EU ETS2 will be implemented starting from 2027 so ex-post analysis is currently impossible. Models all share territorial scope, also frequency. To maintain consistency the same methodological principles guide data treatment. Each hypothesis has an explanation that is detailed in the next two sections.

3.1.1 Hypothesis 1: The Impact of EU ETS2 on Carbon Prices

This section presents the methodology design and data processing to empirically test the first research hypothesis, which investigates if the second phase implementation of the EU Emissions Trading System (EU ETS2) will likely affect European market carbon prices. The hypothesis expects that the expansion of the scope of the system to buildings and

road transport could alter market dynamics. This expectation stems from its affecting of allowances demand and overall emissions regulation coverage.
A strong linear regression model (rlm) was estimated for examination of this relationship. EUA prices' natural logarithm served as the dependent variable. The model does incorporate key macroeconomic and energy-related explanatory variables that are climatic. Electricity demand (GWh), natural gas price, EU27 GDP (in millions of euros), with monthly average temperature enter as linear terms, while the regression specification includes the Brent crude oil price as a second-degree polynomial to account for potential non-linearities. The model includes also an indicator of market tightness acting as a proxy for market stringency, defined as the electricity demand ratio to available emission allowances (in million tonnes).
The estimated regression model is the following:

$$Log(CarbonPrice)_t = \alpha + \beta_1 \cdot OilPrice_t + \beta_2 \cdot {OilPrice_t}^2 + \beta_3 \cdot EnergyDemand_t + \beta_4 \cdot NaturalGasPrice_t + \beta_5 \cdot GDP_t + \beta_6 \cdot TempAvg_t + \beta_7 \cdot \left(\frac{Demand_t}{Allowances_t}\right) + \varepsilon_t$$

Where:

- $Log(CarbonPrice)_t$ is the natural logarithm of the European Union Allowances price at time t
- $NaturalGasPrice_t$ is the price of natural gas at time t
- $OilPrice_t$ is the price of Brent crude oil at time t
- $EnergyDemand_t$ is the electricity demand within the EU at time t
- GDP_t is the Gross Domestic Product of the EU27 at time t
- $TempAvg_t$ is the average temperature at time t
- $\frac{Demand_t}{Allowances_t}$ ratio between energy demand and total allowances, it is a proxy for the supply-demand pressure
- ε_t is the stochastic error term at time t

The model was estimated on monthly data spanning from January 2008 to December 2024, using a harmonised dataset including macroeconomic indicators, energy market data, and climate variables. Historical values for emission allowances were introduced on a monthly basis by interpolating annual data between 2008 and 2024.

The estimation was carried out using the rlm() function from the MASS package, allowing for a robust estimation framework that mitigates the influence of outliers and relaxes the assumptions of homoscedasticity and normality. Diagnostic tests conducted prior to model selection revealed significant heteroskedasticity and non-normality of residuals in an OLS specification, justifying the use of a robust method.

Once the model was estimated, it was used to produce out-of-sample forecasts for the period 2025–2030, under three distinct macro-policy scenarios:

- Business-as-Usual (BAU): Assumes a continuation of historical trends without the implementation of EU ETS2. Energy demand and fuel prices follow extrapolated historical averages, and allowance volumes remain stable at their 2020–2024 average.

- ETS2 – Low Emissions Scenario: Models the introduction of EU ETS2 starting in January 2027. Energy demand is reduced by 10% post-implementation, allowance volumes remain unchanged, and a regulatory price cap of €45/tCO_2 is applied from 2027 to 2029 to simulate transitional safeguards. GDP projections are based on a conservative compound annual growth rate.

- ETS2 – High Emissions Scenario: Also assumes the implementation of EU ETS2 in 2027, but under a less effective policy environment. Energy demand increases by 5% and allowances are reduced by 10% from 2027 onwards, while the same price ceiling of €45 is enforced through 2029.

It is important to clarify that no policy dummy variable for EU ETS2 is included in the regression equation itself, as the model is estimated only on pre-policy historical data. The policy effects are introduced ex post during the forecasting phase by modifying the values of selected covariates in line with scenario-specific assumptions starting in 2027. This approach maintains the statistical integrity of the model while allowing for counterfactual scenario simulations consistent with expected policy trajectories.

Predicted EUA prices were obtained in log scale and back-transformed to their original level using the smearing estimate method (Duan, 1983). This corrects for the retransformation bias due to the non-linear nature of the exponential function. The smearing factor, calculated as the mean of the exponentiated residuals, was applied consistently across all forecasted values.

This modelling structure enables a comprehensive simulation of EUA price paths across contrasting regulatory and macroeconomic environments. It supports an anticipatory analysis of the potential impacts of EU ETS2 on carbon markets, offering valuable insight for regulators, investors, and policymakers interested in the interaction between carbon pricing, policy expansion, and market stability.

Data collection and frequency harmonisation

A significant methodological consideration involved the alignment of data frequency across all the variables used. Since EUA prices and most of energy indicators are available at monthly intervals, the entire dataset was harmonised to a monthly frequency. However, some macroeconomic indicators, such as Gross Domestic Product (GDP), were originally provided at quarterly frequency by Eurostat. Due to this reason a linear interpolation was used to estimate monthly values ensuring consistent temporal resolution throughout markets and allowance pricing. The data collection effort focused on ensuring both temporal coverage and source reliability. The time range includes 17 years of monthly observations and includes data from both institutional and well-established secondary sources. All variables were selected based on their theoretical relevance and empirical support in the literature on carbon markets and allowances pricing. The following section details all the variables included in the model.

Carbon Price

The dependent variable is the price of European Union Allowances (EUAs) measured on a monthly average basis. Data were sourced from *SandecoCO2*, an independent data platform that consolidates information from the European Energy Exchange (EEX) and other official carbon market publications. EUA prices represent the market's expectation of the marginal cost of compliance and therefore it serves as an effective benchmark for the evaluation of policy-driven shocks such as the implementation of the EU ETS2.

Natural Gas Price

Natural gas prices are a critical driver of carbon price because of their direct influence on the fuel-switching behaviour of electricity producers. When natural gas price becomes cheaper than coal, it reduces the emission intensity and so the affects EUA demand. Data for natural gas prices were obtained from the FRED database, specifically the series provided by the International Monetary Fund (IMF) under the code PNGASEUUSDM. Prices were originally reported in USD per million British thermal units (MMBtu) and converted into euros using monthly exchange rates. Natural gas is especially relevant for this analysis given its transitional role in the European energy mix and its frequent use as the marginal technology in power generation

Oil Price

Oil prices were proxied by Brent Crude Oil futures, were retrieved from Yahoo Finance under the ticker BZ=F. As did with the Natural Gas Price, Oil prices were converted from USD to EUR to maintain the currency consistency. Industrial production, transportation fuel costs, broader market sentiment are all affected by Oil Price which in this way impact indirectly on the EUA prices. Though not directly tied to the EU ETS, which primarily covers power and industry, oil price changes often serve as a leading indicator of energy cost pressures across the economy.

EU Energy Demand

The European Union energy demand variable captures gross inland energy consumption and is used as proxy for overall energy usage in the economy. It was retrieved from Ember Climate**,** using the dataset *europe_monthly_full_release_long_format***.** This dataset contains monthly generation, emissions and demand data for 85 geographies representing more than 90% of global power demand. Data is collected from multi-country datasets (EIA, Eurostat, Energy Institute) as well as national sources (e.g., China data from the National Bureau of Statistics). The selected indicator reflects energy "available to the internal market" (code: AIM) and is reported in gigawatt-hours (GWh). The data taken in consideration are only the ones concerning the European Union. This variable is essential in capturing the scale of energy activity that contributes to the demand for emissions allowances, especially in an environment where cap-and-trade dynamics depend on total energy throughput.

Gross Domestic Product

The variable GDP was sourced from Eurostat, specifically under the code *namq_10_gdp,* the indicator used was [B1GQ] Gross Domestic Product at market prices. It represents the aggregate economic output of the EU27 and it is seasonally and calendar adjusted. Since GDP data are published quarterly, a linear interpolation was used to obtain monthly estimates. GDP acts as a high-level indicator of economic activity and is expected to be positively correlated with both energy consumption and emissions generation.

Temperature

Monthly average temperature data were obtained from the Copernicus Climate Data Store, using ERA5-Land hourly dataset. For this test data were aggregated across the geographic coordinates of the European Union encompassing all the 27 States. Hourly temperature values were averaged to produce monthly observations. Temperature serve as proxy for seasonal energy demand, this because colder months represent increased heating demand, while hotter months increase cooling needs. Both affect emissions indirectly via power and building sector energy use.

Allowances

The data on verified emissions and allocated allowances used in this analysis were retrieved from the EU ETS Data Viewer provided by the European Environment Agency (EEA). This platform offers structured and aggregated access to the European Union Transaction Log (EUTL), which is managed by the European Commission. The EUTL records and verifies all transactions under the EU Emissions Trading System.

Forecasting Approach

A unique aspect of this analysis involves using scenarios to forecast the possible path of EUA prices between 2025 and 2030. Based on a log-linear regression model, the projection methodology was estimated through monthly EUA price data from January 2008 until December 2024. The dependent variable is the natural logarithm that is of the EUA price. Quadratic Brent crude oil prices and energy demand (in GWh) and natural gas prices are all within the set of predictors, as are average monthly temperatures and real

GDP for EU27 (in million euros) and a ratio between energy demand and allowances as a proxy for market stringency. In forecasting, three distinct scenarios were developed. These scenarios included a Baseline scenario, an ETS2 with low emissions scenario, also an ETS2 High Emissions scenario. The Baseline scenario extrapolates those trends in exogenous variables such as those of fossil fuel prices and GDP with historical averages as well as time-series regressions, as it assumes that there is no structural policy change after 2024. The allowances are fixed at the average level from 2020–2024. The ETS2 scenario reflects what is expected for the EU ETS2 implementation from 2027 onwards as it incorporates a simulated policy shock involving a 10% reduction to energy demand and no change to allowances issuance after 2027. Toward an expected outcome, stronger decarbonization incentives with improved energy efficiency lead. The regulatory extension for buildings and road transport causes this reflection of the outcome. A price cap of 45 €/ton is imposed from 2027 until 2029. That mirrors provisional protections. Finally, the High Emissions scenario models just a specific situation. Policies get implemented in a weaker or delayed way. A 10% allowance volume reduction reflects on tightening supply given high carbon intensity, assuming a 5% energy demand increase from 2027. Predicted values were at first generated in log scale for all the scenarios, as they were subsequently changed to the original monetary scale through use of the smearing estimate method (Duan, 1983). This correction is one which ensures that consistent forecast comparability is there, as it compensates for the bias that was introduced by the non-linear transformation. For all simulated paths, the mean of the exponentiated residuals was applied uniformly as the smearing factor. For improved interpretability, forecasts were generated monthly then aggregated into quarterly and annual averages. Evaluating comprehensively how EU ETS2 will likely impact carbon price trajectories uses scenario comparisons. Specifically, the low emissions scenario represents how regulatory expansion could change market expectations going forward, while the High Emissions case depicts policy inaction's potential costs hypothetically. This strengthens a firmer grasp of carbon market dynamics later on since projections triangulate under policy assumptions, and aids discussion on how well carbon pricing tools work in the EU context.

<u>Estimation Results and Diagnostics</u>

The regression model was estimated via strong linear regression (rlm) to accommodate potential outliers also relax strict Ordinary Least Squares (OLS) estimation assumptions, particularly regarding homoscedasticity with residual normality. Strong regression use suits the context of economic time series data such as EUA prices, which behave non-linearly and shock structurally. This method ensures more reliable parameter estimates via reducing anomalous observations' influence also addressing classical regression assumptions' violations.

A set of diagnostic tests was conducted in order to validate the specification and to assess its robustness. The Breusch-Pagan test showed heteroskedasticity in the residuals. The test did produce a result that was highly important (p-value < 0.001) because it did indicate that the variance of the error terms is not constant across observations. This finding suggests strong regression techniques are appropriate for the situation. Since they do not rely on the homoscedasticity assumption, they are of a better suit for this empirical context.

In addition, an evaluation of multicollinearity was conducted among all of the explanatory variables, this evaluation is made using the Variance Inflation Factor (VIF) in order to do it. Energy demand plus the energy demand-to-allowances ratio had elevated values after the VIF analysis. These two variables are showing values that are particularly high. These results do suggest that things correlate to a certain degree, which, although it does not create a problem for estimating consistently, may affect just how one interprets coefficients individually. Despite theoretical relevance as well as contribution to model fit, no variable was excluded since all VIF values remained within tolerable bounds for strong regression.

Important criteria for information helped model fit assessment. −167.94 was the log-likelihood value for the estimated model. AIC along with BIC were correspondingly 353.89 and 383.75, respectively. These numbers affirm the descriptive capability is adequate. They do also show how the model complexity is in balance. To examine the residual distribution further, a Shapiro-Wilk test was performed which yielded a p-value of 0.0107, suggesting slight departures from normality. Nonetheless, residual plots such as histograms and also Q-Q plots did not reveal deviations that were substantial, and this confirmed the general adequacy of the model.

The model was estimated with the natural logarithm of the EUA price as the dependent variable to stabilize variance and reduce the impact of outliers. As regressors included monthly average temperatures, natural gas prices, energy demand in GWh, market tightness proxy ratio of energy demand to allowances issued, and GDP for the EU27 plus a second-order polynomial of Brent crude oil prices.

Due to it having been built upon this very estimated model, the forecasting procedure was implemented for simulation of EUA prices over this 2025–2030 period. Scenario Base represents the baseline scenario it mirrors past macroeconomic plus energy market trends. This scenario has no regulatory changes after 2024. Projections existed for future values of the explanatory variables. They were derived below as follows:

- Brent oil and natural gas prices were assumed constant at their historical average values over the 2019–2024 period;
- Energy demand was projected via linear extrapolation of the historical trend;
- Monthly temperatures were calculated as averages by calendar month, preserving seasonal climatological patterns;
- GDP was forecasted using a Compound Annual Growth Rate (CAGR) derived from the observed growth between 2008 and 2024;

Allowances were set around the average level seen during 2020–2024.

Then, two alternative scenarios about simulating the policy impact of the EU ETS2 system, expected to start in 2027, were constructed. The low-emissions ETS2 scenario saw energy demand decrease by 10% after 2027 as allowances remained constant. The price is capped at 45 €/ton from 2027 to 2029. Possible transitional regulatory safeguards were reflected by this. This scenario acts as an effective regulatory framework. Strong behavioural as well as structural responses are part of it. On the other hand, the high-emissions ETS2 scenario assumes a weaker policy implementation since energy demand grows by 5% after 2027 as well as the volume of allowances sees a 10% reduction, which is a delayed or a suboptimal policy response within high carbon intensity.

The estimated regression model was applied to all of the three scenarios. This was done for forecasting EUA prices over the simulation period. The predictions initially were generated in a logarithmic form. Duan (1983) did develop the smearing estimate method, and it was used for the purpose of back-transforming the predictions to their original monetary scale. This technique corrects in regard to the non-linear bias if exponentiating and yields unbiased price estimates that are. Across each of the three scenarios, the smearing factor was applied consistently, calculated as the average of residuals from the exponentiated strong regression.

Resulting forecasts are three separate time series showing possible EUA price paths with Business-as-Usual, ETS2 low-emissions, and ETS2 high-emissions scenarios. These projections offer support to any comparative analysis of the expected policy effectiveness plus a subsequent assessment for regulatory impacts with the analytical foundation. The simulated trends, especially under the ETS2 configurations, contribute to a deeper comprehension of how carbon pricing mechanisms may evolve as they respond to future market and policy conditions.

3.1.2 Hypothesis 2: The Impact of EU ETS2 on Emissions Reduction

This section outlines both the empirical strategy and data sources used to test Hypothesis 2, which evaluates whether implementing the second phase of the European Union Emissions Trading System (EU ETS2) will measurably reduce CO_2 emissions in the sectors newly covered by the scheme, namely buildings and road transport. Whereas Hypothesis 1 focused on ETS2's effects on carbon pricing, this second model investigates the system's environmental effectiveness because it quantifies carbon prices' impact on sector-specific emissions. In the Buildings and Transports sectors, the econometric approach relies separately upon a multiple linear regression model in which the dependent variable remains annual CO_2-equivalent emissions ($MtCO_2$ eq). Independent variables are sectoral proxies, macroeconomic drivers such as GDP, climatic indicators like HDD and CDD, and forecasted EUA prices. Vehicle Kilometers, Building Energy Use, Electricity Prices, and Energy Taxation are these sectoral proxies for energy demand. The data extends from 2008 to 2023 as it is reshaped into a long format in order for us to estimate sector-specific results by using a pooled regression structure with sector dummies. For assessing that relationship between EUA prices and emissions, the variable EUA_Price is included as a continuous regressor. The model can then measure how emission levels respond to carbon price changes. It assumes a linear and negative marginal effect consistent with the theoretical framework for cap-and-trade systems. In order to address potential heteroskedasticity, the regression model was estimated through use of strong standard errors via the lm_robust function in R. The estimated model is used to project future emissions from 2025 to 2030 under two scenarios defined ex ante:

- *ETS2 Low*, assuming lower energy demand and stable allowance supply;
- *ETS2 High*, assuming higher energy demand and tighter allowance constraints.

These assumptions were used in a previous model to simulate EUA price trajectories for each scenario. The resulting prices were then used as explanatory variables in the current emissions model. Therefore, while the scenarios were constructed based on expected emissions and market balance, the emissions projections derived here are conditional on the simulated carbon prices, which reflect different levels of stringency in the ETS2 framework.

The regression equation is the following:

$$Emissions_{t,s} = \alpha + \beta_1 \cdot EUA\,price_t + \beta_2 \cdot HDD_t + \beta_3 . CDD_t + \beta_4 \cdot VKM_t + \beta_5 \cdot \text{BuildingEnergyUse}_t + \beta_6 \cdot ElectrictyPrice_t + \beta_7 \cdot EnergyTaxes_t + \beta_8 \cdot GDP_t + \gamma \cdot \text{Sector}_s + \varepsilon_{t,s}$$

Where:

- $Emissions_{t,s}$ is equal to the Annual CO_2-equivalent emissions ($MtCO_2$ eq) for sector s (Buildings or Transports) at time t
- $EUA\,price_t$ is the Price of EU Allowances (€/tCO_2) at time t. It reflects the marginal cost of carbon emissions
- HDD_t are the Heating Degree Days, a measure of heating needs due to cold temperatures at time t
- CDD_t are the Cooling Degree Days, a measure of cooling needs due to warm temperatures at time t
- VKM_t is the sum of freight and passenger vehicle kilometers (VKM), representing transport demand at time t
- $\text{BuildingEnergyUse}_t$ is the Final energy consumption in the buildings sector, expressed in GWh at time t
- $ElectrictyPrice_t$ is the Average electricity price for households in the EU27 (€/kWh) at time t
- $EnergyTaxes_t$ are the Energy-related tax revenue as a percentage of GDP at time t, reflecting the fiscal burden on energy consumption

- GDP_t is the Gross Domestic Product of the EU27 at time t, capturing the overall economic activity
- Sector $_s$ is the Dummy variable indicating the sector (Buildings = 1, Transports = 0)
- $\varepsilon_{t,s}$ is the stochastic error term capturing unobserved influences on emissions for sector s in year t

In this specification, emissions are regressed on a set of economic, climatic, and energy-related variables. The variable `Sector` captures fixed effects across the Buildings and Transports sectors, while robust standard errors account for heteroskedasticity. The estimated coefficient on EUA_Price quantifies the marginal impact of carbon price variation on emissions.

Data collection and frequency harmonisation

EUA price

The price of emission allowances in the European Union represents the cost of emitting one tonne of CO2 and is the central policy signal in the Emission Trading System. EUA prices were not observed but obtained through forecasted values derived from the model estimated in Hypothesis 1 under a low-emissions scenario. This continuous variable allows for the quantification of the marginal response of emissions to changes in carbon pricing.

$MtCO_2$_Buildings

This variable isolates CO_2 emissions specifically from the residential and tertiary building sectors. These emissions are primarily linked to space heating, cooling, water heating, and cooking. The data were collected from the Eurostat greenhouse gas inventory and are expressed in $MtCO_2$ eq. Given that buildings are a key focus of the EU ETS2 expansion, this sectoral breakdown allows for a more precise assessment of how the policy may influence emissions through changes in energy efficiency, heating technologies, and electrification.

$MtCO_2$_Transports

This variable captures the CO_2 emissions originating from road transport, excluding aviation and maritime. The data, available from Eurostat and EEA emissions databases, are expressed in $MtCO_2$ eq. The inclusion of this variable enables the model to isolate the policy's potential impact on transport emissions, particularly as ETS2 introduces carbon pricing mechanisms in a previously unregulated sector. This allows for an evaluation of the behavioural and technological responses to carbon costs in personal and freight mobility.

Heating Degree Days (HDD)

Heating Degree Days are calculated as the sum of the differences above the daily average outdoor temperature and a base temperature (18°C), for all days when the average is below the base. HDD values were sourced from the Copernicus ERA-5 Land dataset and aggregated over the EU27 region. They control for weather induced variability in heating related emissions.

Cooling Degree Days (CDD)

Cooling Degree Days reflect the energy demand for space cooling and are calculated as the sum of the differences above a cooling threshold of 22°C. As HDD, CDD data are derived from ERA-5 Land dataset, CDD controls for increased electricity use during hotter months.

Vehicle Kilometres (VKM)

Vehicle Kilometres (VKM) measure total road transport activity and were constructed by summing both freight and passenger components. Freight VKM were directly obtained from Eurostat, road_go_ta_vm. Passenger data, originally in passenger-kilometres, were converted into vehicle-kilometres by dividing by an average occupancy rate of 1.5 passengers per vehicle (European Environment Agency (EEA), TERM Report 2016 – Indicator, TERM 31).

$$Vehicle\ Km\ Passengers = \frac{Passengers\ Km}{1.5}$$

The two components were then aggregated to produce a harmonized indicator of total road activity.

Building Energy Use

Building energy use represents the final energy consumption in the residential and commercial sectors. Data were retrieved from the Eurostat dataset nrg_cb_em, originally available in Terajoules (TJ) for the period 2010–2022 were converted to Gigawatt-hours (GWh) using the factor 1 TJ = 0.27778 GWh. Missing years (2008, 2009, and 2023) were estimated by carrying forward or backward the closest value.

Electricity Price (Households)

Electricity prices for households were taken from Eurostat's biannual reports and averaged across consumption bands. Expressed in €/kWh, this variable captures changes in energy cost and potential demand responses.

Energy Taxes as % of GDP

This variable reflects the share of energy-related tax revenues in GDP. Data were retrieved from the European Commission's *Taxation Trends in the European Union*. Missing values for 2021–2023 were linearly interpolated. It helps isolate the effect of ETS2 from other fiscal measures.

Gross Domestic Product

GDP, expressed in million euros (chain-linked volumes, base 2020), was retrieved from Eurostat and aggregated annually. It controls for macroeconomic activity and its correlation with energy consumption and emissions.

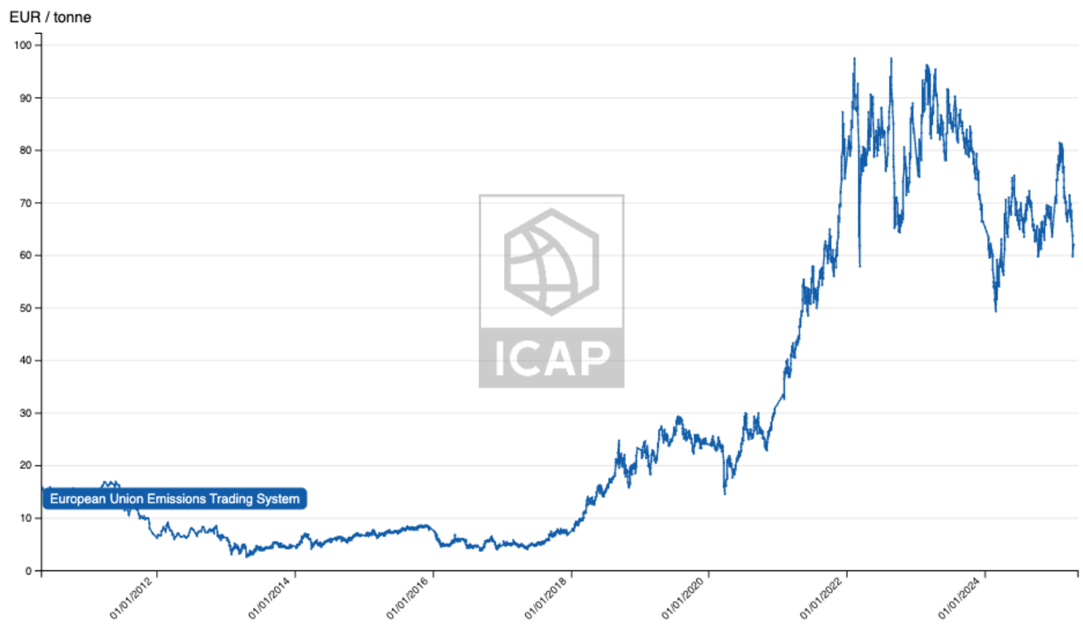
Also, in this model some diagnostic tests of the model were run. As with the model used for H1, diagnostic tests were also run for the H2 model to assess its validity, as previously explained during the methodological discussion of H1. The tests were the following: *Breusch-Pagan test, Shapiro-Wilk test, Variance Inflation Factor (VIF)*, *Log-likelihood, Akaike Information Criterion (AIC), Bayesian Information Criterion (BIC).* In addition to the standard diagnostic tests, a correlation matrix was computed to explore the linear relationships among the independent variables. Specifically, the matrix included HDD, CDD, VKM, building energy use (GWh), average electricity prices in the EU27, energy taxes as a percentage of GDP, and GDP itself. The resulting correlation coefficients were visualized using a heatmap generated with the ggcorrplot package in R, allowing for a clear graphical representation of pairwise correlations. This step was instrumental in identifying potential issues of multicollinearity before estimating the model.

3.2. Analysis of Carbon Price Trends

In order to ease comprehension of the dynamics of carbon prices that are analysed in this thesis, to retrace the evolution of emission allowance prices is necessary throughout the various phases of the EU Emissions Trading System (EU ETS). Since its launch in 2005, the EU ETS has gone through multiple phases, each characterized by specific regulatory adjustments with market responses greatly influencing price dynamics, reflecting the progressive development as well as maturation of the EU emission trading system plus its ability to internalize carbon costs within the EU economy. During some of the first phases (2005–2007), EUA prices were, in fact, volatile, and the prices collapsed ultimately since the allowances were overallocated, which then created a surplus and weakened the market's credibility (European Commission, 2016). Allowances could not be banked into the following period at this phase's end, so this made companies offload surplus permits leading to a sharp price drop (Schmalensee & Stavins, 2017). In phase II, the 2008 financial crisis did reduce the industrial production a bit. This generated less pollution and worsened the excess of permits. The market became complex, and EUA prices declined since the Clean Development Mechanism (CDM) and Joint Implementation (JI) brought in international credits (European Commission, 2016; Directive 2009/29/EC, 2009). An important structural reform during phase III (2013-2020) was marked. Market balance began to be restored via increased auctioning use (especially for the power sector) and replacing National Allocation Plans (NAPs) with a single EU-wide cap. Nonetheless, allowance oversupply persisted. Due to this oversupply, the Market Stability Reserve (MSR) was introduced in 2019 to regulate surplus volumes automatically (European Commission, 2015). Grubb (2012) noted that the cap was designed in order to decline annually. This design contributed in fact to a more then stable price path. EUA prices increased consistently within the fourth phase (2021-2030). The prices were driven by stronger climate targets, a more aggressive linear reduction factor (raised to 4.3% per year from 2024), and market anticipation of tighter future supply (European Commission, 2024). The announcement of that “Fit for 55” legislative package, which even included the creation of EU ETS2, further reinforced such bullish sentiment within the carbon market. Notably, EUA prices rose up from around €25/tCO_2 back in early 2020 up to over €90/tCO_2 by very late 2023, and this indicated that policy ambition and also market expectations aligned.

Figure 2. Historical EUA Spot Prices in the EU Emissions Trading System (2012–2024)

The figure illustrates the evolution of EUA spot prices over more than a decade, highlighting periods of stagnation, market reform impacts, and the post-2020 price surge linked to stronger EU climate targets and the introduction of the Market Stability Reserve.



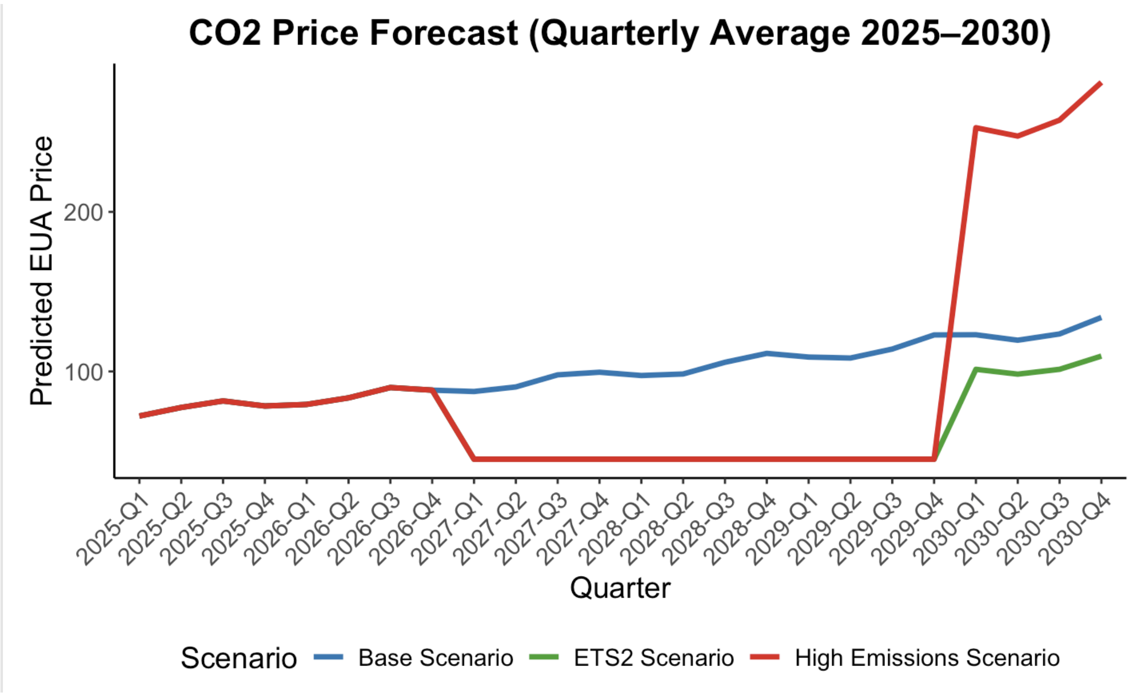
Source: ICAP, EUA price data (2024)

The pricing dynamics of the EU carbon market are influenced through a complex set of drivers, which do combine market fundamentals, macroeconomic conditions as well as regulatory signals. In its core, the EUA price reflects when supply and demand are imbalanced, but elements mediate this relationship. With regard to the supply side, the cap for the year determines the allowance quantity, which is reduced each year via the linear reduction factor (Directive 2003/87/EC, 2003). The shift to auctioning has reinforced market discipline and also the MSR has emerged as a key stabiliser which withdraws allowances from the market when the Total Number of Allowances in Circulation (TNAC) exceeds a certain threshold (European Union, 2015). The 2018 amendment has added into it a permanent scarcity element for the system. This amendment allows for the cancellation of excess allowances, and also it strengthens long-term price signals (Perino & Willner, 2016). Demand greatly depends on energy consumption, fuel switching dynamics, plus macroeconomic activity. For example, natural gas prices have influence on power producer decisions between gas or coal. This decision affects emission intensity thus the EUA demand. When gas turns relatively cheaper, then emissions will fall, and that reduces all EUA demand potentially to lower some prices (Singh et al., 2024). Temperature variations influence seasonal energy use for heating as well as cooling. Volume of emissions is affected as a result of each of these variations. For response to policy announcements, investor and market sentiment is another key factor. EU ETS2 was formally proposed and also will soon be implemented therefore it has introduced expectations for a more thorough carbon pricing regime. Price expectations are being shaped by EU ETS2's planned coverage of road transport and building sectors, with its full reliance on auctioning (European Commission, 2024; Günther et al., 2024), though its implementation is expected in 2027. As stressed in Chapter 3.1.1, EUA prices incorporate anticipated regulatory stringency well before the actual implementation of the market due to forward-looking behaviour. In the carbon market, financial actors are present to an increased degree. They treat EUAs as speculative or hedging instruments that contributes to price volatility and shifts in liquidity. As the system matures more, it converges even with financial markets by way of derivatives such as EUA futures, and that makes the system sensitive to broader financial cycles as well as risk appetite (Mansanet-Bataller & Pardo, 2008). Market psychology, policy design, macroeconomic fundamentals, and energy market dynamics shape EUA prices.

Understanding how EUA (European Union Allowance) prices might evolve given upcoming regulatory changes requires assessing the market and policy implications of the expanded EU ETS framework. In this context, a quantitative forecasting model was developed to simulate EUA price dynamics under three scenarios: a Business-as-Usual (BAU) trajectory, a High Emissions scenario, as well as an ETS2 low-emissions scenario. Harmonised monthly data from January 2008 until December 2024 informs this forecasting exercise. It also includes explanatory variables that are recognised in literature as key drivers in the formation of carbon prices. These include Brent crude oil prices specified with some second-degree polynomial, natural gas prices, and real GDP within the EU27. The average of monthly temperature, electricity consumption as of an energy demand proxy, and also the ratio between energy demand and allowance supply are included here. Energy market fundamentals, macroeconomic cycles, and seasonal effects are captured by this model structure like prior empirical work (e.g., Chevallier, 2012; Bunn & Fezzi, 2007). We estimated by strong linear regression (rlm) because it is more resilient to outliers. Linear regression (rlm) resists heteroskedasticity better than

Ordinary Least Squares (OLS). The logarithm for EUA prices is used as the dependent variable because that stabilizes variance. Also, that reduces the impact from extreme observations. A policy dummy was not needed since the EU ETS2 was inactive throughout the estimation period. Therefore, the regression model did not happen to include one. Instead, it was because the values of independent selected variables were altered as of 2027 that the effects from ETS2 were introduced by definition ex post during that forecasting phase. The projections were then back-transformed onto the original scale using Duan's smearing estimate method (1983), plus this ensured unbiased then statistically consistent price predictions across all scenarios. Since policy does not intervene after 2024 as historical trends continue, the Business-as-Usual (BAU) scenario is the baseline. EUA prices do exhibit a more gradual and steady increase under this trajectory. It mirrors increasing energy needs plus the gradual constraining of emission limits. Alternatively, the ETS2 scenario models when the new system is introduced under a controlled low-emissions pathway. This situation includes a €45 per tonne price cap during 2027–2029 for possible market transitions plus stable allowance volumes and a 10% energy demand cut starting in 2027. EUA prices do temporarily plateau, and then they recover starting in 2030 when the cap expires, and market fundamentals return. The High Emissions scenario captures the opposite trajectory within its simulation of a less effective or delayed policy context. After 2027, energy demand is assumed to rise by 5% and allowance volumes are reduced by 10%, so market pressure increases. EUA prices stay artificially low during this period however because the application of the same €45 price cap until 2029. Once when the cap is lifted up, then prices surge up sharply, peaking above €250 per tonne by the end of 2030. This highlights how sustained carbon-intensive activity affects things powerfully but belatedly under constrained allowance supply. Figure 3 shows these different price paths below. The blue line representing the BAU scenario has a smooth upward trend. The green line captures the ETS2 scenario, which shows initial price suppression coupled with moderate recovery follows thereafter. The High Emissions scenario, depicted via the red line, shows an initial collapse due to the cap, then a dramatic spike after constraint removal. These trends do stress how regulatory design does interact so as to shape price dynamics within carbon markets. Enforcement timing as well as allowance management do have an impact.

Figure 3. Forecasted EUA Prices under Base, ETS2, and High Emissions Scenarios



Source: elaboration based on model 1 simulation, see Appendix A

The EUA price projections derived from the forecasting model offer a firm basis for evaluation of the wider effects of EU climate policy as well as carbon market activity from 2025 to 2030. The simulation does highlight market expectations' responses to different trajectories in regulatory implementation and macroeconomic conditions by a comparison of three distinct scenarios that are: Base, ETS2, and High Emissions.

This model reveals how divergent policy frameworks along with economic environments may produce non-linear and counterintuitive outcomes, unlike deterministic projections that assume uniform growth in carbon prices. In particular, these results do challenge the assumption that is common that in the event emissions trading expands its scope, EUA prices will automatically rise. The model stresses that price trajectories, along with jointly, are determined via regulatory design and market structure. Evolving fundamentals such as energy demand, GDP growth, with fossil fuel price dynamics also determine them.

The Base Scenario contains no newly introduced regulatory measures after 2024. It can represent a business-as-usual counterfactual for it. EUA prices do gradually increase over a period under such a trajectory, driven mainly by the emissions cap that is tightening, the Market Stability Reserve's (MSR) operation, and energy demand increases that are moderate. The model does assume that key variables such as GDP and energy consumption do continue along historical trends, and allowance volumes do remain fixed at their recent average.

The ETS2 Scenario is reflective of the introduction into use of the EU ETS2. After 2027, it shall function with a managed low-emissions path. Allowances remain constant here; a temporary price cap of €45 per tonne is introduced for the 2027–2029 period, and a 10% reduction in energy demand is imposed from the implementation year onward. These assumptions mirror the effects of electrification, of policy-induced behavioural shifts, and of complementary decarbonisation initiatives. EUA prices do moderate temporarily as the levels stabilize to below the BAU trajectory, and prices will increase again moderately once the price cap lifts in 2030.

Conversely, the High Emissions Scenario assumes ETS2 gets formally implemented in 2027 but has a policy environment showing weaker enforcement plus transformation delays. In this case energy demand increases 5% post-implementation while fossil fuel prices stay relatively low and allowance volumes drop 10%. Prices initially flatten because of the cap, then sharply correct upward starting in 2030. This spike does reflect all of the pent-up demand for allowances. Enduring carbon intensity comes with a limited supply.

The same strong regression model, from which all three scenarios derive, is estimated using monthly data from 2008 to 2024. EU ETS2 was not operational throughout the estimation period so no policy dummy was included. Policy impact, instead, is introduced through modifying key explanatory variables' values from 2027 during the simulation phase. This approach ensures internal consistency and avoids endogeneity while allowing projections that look forward sensitively toward policy.

The smearing estimate method that Duan described in 1983 was applied so the log-transformed predictions could be translated back. This yielded levels for EUA prices with euro denomination. The smearing factor is calculated as from the model the mean of exponentiated residuals. This factor is applied in a uniform way across all of the scenarios for ensuring comparability and statistical coherence.

Alterations to policy assumptions along with economic factors do greatly affect eventual EUA prices as those projections will show. Under the ETS2 Scenario, prices stay subdued between 2027 and 2029 because there is a price cap, reflecting the regulatory intent for reduced distributional shocks during the early implementation phase. The removal of the cap allows for prices to gradually rise up. However, improved systemic efficiency and also broader cost-sharing across the sectors keep prices lower than those in the Base scenario. An expanded ETS may help prices stabilize as environmental ambition continues, this outcome suggests, if designed well.

Risks are depicted within the High Emissions Scenario. Policy implementation may be delayed or ineffective for us, which is dangerous. Prices initially are suppressed by the same regulatory cap. They increase greatly after 2029 to over €250 per tonne by 2030. Mounting emissions do drive this spike, coupled with an increase in the demand for allowances. Substitution of technology has a bit of lag. Because the ETS2 as well as High Emissions scenarios diverge, they underscore that carbon pricing outcomes are sensitive to climate policy's stringency beside credibility and how fast decarbonisation occurs.

Key social factors arise from EU ETS2's introduction. Households and small businesses face direct carbon costs when road transport and buildings are included, despite the ETS2 scenario having more moderate prices than alternatives. Effects that are disproportionate may occur for lower-income groups spending more income on energy. The Social Climate Fund, established under the Fit-for-55 package, plays a role that is critical for this reason as a mechanism in order to preserve political and institutional support for the ETS2 framework and as a financial cushion. Modelled EUA trajectories imply a lot for financial market expectations and investment decisions past equity concerns. The ETS2 scenario's relative stability offers a predictable carbon price signal that is important for institutional investors, energy utilities, as well as financial intermediaries involved in that long-term planning. Stable price expectations provide support for climate-aligned investment strategies, and those include strategies that are governed by the EU Green Bond Standard and ESG-aligned capital portfolios. Furthermore, carbon pricing improves upon the financial viability of decarbonisation projects in previously uncovered sectors and strengthens the link between private capital flows and public climate goals.

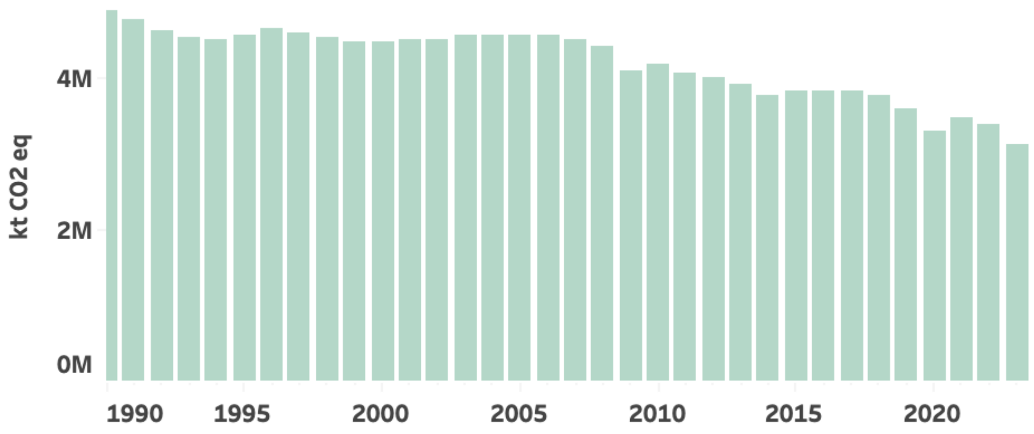
EUA prices vary among scenarios much before 2027, indicating policy credibility. The anticipation of the market is also of importance. Investors as well as market participants react to signals along with legislative timelines. They react to clear political commitments instead of formal implementation then. Thus, consistent regulatory communication, transparent market rules, and effective governance are necessary. Ambiguity in design or enforcement may increase system volatility, spark planned behaviour or diminish public trust.

The model suggests, in sum, ETS2's expansion of EU ETS does not cause price inflation inevitably. The policy could instead give rise to a more efficient market functioning, a greater price stability, and a stronger alignment between environmental integrity and economic equity if a decarbonisation framework that is credible and inclusive is used. The essence exists in the consistency, drive, and civic equity of the execution. The important point does not lie in the system's scope alone.

3.3. Analysis of Emissions Reduction

Prior to when introducing these simulated trajectories for the emissions, contextualising of that relevance for sectors newly introduced under the EU ETS2 is necessary in this scenario. Understanding all of the European Union's total emissions is also useful for purposes beyond just sector-specific items. Figure 4 from 1990 up to 2022 provides for us a historical overview of the total greenhouse gas emissions of the EU27. Emissions have declined persistently and non-linearly during the past thirty years, particularly after 2008. This corresponds with structural economic changes, as well as the European Commission (2024) implemented increasingly stringent environmental policies. In the graph, the data do show emission reductions did markedly accelerate after the adoption of the 2020 Climate and Energy Package and an additional drop during the Covid-19 pandemic in 2020, followed then by a temporary rebound (EEA, 2024). This long-term perspective confirms the structural nature to the EU’s decarbonisation efforts but also highlights the difficulties present in achieving steep reductions without new regulatory instruments support (Görlach et al., 2022). Since 1990 entities have emitted over 30% less but abatement still does not pace quickly enough to reach the 2030–2050 climate neutrality goals (European Commission, 2024). The introduction of the EU ETS2 seems to be a mechanism that is complementary. It seems a key impetus for quickening too (Günther et al., 2024). The European Union ETS2, by targeting unregulated sectors like transport as well as buildings, seeks to close a major policy gap remaining in the EU’s climate architecture (Held et al., 2022).

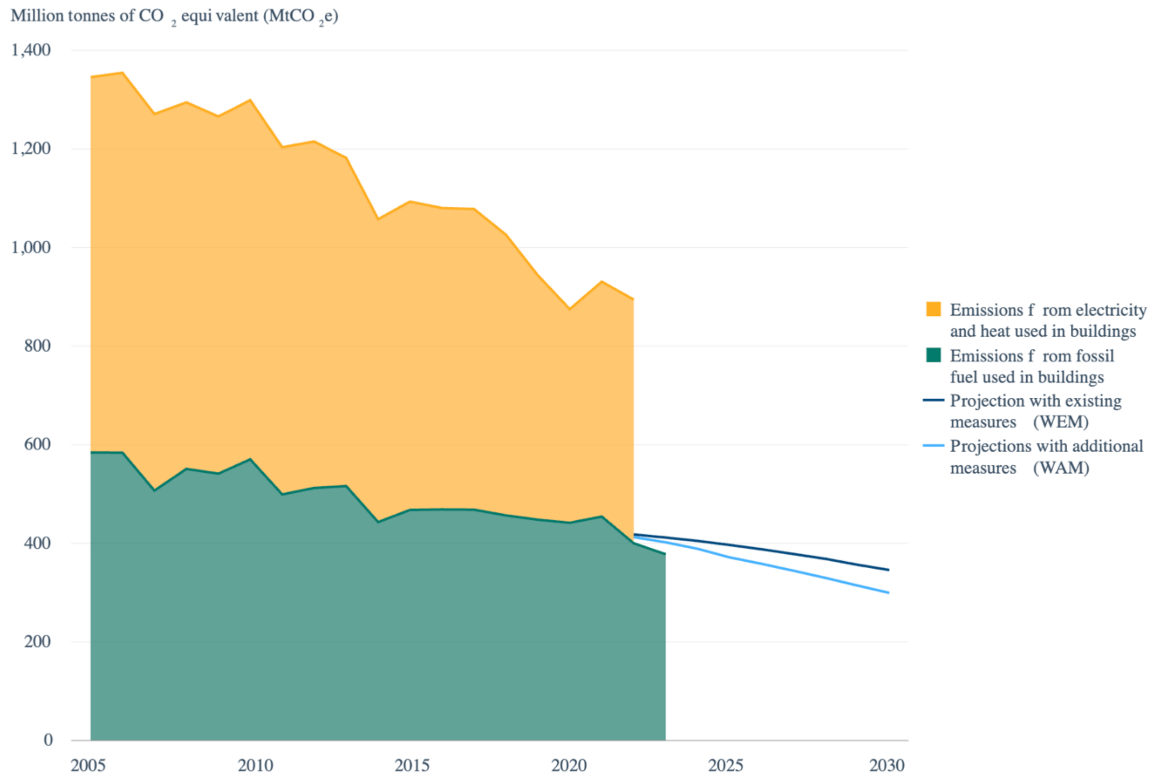
Figure 4. Emissions of GHG in the European Union



Source: EEA greenhouse gases — data viewer

As stated earlier, the potential emission reduction from the EU ETS2 needs further context. It is important to consider the emission trajectories of the two key sectors of the new trading system that works alongside the existing one. The largest polluters and unregulated sectors until the year 2027 as well as major contributors to greenhouse gas emissions in the European Union are due to their heavy reliance on fossil fuels in addition to relatively slow rates of decarbonisation compared to industry and power generation (OECD, 2020; Rickels et al., 2023). Figure 5 depicts how greenhouse gas emissions from building energy use have gradually declined. Yet, this reduction including fossil fuel use with power usage has not been enough during the last two decades (EEA, 2024). The figure points to the separation of emissions based on source. Fossil fuels account for a key portion of the total emissions. Even with energy efficiency improvements plus some electrification, projections under the WEM framework suggest only limited reductions around 2030. A more steep downward trend emerges when additional measures such as the introduction of EU ETS2 are assumed (WAM: With Additional Measures) (European Commission, 2024). This difference highlights stronger incentives are required, such as carbon pricing, to hasten residential and tertiary energy use decarbonisation (Flues & Van Dender, 2017; Günther et al., 2024).

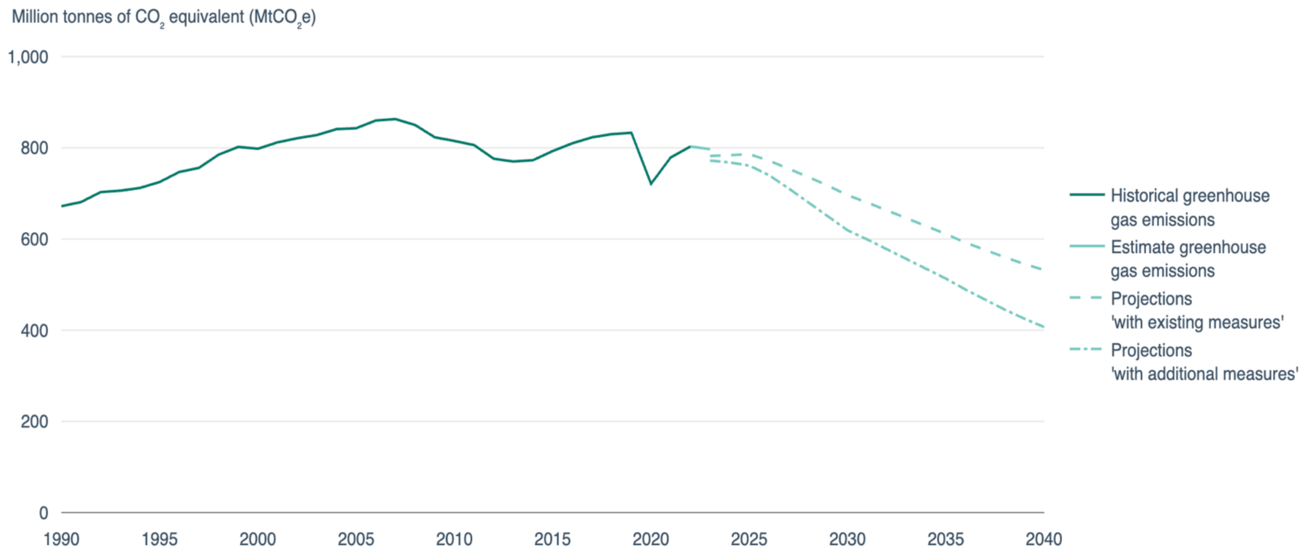
Figure 5. Greenhouse gas emissions from energy use in buildings in Europe



Source: EEA – European Environmental Agency

The transport sector does remain as a major challenge. To reach all of the EU's climate strategy goals depends upon overcoming this same challenge. Figure 6 shows the historical trajectory as well as future projections for total greenhouse gas emissions from transport, including road transport, and road transport is the main focus of the EU ETS2 expansion. While the emissions for this sector have stabilised, probably because standards made fuel efficient and shifts partially changed modes, the decline that people expect under the current regulatory pathway remains insufficient to meet climate neutrality targets (Pahle et al., 2024). Nevertheless, the additional scenario, otherwise known as WAM, because it also includes further policy interventions such as carbon pricing as well as the electrification of vehicle fleets, results in greatly lower emissions projections (OECD, 2020; Günther et al., 2024).

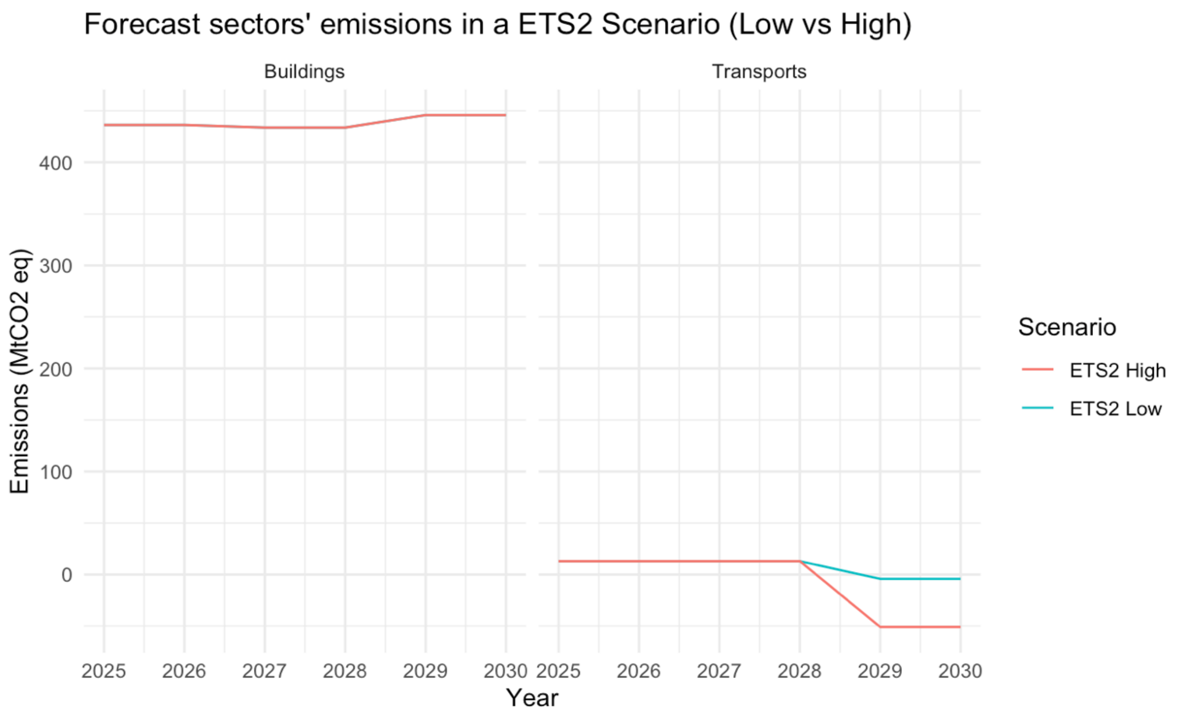
Figure 6. Greenhouse gas emissions from Transports in Europe



Source: EEA – European Environmental Agency

Figures 5 and 6 together strengthen the justification for including transport and buildings in a new Emissions Trading System. Both sectors are able to reduce substantially, but strong price signals as well as binding emissions caps have not existed yet, so the potential has still remained largely untapped (Held et al., 2022). EU ETS2 is anticipated to internalise the external costs that relate to carbon plus influence decisions regarding investment in technologies for heating and mobility and then foster a path that is cost-effective for emissions reduction (Rickels et al., 2023) because it introduces pricing for carbon based on auctions in all of these sectors. The evidence that comes from the projected emission pathways supports this logic, because it also reveals that the adopting of additional policy instruments closes the gap that exists between current trends and long-term decarbonisation goals (European Commission, 2024; OECD, 2020). Concrete reductions which are in Greenhouse Gas Emissions (GHG) ultimately do measure and do capture an emission trading system's effectiveness. Carbon pricing operates through the market mechanisms and theoretical underpinnings detailed in sections 3.2. In this section, the focus shifts to the environmental dimension in order to explore whether or not the implementation of the EU ETS2 is expected to deliver measurable emission reductions across the European Union, and quantitative analysis was indeed developed for such a purpose, building directly upon the econometric framework as described in section 3.1.2. For buildings and transport sectors newly covered under the EU ETS2, the simulation of annual GHG emissions evolution expressed as $MtCO_2$ equivalent under two policy scenarios. The multiple linear regression model used, was estimated through heteroskedasticity-strong methods. Reflecting diverging assumptions concerning future energy demand as well as allowance availability, these scenarios, labelled ETS2 Low and ETS2 High, correspond to distinct EUA price trajectories which are derived from that forecasting model within Hypothesis 1. This ensures internal consistency within the pricing and emissions analyses because it allows us to trace a coherent causal chain from regulatory design to market response and, ultimately, to environmental outcomes. The projections do span the period from 2025 to 2030 and do rely on a set of independent variables that do include macroeconomic conditions (GDP), climate drivers (Heating and Cooling Degree Days), sector-specific energy indicators (vehicle kilometres for freight and passengers, building energy use), average electricity prices, and energy-related taxation, which are included. The key explanatory variable, EUA price, is introduced as a continuous regressor, and this enables the model to capture the marginal effect from carbon cost variations on emissions levels across both sectors

Figure 7. Forecasted Emission Reductions under ETS2 Low and ETS2 High Scenarios



Source: elaboration based on model 2 simulation, see Appendix B

Under the ETS2 High scenario, emissions should decline more sharply in both sectors since EUA prices are higher than under the ETS2 Low scenario. This divergence becomes particularly pronounced at once. It especially stands out toward the projection horizon's final years. For example, also in 2030, building sector emissions for ETS2 High should be more than 42 $MtCO_2$ eq lower than they are under ETS2 Low. These matches reducing emissions close to 10%. The transport sector does see an effect that is similar, although it is smaller numerically. Statistically meaningful, these differences suggest higher carbon prices, induced through stricter policy parameters, can effectively incentivise decarbonisation even in historically resilient sectors. EU ETS2 model results indicate it may create large extra emissions cuts versus a lower carbon price policy course. It does so by extending carbon pricing to the buildings along with transport sectors. For sectoral emissions, changes in the EUA price are what they are sensitive to, mainly driving the effect. The regression framework considers the EUA price as being a key explanatory variable. As behavioural adaptations get more efficient, plus technological uptake and building energy use, the estimated relationship indicates higher carbon prices decrease emissions greatly. The simulation uses sector-specific assumptions based on empirical data to enact the ETS2 policy scenarios. Input variables in both ETS2 Low as well as ETS2 High were adjusted. The adjustment reflected also the anticipated systemic responses to policy implementation as well. These include electricity prices modestly increasing (between 3% and 5%), vehicle kilometres travelled along with building energy demand reducing up to 10%, also energy-related taxation and GDP marginally increasing. These parameter changes were selected based on policy evaluation studies and historical averages, in order to ensure internal consistency and realism in the forecast, while avoiding overestimation of carbon pricing impacts. From a policy standpoint, the EU ETS2 can act as one important mechanism for aligning short and medium-term decarbonisation pathways with the EU's 2030 climate targets, as indicated by the projected emissions trajectories. By integrating previously unregulated sectors, the policy caps prices, broadens effective coverage through market-based mitigation, also coheres the Union's climate architecture internally. While how much the estimated reductions absolutely reduce depends on the EUA price trajectory adopted, ranging from conservative to stringent, the emissions savings associated with the high-price scenario suffice atop serious consideration as policymakers continue to implement as well as refine ETS2 policy instruments. Furthermore, the results show carbon pricing as a coordination tool instead of only a cost signal since it directs mitigation work toward areas where marginal reduction could be best. Here the policy betters economic efficiency within emissions areas. It also encourages cost-effective mitigation in places where mitigation is most attainable. To strengthen the transition's political feasibility, this reinforces pairing the EU ETS2 with other instruments. Instruments must be complementary and include redistributive measures like the Social Climate Fund for reducing social impacts.

3.4. Preliminary Discussion: Pre- and Post-EU ETS2 Differences

The introduction of the EU ETS2 constitutes a structural transformation because the European Union governs its climate differently at this point, shifting away from carbon pricing in concentrated sectors to a more inclusive architecture that does incorporate buildings as well as road transport, which they had not covered previously. This regulatory expansion as well as the emissions base that is subject to market instruments redefines EU climate policy's scope, complexity, and behavioural dynamics.

The frameworks before and after EU ETS2 differ initially because they include different sectors and emitters emit variably. Before 2027, the EU Emissions Trading System mainly addressed emissions from heavy industry, electricity generation, together with intra-EU aviation. These sectors were characterized through relatively few yet quite large point sources. This structure enabled entities to monitor in a central way and comply in a streamlined way, because of the technical capacity and institutional experience of regulated entities (Görlach et al., 2022). Alternatively, buildings and road transport include millions of diffuse emission sources because they make direct regulatory oversight greatly more complex. To that end, in order to extend the cap-and-trade system to all of these sectors, regulators had to then adopt upstream regulation at that point of fuel distribution, where fuel suppliers must comply (European Commission, 2024). This design innovation ensures scalability and preserves integrity within the market mechanism. It does enable the EU ETS2 to send out a uniform carbon price signal across quite highly fragmented consumption patterns.

The design for the carbon market itself is important. A second and very critical difference concerns with this design. The ETS2 system is at first configured as a separate trading scheme, unlike the pre-existing EU ETS, which operates with but a single cap and a unified registry. It has its own cap, allowance registry, and a price corridor including minimum and maximum price thresholds (Held et al., 2022). Through this segmentation, the new system can accommodate the unique characteristics of the sectors involved, but it can moderate volatility during its early implementation. However, it also can spark some worries because market integration occurs throughout the long term. If we question whether allowances are fungible, explore potential arbitrage opportunities, also find parallel markets administratively burdensome, this highlights the need for a long-term vision on system convergence (Günther et al., 2024). A future linkage between the two ETS regimes could improve market efficiency, liquidity, and price discovery, and abatement costs converge over time.

A further prominent difference lies in just how the newly regulated sectors are expected to behaviourally as well as technologically respond. Process optimization, fuel switching, and capital-intensive investments in cleaner technologies mainly achieved emission reductions in the original EU ETS, often within a narrow set of industrial players. However, in buildings and transport, people can alter their conduct like using vehicles less, embracing electric heating, or changing mobility patterns plus greatly contribute. Households as well as small businesses are included here, which introduces a new layer in terms of price sensitivity also consumption elasticity while it improves the potential for responsiveness when it comes to carbon pricing though policy designers must design carefully in order to avoid regressive effects (Pahle et al., 2024). Transport fuels and heating costs are especially relevant here. Distributional impacts could disproportionately affect lower-income households. The establishing of the Social Climate Fund is in direct response to these challenges, and it offers financial support for more vulnerable groups and ensures the political feasibility of the reform (Nysten, 2024).

Furthermore, it is the case that the reduction potential differs greatly across phases. Across phases baseline dynamics also differ greatly. ETS sectors' decarbonisation was helped by regulatory pressures previously (European Commission, 2016). Economic structure changes helped the process through coal-to-gas switching plus deindustrialisation. Marginal abatement costs have risen as a result of this, so reductions are becoming more difficult as well as expensive. Buildings and transport, in contrast, remain carbon-intensive still. Cost-effective reductions are possible through electrification, renovation, and modal shifts (Held et al., 2022). Section 3.3 modelling results confirm this showing under the ETS2 High scenario these sectors' emissions can be greatly reduced relative to a low-price path particularly when complementary energy demand shifts are combined with higher EUA prices. For the High scenario, the reduction path seems relatively steep, suggesting potentially higher elasticity of emissions to carbon prices in these sectors. However, systemic bottlenecks such as the availability of technology or of infrastructure must be addressed.

From 2027, EU ETS2 implementation introduces a narrower horizon regarding temporal dynamics and policy windows, unlike the original EU ETS multi-phase evolution, launched in 2005. This condensed timeline imposes pressure upon policymakers to generate credible market signals. Concrete results must be delivered by 2030, the first major climate target year. Nevertheless, ETS2 benefits because institutions have learned for nearly two decades also have gained perceptions when they designed the Market Stability Reserve, progressively shifted to auctioning, plus corrected distortions induced by surplus. The ETS2 price corridor and potential market safeguards represent lessons learned from EU ETS early price volatility and market oversupply.

The merging of both climate and also fiscal policies is just another major shift. The initial EU ETS functioned separately from wider tax schemes. ETS2 enters a setting where consumer incentives are shaped by energy taxes, subsidies, and fiscal transfers. For instance, energy-related taxation considered as a percentage of GDP is included within the econometric model (see section 3.1.2) because that helps to isolate the actual effect of carbon pricing away from many other overlapping fiscal instruments. This intersection underscores the importance of policy coherence and cross-sectoral alignment, especially where the same actors face multiple price signals.

Importantly, the two systems' structural segmentation implies that price interacts may remain limited in the short term, but expectations can already visibly spill over. EUA prices respond not only to immediate fundamentals but also to anticipatory market behaviour, as section 3.2's analysis shows. Because market participants are forward-looking, the announcement and design details of ETS2 have already influenced carbon price dynamics in the existing market. This shows how price, credibility, and perception form interdependently a relevant element while the system transitions before maturing fully.

Finally, EU ETS2 represents a more decentralised citizen-facing version of carbon pricing, from a governance perspective. The system places a premium upon political legitimacy, transparency, and public communication by including sectors affecting individual consumers. The industrial actors were dominant within the compliance landscape for the original ETS. ETS2, however, introduces a broader spectrum of stakeholders along with fuel suppliers, local governments, and civil society organisations. Managing social fairness along with participatory processes requires an expanded governance architecture capable of market operations. The fostering of public support depends upon the transparent recycling of auction revenues. These revenues could be earmarked to go for social compensation or for energy efficiency programs.

In the end, the regulatory environment shifted over from pre-ETS2 into post-ETS2. That shift means emissions coverage expands beyond quantity. It marks just how carbon pricing has been designed experienced and embedded within the European Union's broader social and economic fabric a qualitative transformation. Emissions trading is repositioned by EU ETS2 introduction as a cross-sectoral policy lever affecting fiscal, technological, and behavioural trajectories not just like an industrial compliance tool. This preliminary discussion prepares one for interpreting empirical results in Chapter 4 and also stresses that the EU ETS2 systemically helps one achieve climate neutrality by 2050.

Chapter 4:
Discussion of Results and Implications

4.1. Interpretation of Findings

This section interprets the data findings from the models developed for testing this thesis's two main hypotheses. Chapters 2 and 3 outlined for us the theoretical foundations and also data sources and the modelling strategy. This section at present seeks to give light to the meaning and importance of all the results in regard to European climate policy, energy markets, and environmental economics.

The two hypotheses examined distinct but interrelated dimensions within the EU ETS2: the first anticipates its effects on carbon prices, while the second can reduce greenhouse gas emissions in the newly regulated sectors of buildings and road transport. The analysis employed strong linear regression models using annual also forecasted data to simulate counterfactual plus policy scenarios, and this allowed a comparison between Business-as-Usual (BAU) and EU ETS2 implementation pathways.

The interpretation presented here draws on statistical importance, direction with magnitude of coefficients, also model diagnostics. The interpretation also uses scenario simulations for assessing the models' internal consistency, explanatory power, with policy relevance. It also considers the alignment of results to existing literature, economic theory, and regulatory expectations that surround the expansion of emissions trading schemes. Special attention is given to the macroeconomic and climatic variables that interact with the decarbonisation process and to sectoral emissions' responsiveness to price variation and to the role of EUA prices as a behavioural and technological signal.

This section compares empirical results in the two models seeking to identify if EU ETS2 likely achieves objectives as well as the mechanisms realizing outcomes. The strengths in the modelling approach and limits for causal inference in complex policy environments with multi-variables are highlighted. Section 4.2 follows onward with a discussion relating to market and policy implications. The aim is founding it soundly.

4.1.1 Interpretation of Findings on Hypothesis 1: The Impact of EU ETS2 on Carbon Prices

The first hypothesis examined in this thesis, as introduced in Chapter 3, section 3.1.1, sought to determine if the EU ETS2 implementation would considerably affect carbon price development in the European Union over the medium-to-long term. A multivariate regression model for investigating this hypothesis was developed using monthly historical data on EUA prices from January 2008 to December 2024. The model incorporated a range of explanatory variables with well-established links to carbon price dynamics in the literature, including Brent crude oil prices (specified as a second-degree polynomial), energy demand (in GWh), natural gas prices, average monthly temperature, GDP for the EU27, and a proxy for market stringency computed as the ratio between energy demand and available allowances.

To stabilize variance, the EUA price, which is the dependent variable, was transformed into its natural logarithm. This transformation also addressed heteroskedasticity, a problem identified during the initial diagnostic tests. Furthermore, a robust regression technique was employed using the rlm() function from the MASS package. This was necessary because of the presence of non-normal residuals and persistent heteroskedasticity, which would invalidate the assumptions underlying Ordinary Least Squares (OLS) regression.

Initial OLS estimations revealed major violations of classical linear regression assumptions. For residual normality, the Shapiro-Wilk test yielded $W = 0.97913$, p-value $= 0.003962$, while the Breusch-Pagan test indicated significant heteroskedasticity ($BP = 45.905$, $df = 7$, p-value < 0.000001). In response, the model was re-estimated using robust regression with the dependent variable log-transformed. This specification resulted in improved residual behaviour and a better model fit. Residual normality improved substantially, as the Shapiro-Wilk test then reported $W = 0.98211$, p-value $= 0.01071$, which still below the rejection thresholds, even though the robust model has improved the results in these diagnostic tests. Thus, although the model does not fully meet every classical assumption, its transformation and robust estimation considerably improved empirical validity. These limitations are discussed further in Chapter 4, Section 4.3.

The final model achieved an adjusted R^2 of approximately 0.6992. Therefore, the selected covariates explain nearly 70% of the variation in the (log-transformed) EUA price series over the estimation window (2008–2024). While this indicates a strong explanatory power, it also reflects the influence of additional market, policy, and speculative factors that are not fully captured in a single regression framework. Nonetheless, the model provides a statistically grounded basis for policy-relevant price forecasting.

The estimation window did not include the simulation exercise. A price prediction for EUAs from 2025 to 2030 was also performed. Three scenarios were constructed to test counterfactual and policy-based trajectories using the estimated regression model. The Business-As-Usual (BAU) scenario assumes no implementation of EU ETS2, with energy demand and allowances following historical trends and projections. In contrast, the ETS2 Low-Emission Scenario simulates the introduction of the new regulatory framework starting in 2027, assuming a 10% reduction in energy demand and the application of a regulatory price cap of €45/tonne between 2027 and 2029. A third case, the ETS2 High-Emission Scenario, reflects a less effective or delayed policy implementation: it assumes a 5% increase in energy demand and a 10% reduction in allowances from 2027, while maintaining the same price ceiling to reflect transitional constraints.

Forecast outputs were produced on both annual and quarterly bases. The quarterly model was determined to offer more meaningful insights, as it smoothed high-frequency volatility while preserving intra-annual dynamics important to market participants and policymakers.

Under the annual specification, EUA prices are projected to rise steadily in the BAU scenario, from €77.34 in 2025 to €125.47 in 2030. In the ETS2 Low-Emission Scenario, prices remain capped at €45 between 2027 and 2029, and increase to €103.04 in 2030, resulting in a €22.43 difference (−18%) compared to the BAU baseline. The ETS2 High-Emission Scenario shares the same capped prices until 2029 but escalates sharply to €260.84 in 2030, reflecting supply constraints and increased emissions.

Quarterly forecasts confirm and enrich this dynamic. From Q1 2027 onward, the ETS2 scenarios diverge markedly from BAU. For instance, in Q3 2030, the EUA price is estimated at €123.49 in the BAU scenario, €101.34 in the ETS2 Low-Emission case, and €257.51 in the High-Emission case. Similarly, by Q4 2030, BAU prices reach €133.85, compared to €109.62 (Low) and €281.17 (High). These results demonstrate that while well-calibrated policy mechanisms can mitigate price growth through market stabilization, ineffective or delayed implementation may instead trigger excessive price inflation and instability in carbon markets. These projections support a broader interpretation: carbon pricing outcomes are shaped not only by policy expansion but also by the macroeconomic and energy context into which such regulations are embedded. The inclusion of buildings and transport in the ETS2 scenario, along with energy efficiency improvements and stabilizing mechanisms such as the price cap, results in moderated EUA prices despite the broadened market scope. This challenges the common perception that broader carbon pricing necessarily leads to higher prices, suggesting instead that well-calibrated regulatory design can enhance market stability.

When regulatory design includes transitional safeguards and demand-reducing interventions, Hypothesis 1 shows that EU ETS2 may exert a dampening effect on EUA prices throughout the early implementation phase. This outcome hinges critically on the credibility, coherence, and timeliness of policy rollout. The next section of this chapter further explores how these price trends interact with emission trajectories under Hypothesis 2.

Figure 8. EUA prices forecast with annual frequency

Year	Average Base Scenario	Average EU ETS2 Low Scenario	Average EU ETS2 High Scenario
2025	77,34	77,34	77,34
2026	85,78	85,78	85,78
2027	94,35	45,00	45,00
2028	103,75	45,00	45,00
2029	114,06	45,00	45,00
2030	125,47	103,04	260,84

All the estimated price have as currency the Euro (€)

Source: elaboration based on model 1 simulation, see Appendix A

Figure 9. EUA prices forecast with quarterly frequency.

Quarter	*Average Base Scenario*	Average EU ETS2 Low Scenario	Average EU ETS2 High Scenario
2025-Q1	72,08	72,08	72,08
2025-Q2	77,43	77,43	77,43
2025-Q3	81,51	81,51	81,51
2025-Q4	78,33	78,33	78,33
2026-Q1	79,34	79,34	79,34
2026-Q2	83,44	83,44	83,44
2026-Q3	89,91	89,91	89,91
2026-Q4	88,28	88,28	88,28
2027-Q1	87,43	45,00	45,00
2027-Q2	90,29	45,00	45,00
2027-Q3	97,87	45,00	45,00

2027-Q4	99,50	45,00	45,00
2028-Q1	97,45	45,00	45,00
2028-Q2	98,41	45,00	45,00
2028-Q3	105,74	45,00	45,00
2028-Q4	111,31	45,00	45,00
2029-Q1	109,02	45,00	45,00
2029-Q2	108,40	45,00	45,00
2029-Q3	114,04	45,00	45,00
2029-Q4	122,88	45,00	45,00
2030-Q1	122,99	101,32	252,74
2030-Q2	119,57	98,31	247,49
2030-Q3	123,49	101,34	257,51
2030-Q4	133,85	109,62	281,17

All the estimated price have as currency the Euro (€)

Source: elaboration based on model 1 simulation, see Appendix A

At first glance, the projected price dynamics under the ETS2 scenario may seem unexpected against typical economic predictions. Typically, expanding the scope of emissions trading is associated with an increase in aggregate demand for allowances, and this increase would generally be expected to raise EUA prices. ETS2 scenario-specific regulatory assumptions and structural features, however, reduce this effect in the model. Emissions intensity decreases in forecasts based on a low-emission trajectory, where accelerated adoption of decarbonisation measures, such as technological substitution, energy efficiency, and behavioural change, contributes. These dynamics suppress allowance demand. Expanded sector coverage thereby lowers upward price pressure.

Specifically, during its starting period, the ETS2 system is also modelled to operate separately from the EU ETS. Through distinct mechanisms, this regulatory segmentation introduces auctioning and enforces a price corridor. Most notably, from 2027 to 2029, a price ceiling of €45 per tonne of CO_2 is introduced to limit upward volatility during the system's early years. This cap was operationalised in the model by adjusting forecasted EUA prices directly, whenever they exceeded €45 during that period. Thus, ETS2 scenario prices were moderated not as a modelling artefact, but because policy was explicitly designed to buffer the transition period and preserve social acceptability.

The BAU scenario extrapolates EUA price trends from a historically unified market. New policy constraints and structural safeguards do not apply. It reflects a more pronounced and uninterrupted price escalation, driven by gradual cap tightening and persistent energy demand growth. The divergence in projected prices reflects a fundamental contrast in regulatory architecture: while the BAU scenario maintains exposure to market volatility, the ETS2 trajectory integrates instruments designed to dampen shocks and deliver price stability amid systemic change.

In methodological terms, using quarterly frequency in the forecast model provides superior granularity. It also allows for higher-value interpretation of results. Seasonal patterns, such as increased winter heating or summer cooling demands, are better captured at high frequency, improving both descriptive and predictive accuracy. Quarterly averages help reduce aggregation bias and avoid the flattening effect typical of annual data, which can obscure specific policy impacts or behavioural responses.

This distinction becomes especially relevant when implementing ETS2. Since the policy takes effect in 2027, non-linear short-term reactions, such as investor anticipation, business deferral, or price adjustments, can be expected. A quarterly model is more likely to capture these transitional effects. Indeed, this model reveals a sharper divergence between ETS2 and BAU prices during the 2027–2028 period. The annual model smooths these changes, underestimating the short-term disruption and adaptive dynamics. Impact assessments, stakeholder consultations, and policy development benefit from this periodic resolution.

Still, the decision-making context influences the choice between quarterly and annual modelling. The EU 2030 climate goals are long-term targets typically framed in annual terms, ensuring compatibility with high-level policy planning. Quarterly models, while analytically rich, serve better in assessing behavioural and market dynamics. Annual models retain relevance for macro-level coordination and strategy alignment.

Regression coefficients were assessed, and model outcomes broadly confirmed theoretical expectations. Brent crude oil entered as a second-order polynomial and related non-linearly, but overall positively, with EUA prices. The first-order coefficient was positive and relevant, indicating that rising oil prices correlate with increasing EUA prices, especially in higher ranges. This supports oil's influence on carbon markets via fuel substitution and overall energy cost structures.

Energy demand showed a strong and positive association with EUA prices ($\beta = 0.0000$, $t = -5.64$). This association emphasises how aggregate energy consumption drives emissions and hence allowance demand. GDP also had a positive relationship with carbon prices, with a coefficient close to zero due to its unit scale (millions of euros), but a statistically meaningful t-statistic of 1.05, confirming macroeconomic activity as a price driver.

Natural gas prices had a positive effect on EUA prices ($\beta = 0.0169$, $t = 2.47$), statistically significant. This confirms gas's role in marginal abatement cost and fuel-switching behaviour between gas and coal. Temperature had a weaker but still positive effect ($\beta = 0.0064$, $t = 0.82$), reflecting seasonal impacts on energy use linked to heating and cooling, though the effect was not strongly significant.

The robust regression model exhibited acceptable properties from a statistical diagnostics standpoint. Residual behaviour had limitations. The residual standard error was approximately 0.70, indicating moderate scatter around predicted log-EUA values. The model returned a log-likelihood of −167.94 and achieved AIC and BIC values of 353.89 and 383.75 respectively, indicating a balanced trade-off between complexity and model fit.

Variance Inflation Factor (VIF) values remained within tolerable limits for multicollinearity. Multicollinearity was thus not a serious concern. The highest VIF was linked to the energy demand-to-allowances ratio (GVIF ≈ 5.4). While elevated, it did not surpass critical thresholds, and its theoretical importance justified inclusion to capture market stringency. All other covariates, including oil, GDP, and temperature, had VIFs below 2, confirming minimal distortion in model interpretability.

To summarise, EUA price trajectories are lower under the ETS2 scenario relative to the baseline, due to deliberate integration of market-stabilising elements such as behavioural elasticity, supply constraints, and price caps. This does not signal weakened regulatory ambition. The quarterly frequency model confirms that these effects are especially pronounced in the early implementation years. The model confirms this. Altogether, regression results and scenario simulations offer a nuanced, evidence-based understanding of how carbon pricing might evolve under differing policy regimes—providing meaningful insight to European regulators, investors, and stakeholders in the climate policy sphere.

4.1.2 Interpretation of Findings on Hypothesis 2: The Impact of EU ETS2 on Emissions Reduction

The second hypothesis examined in this thesis assesses the potential that exists for the EU ETS2 to induce effective greenhouse gas (GHG) reductions because of its extension of carbon pricing to both the building and transport sectors. The first hypothesis focused upon price formation dynamics within the carbon market. This test, unlike that hypothesis, shifts attention to environmental effectiveness since it evaluates whether carbon pricing mechanisms translate into measurable emission reductions together with to what extent they do. A multiple linear regression via the lm_robust function estimated an econometric model with heteroskedasticity-strong standard errors to address this question. The sector-specific emissions that are expressed in $MtCO_2$ equivalent represent the dependent variable, which is separately measured specifically for transport and buildings sectors and then transformed into long-format data for allowing simultaneous estimation across different sectors. The explanatory variables reflect economic, climatic, also energy-related drivers, with those drivers being EUA price (the central policy variable), Heating Degree Days (HDD), Cooling Degree Days (CDD), Vehicle Kilometres (disaggregated into freight and passengers), Building Energy Use, average electricity prices, energy-related taxation (as a share of GDP), also aggregate GDP. Sector captures structural differences between buildings and transport emissions as a factor. The estimation data span from 2008 to 2023 and the model uses EUA price as a regressor to show how carbon prices affect emissions. Diagnostics were applied for testing model robustness to ensure statistical validity. They assessed multicollinearity through Variance Inflation Factor (VIF). Several predictors, GDP plus VKM_freight most notably, presented high VIF scores (above 50) because they suggested strong interdependencies among macroeconomic along with sectoral variables. This can inflate standard errors for individual coefficients, but the including of them is still justified here. They are important in order to capture the emissions dynamics. The Breusch-Pagan test confirmed heteroskedasticity (p-value = 0.00547) therefore it validated the use of strong standard errors. Normality of residuals was supported using the Anderson-Darling test (p-value = 0.9588). The test indicated that the distributional assumption in inference was adequate. Model quality indicators like the Akaike Information Criterion (AIC = 321.6) and the Bayesian Information Criterion (BIC = 339.2) balance explanatory power and model complexity. Alone, we cannot interpret these values. However, they give a sound standard for model accuracy considering sectoral breakdown and predictor count.

The coefficient that was linked to that EUA price was negative and of statistical importance. This affirmed that the price-emission link moved as expected. Emissions reductions in both sectors support that CO_2 emission costs increase as a hypothesis. The effect was importantly captured across two contrasting policy scenarios (ETS2 Low and ETS2 High), with sharper emissions reductions associated with higher EUA prices especially within the building sector that exhibits greater price elasticity. The model identifies that there is a causal pathway between carbon pricing and emissions reduction in the instance where EUA prices rise so as to incentivise shifts in behaviour that will include a lowering of vehicle usage along with technological substitution that shall include adoption of heat pumps or a retrofitting of buildings. Other covariates behaved just as it was expected: vehicle kilometers in addition to GDP had quite positive relationships that were with emissions, due to reflecting of demand-side growth effects, while energy prices together with taxes contributed marginally for downward pressure that was on emissions levels. It was found to be negative and statistically meaningful under even strong standard errors, with regard to the coefficient associated with the forecasted EUA price—the central policy variable of interest. The model's central idea links sector emission cuts to CO_2 output spending increases. The model does not do a formal estimate of an elasticity. However, the magnitude and direction of the coefficient suggest that higher EUA prices induce a measurable behavioural and technological response within the transport and building sectors. This finding is in alignment with the prior empirical evidence that emissions do respond to carbon pricing signals (Görlach et al., 2022; Flues & Van Dender, 2017).

The behaviour of some other explanatory variables further supports some negative impact of EUA prices. For freight and also for passengers, Vehicle Kilometres exhibited coefficients that were positive and that were important. This indicates that transport activity increases emissions up to a higher degree. During the forecasting phase, we did assume VKM reduces by 10% from 2027 onward, since such behavioural changes and cleaner mobility investments are anticipated as EU ETS2 implements.

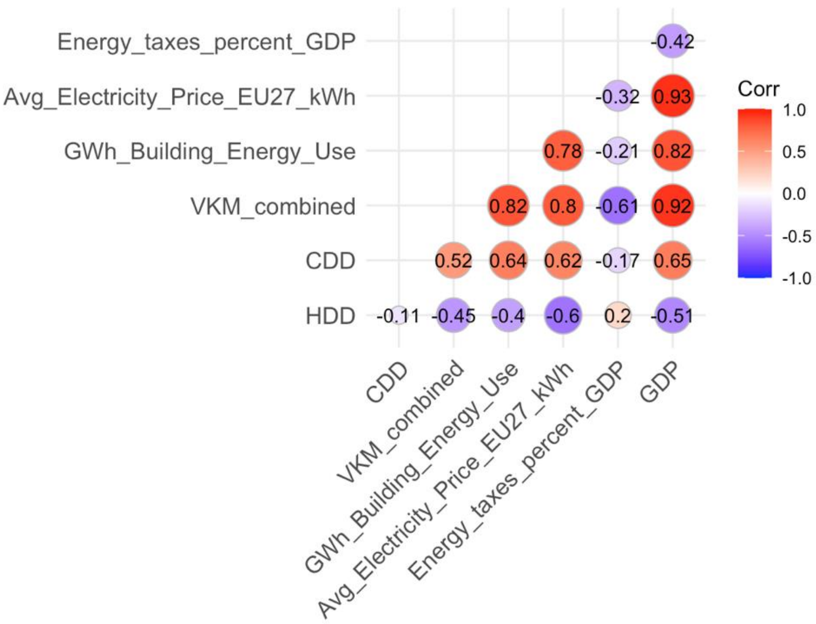
Likewise, the variable captures building energy use as another target sector of EU ETS2 and it also associates positively with emissions. Scenario simulations reduced this variable by 10% to reflect anticipated improvements in energy efficiency as well as fuel switching. These assumptions are similar to assumptions used in Hypothesis 1 for modelling EUA price trajectories. Therefore, frameworks for modelling maintain internal consistency.

Climatic variables behaved as expected: Heating Degree Days (HDD) showed a large positive effect that was meaningful; this confirmed that colder years, which increase heating needs, also raise emissions—especially in fossil-fuel-reliant building stocks. Cooling Degree Days or CDD had a more smaller but positive effect and this points to a modest rise that is in electricity-related emissions during hotter periods which is due to air conditioning demand.

The role of fiscal instruments appeared to be weaker. Energy taxation and electricity prices did too. Electricity prices associated in a positive way with emissions but with a small, relatively unstable coefficient, which is consistent with the limited short-run elasticity of residential electricity demand (Held et al., 2022). Varied importance within energy taxation, expressed as a percentage regarding GDP, occurred across specifications, likely arising from cross-country heterogeneity as well as overlap alongside subsidies and standards.

High multicollinearity was exhibited by GDP, especially with VKM_freight and Building Energy Use. GDP is statistically important though positively associated with emissions. Nevertheless, it was retained inside the model to control for macroeconomic trends because they might otherwise confound the policy effect of carbon pricing. For exploring these dependencies a correlation matrix was computed (Figure 10) confirming structural relationships rather than random collinearity. This supports such interpretation given policy effects do drive emissions reductions that are found under the ETS2 scenarios. The reductions are not simply because of the fact that cyclical economic conditions exist.

Figure 10. Correlation matrix of the independent variables



Source: elaboration based on model 2 simulation, see Appendix B

This analysis complements multicollinearity assessment based on VIF and aids in understanding the model's structural interdependencies. The dataset's correlation heatmap reveals clear pairwise associations among explanatory variables. GDP correlates very strongly as well as positively with VKM_freight (ρ = 0.94) plus also with Building Energy Use (ρ = 0.86). Furthermore, VKM_freight and VKM_Passengers correlate highly (ρ = 0.87). With these findings, multicollinearity is confirmed as the VIF analysis had suggested particularly among variables economically and logically linked through economic growth, transportation activity, and common trends in energy consumption.

Over time, aggregate indicators do often co-move within macro-sectoral regression settings in which such multicollinearity is typical. Instead of treating this as being the model's defect, the specification reflects the real-world dynamics for embracing these interrelations. In order to retain both the theoretical and policy-relevant dimensions of the analysis, collinear variables were not excluded at all. This choice allows for a more complete representation of the mechanisms driving emissions, although it may result in slightly inflated standard errors for some regressors. Even within this context, the model's explanatory power remains strong, and the key coefficients' robustness, especially EUA_Price and sectoral energy indicators, is not compromised.

The model was used to simulate emission trajectories under the two ETS2 scenarios (Low and High EUA price) for 2025–2030, along with this. This was based upon this very strong framework. The Low scenario, described earlier in chapters and in line with the policy architecture, assumes moderate carbon prices due to lower energy demand and higher allowance supply, while the High scenario reflects rising EUA prices and stricter constraints. Each sector's forecasted emissions were derived independently. Assessment of the differential impact regarding the EUA price path occurred via aggregation.

In the ETS2 Low scenario, emissions for the buildings sector do decline gradually, and they reach about 388.9 $MtCO_2$ eq in 2030. In the ETS2 High scenario, the same sector declines more steeply and reaches to around 346.6 $MtCO_2$ eq in the same year because it reduces more than 42 $MtCO_2$ eq or nearly 11%. In the transport sector, the difference is smaller in absolute terms but it is directionally consistent. Emissions fall from approximately 27.5 $MtCO_2$ eq below ETS2 Low to about 26.3 $MtCO_2$ eq under ETS2 High in 2030, and this results in a 4.5% reduction.

Higher carbon prices exert a clear downward pressure upon emissions across sectors both mentioned, these reductions do suggest though they differ in their scale. The buildings sector is more sensitive to emissions since feasible technological substitutions are wider ranging like heat pumps. In road transport, behavioural inertia plus infrastructure constraints slow the rate of change so this makes sensitivity to emissions lower. Importantly, the forecasts do rely upon harmonised input assumptions across scenarios, as these same assumptions include stable climate conditions, constant GDP growth trends, as well as fixed sectoral energy drivers except for the EUA price being a key differentiating factor. These emissions divergences relate causally to different carbon price paths, guaranteed via this consistent modelling.

The simulated pathways that are taken together indicate that the EU ETS2 can deliver measurable policy-relevant emissions reductions in two challenging sectors for decarbonisation in the event that an adequately high EUA price accompanies it. These results do reinforce all of the rationale for the combination of carbon pricing with other complementary instruments, and we should maintain a predictable and credible price corridor throughout the early years of EU ETS2 implementation.

From a theoretical view, the data give firm empirical backing for the basic idea of cap-and-trade since a sound carbon price that is binding can cut emissions well at low cost. It is confirmed by the regression results that the EUA price does statistically and negatively influence the emissions in the building and transport sectors regarding EU ETS2. This confirms the core process emissions trading schemes use for operation. Though the effect size is moderate, its direction and importance align with the economic logic of creating behavioural and technological changes through price signals alongside internalising carbon's external costs (Günther et al., 2024; Flues & Van Dender, 2017).

Introducing ETS2 in the capacity of a parallel system, which was initially separated from the original EU ETS, is further strengthened through the model. For newly regulated sectors, emissions responsiveness to price signals seems more pronounced. Buildings in particular still present a relatively high emissions baseline with greater marginal abatement potential. This supports the policy logic of maintaining differentiated price corridors as well as caps while initially implementing it, thereby avoiding distortions that could arise if it rigidly integrates with existing sectors. With efficiency measures, fuel switching, and electrification scaling up, market linkage may be more feasible in the medium term, yielding convergence in marginal abatement costs. However, such a transition that is complete would require for policymakers to coordinate policy in a careful way, particularly in respect to how they allocate allowances and in respect to how market stability mechanisms work plus operate—topics that will be addressed in chapters that are subsequent.

Effective policy enforcement is another important assumption. The model is constructed based on the assumption regarding the full implementation of the EU ETS2 framework. Included is accurate emissions reporting, and also the use of auctioning as the primary allocation mechanism, plus exemption regimes are not wide-ranging. An ideal institutional scenario is shown. ETS2 effectiveness will depend quite strongly on the administrative capacity that is available, especially in the management of a fragmented emitter base. It is also affected by political resolve to keep the cap-and-trade system sound long term. Future research will be needed to validate these projections as empirical data under the ETS2 regime become available. Such research will be of importance.

Finally, the empirical results of Hypothesis 2 reinforce the view that carbon pricing expands to the buildings and transport sectors under EU ETS2, so this expansion reduces GHG emissions in a statistically strong as well as policy-relevant way. Rising EUA prices calibrated via Hypothesis 1's separate forecasting model demonstrably impact emissions trajectories downward. This rings true when paired with behavioural and technological reactions like improved building energy performance and reduced vehicle use. Strong standard errors in the model reduce the inference impact though statistical limitations exist like multicollinearity and heteroskedasticity. In general, the specification does remain theoretically coherent as well as empirically grounded.

Emissions scenarios made within the ETS2 Low and ETS2 High price trajectories depict plausible pathways for emission reductions in the examined sectors. Projections display a decline for both. That decline aligns to the EU's Fit-for-55, also climate neutrality targets. More importantly, the results underscore that carbon pricing plays a critical coordinating role within the broader climate policy mix though it is not a panacea. It acts just as a regulatory tool to enforce the Union's environmental commitments, as well as a market signal meant to guide investment. Subject to scenario analysis's usual caveats, these findings provide a strict meaningful basis for the discussion that follows in Chapter 4, where they will explore the EU ETS2 implementation's broader implications.

4.2. Market and Policy Implications

This section interprets the data findings from the models developed for testing this thesis's two main hypotheses. Chapters 2 and 3 outlined for us the theoretical foundations and also data sources and the modelling strategy. This section at present seeks to give light to the meaning and importance of all the results in regard to European climate policy, energy markets, and environmental economics.

The two hypotheses examined distinct but interrelated dimensions within the EU ETS2: the first anticipates its effects on carbon prices, while the second can reduce greenhouse gas emissions in the newly regulated sectors of buildings and road transport. The analysis employed strong linear regression models using annual also forecasted data to simulate counterfactual plus policy scenarios, and this allowed a comparison between Business-as-Usual (BAU) and EU ETS2 implementation pathways.

The interpretation presented here draws on statistical importance, direction with magnitude of coefficients, also model diagnostics. The interpretation also uses scenario simulations for assessing the models' internal consistency, explanatory power, with policy relevance. It also considers the alignment of results to existing literature, economic theory, and regulatory expectations that surround the expansion of emissions trading schemes. Special attention is given to the macroeconomic and climatic variables that interact with the decarbonisation process and to sectoral emissions' responsiveness to price variation and to the role of EUA prices as a behavioural and technological signal.

This section compares empirical results in the two models seeking to identify if EU ETS2 likely achieves objectives as well as the mechanisms realizing outcomes. The strengths in the modelling approach and limits for causal inference in complex policy environments with multi-variables are highlighted. Section 4.2 follows onward with a discussion relating to market and policy implications. The aim is founding it soundly.

4.2.1 Implications of Hypothesis 1: Carbon Price Dynamics Under EU ETS2

The empirical results from the first model do suggest that introducing the EU ETS2 will likely influence measurably and with differentiation the trajectory of EUA prices in the European carbon market. Low average EUA prices are shown in simulations based on the low-emissions policy under EU ETS2 compared to the Business-as-Usual (BAU) case, despite expectations that broader market coverage drives up carbon prices due to more allowance demand. This outcome highlights the way policy design interacts in an important way with emissions pathways and with technological assumptions.

About 68% of the variance within log-transformed EUA prices during the estimation period was captured by the regression model. However, its forecasting output defies the common belief that price pressure increases linearly with market expansion. The ETS2 scenario includes decarbonisation incentives like electrification as well as efficiency gains. Despite an enlarged regulatory scope, demand reduction leads to weaker allowance demand with declining emissions. Underlying demand dynamics are shaped by behavioural responses, technological uptake, and macroeconomic trends, so cap stringency does not solely determine carbon prices though a core finding in cap-and-trade literature is reinforced (Chevallier, 2012; Bunn & Fezzi, 2007).

It seems that EU ETS2 is going to stabilize the market rather than to destabilize it. This is from a market perspective. This matters much more when financial actors increasingly influence a context via speculation raising carbon market price volatility. The carbon market's credibility can improve as a long-term price signal if the EUA price path is more predictable and moderate, such as under the ETS2 scenario. This reputation is needed for directing green investment choices and also future planning.

The forecast offers additional understanding as well. EU ETS2 will formally begin in 2027 but ETS2 and BAU prices start diverging beforehand. This anticipatory dynamic reflects carbon markets' forward-looking nature given that announced policies and expectations are priced in well in advance. Legislative clarity and also policy signalling shape market behaviour given that they truly are critical. EU institutions thus can communicate with transparency, timeliness, and credibility to directly form prices and reduce uncertainty.

These findings stress the value of emissions pricing for it aligns with broader decarbonisation strategies on the policy front. Reduced EUA prices seen in the ETS2 scenario show an internally consistent structure as allowance supply aligns with emissions declining structurally, not poor regulation. Technological efficiency as well as behavioural adaptation are able to achieve reductions. Price moderation is compatible with environmental ambition together with reinforcing it by making compliance more sustainable socially and politically.

Regarding an investment perspective, stability in EUA prices, even at slightly lower levels, improves planning horizons and reduces capital risk because sectors are undergoing transition. If stable carbon pricing is integrated within financial regulation like the EU

Taxonomy, the Sustainable Finance Disclosure Regulation (SFDR), as well as the Green Bond Standard, the moderate, coherent trajectory forecasted for EUA prices under ETS2 would ease it. The carbon price in this context acts more as a calculated anchor instead of as a speculative signal intended for green investment.

Still, this modelling exercise poses some relevant questions for governance of just a dual-market structure. EU ETS and EU ETS2 initially have distinct caps, registries, and auction designs for flexibility. Yet, it presents risks of fragmentation, arbitrage, and regulation complications. The question of the integration between the two systems becomes increasingly relevant, in the medium term. Linked auctions, fungible allowances, and unified market stability reserves may foster liquidity. These mechanisms could act to also reduce administrative overhead. However, such integration would require careful attention toward distributional equity and policy harmonisation. Also, monitoring, reporting, and verification (MRV) systems must align together.

The Market Stability Reserve (MSR) interacts with EUA prices in another policy dimension. The MSR currently acts toward addressing surplus volumes within the existing EU ETS, but someone may need to revise its operation in light of a bifurcated or potentially integrated market. Because the allowance demand does lower in the newly regulated sectors under ETS2, the risk for which surpluses amass might be lower, but is not negligible. For maintenance of effectiveness within a much more flexible trading environment, policymakers will need to assess if MSR design parameters are in need of recalibration.

Broader economic considerations do finally emerge as well. For a successful carbon market, environmental stringency must balance social and economic viability. It seems that the price trajectory is able to do that under the EU ETS2 policy scenario. It projects a path in which carbon pricing still remains strong enough so that it incentivizes abatement, but it is moderate enough so that it minimizes carbon leakage and it avoids disproportionate consumer cost burdens. To preserve market efficiency, this can improve the system's political acceptability along with such measures as revenue recycling and the Social Climate Fund.

Ultimately, the first hypothesis's evidence suggests EU ETS2 could make carbon pricing more stable, transparent, also equitable in Europe. Introducing the policy, quite unlike destabilising the market when embedded within a credible decarbonisation trajectory, offers a framework for climate ambition expansion without adverse price shocks. The planned potential for EU ETS2 as a regulatory instrument is further reinforced. It does also enable the finance for green transition.

4.2.2 Implications of Hypothesis 2: Emissions Reduction under EU ETS2

The findings from the second empirical model estimating potential EU ETS2 emission reductions show strong evidence that cap-and-trade extension to newly regulated sectors is environmentally effective. The model evaluates how emissions from the buildings and transport sectors respond to changes in carbon pricing, as captured by the EUA price. A strong linear regression (lm_robust) on panel data from 2008 to 2023 was its construction method. Since it ensures a thorough assessment of the main drivers of sectoral emissions, the regression incorporates key explanatory variables such as GDP, Heating and Cooling Degree Days (HDD and CDD), vehicle kilometres travelled (freight and passenger), building energy use, electricity prices, with energy taxation.

This model, distinct from the initial model that focused on pricing dynamics, directly simulates emissions outcomes under a pair of EUA price scenarios (ETS2 Low and ETS2 High) because the model uses the prices forecasted within Hypothesis 1. Emissions do see a substantially greater set of reductions with the higher EUA prices under the ETS2 High scenario rather than the ETS2 Low scenario. These differences increasingly pronounce themselves throughout the 2027–2030 projection window. Building sector emissions particularly decline beyond 42 $MtCO_2$ eq more under the high-price path; that equates to a nearly 10% reduction in that year alone.

From these results, several key policy implications arise. They first validate in an empirical manner the EU’s decision that extends emissions trading to both the buildings and the transport sectors, which were historically regulated through command-and-control instruments. The model findings do support the idea that these sectors can be responsive to carbon pricing, and they are in turn well-suited to be governed by market-based mechanisms like ETS2. The policy framework broadens what is the environmental impact, targeting sectors with their high baseline emissions and untapped abatement potential aligning with that rationale.

EUA prices and sectoral emissions do have the expected inverse relationship as the results do confirm, which is a core theoretical premise of cap-and-trade systems. Since the EUA price has a negative and also statistically meaningful coefficient, it shows that in the event carbon costs are higher, then they can measurably change emissions levels for the reason that it validates the economic assumption that pricing mechanisms allocate abatement to the place where it is most cost-effective. This strengthens the argument as well to maintain a sufficiently high and credible carbon price trajectory, for the analysis shows emissions reductions are sensitive to this variable.

The model stresses the contributions of SMEs and households to emissions reductions notably. Entities within the buildings and transport sectors often adjust consumption behaviour more quickly unlike large emitters under the original EU ETS where abatement typically involves capital-intensive investments. This happens in cases when certain policies such as retrofitting subsidies or adopting electric vehicles or also installing heat pumps all support a higher elasticity in the short run when it comes to a response especially. Important emissions cuts on a large scale can combine these shifts, although they are small alone.

Hypothesis 2 underscores ETS2's planned relevance as an instrument regulating the environment also improving economic efficiency plus coverage of the EU climate policy mix. Also, observation of emission trajectories, which gives credence to carbon pricing as a coordination mechanism. Lowest marginal costs see carbon pricing guide abatement especially. The extending of emissions trading into both buildings and transport is consistent with that theory. Empirical evidence justifies this extension in a realistic way.

The model however highlights the carbon-pricing-only strategy's limitations concurrently also. Meaningful emission reductions were delivered by policy scenarios simulated. However, these effects stay reliant upon several underlying assumptions such as the EUA prices' trajectory with how sectors respond behaviourally. The full mitigation potential of the EU ETS2 cannot be unlocked without such complementary measures as clean technology adoption incentives, affordability barrier policies, and administrative transparency efforts. These conclusions align toward broader literature because the literature advocates for the integration of market-based instruments with regulatory and fiscal policy tools (OECD, 2021; European Commission, 2024).

The results from the model have important design implications for revenue recycling. The model affects distributional mechanisms as well. In sectors like buildings and transport, carbon pricing is regressive because energy consumption is important and difficult to reduce. A firm equity-based rationale therefore exists for redirecting revenues from EUA auctions toward compensation policies. This Social Climate Fund is foremost and can assume a vital position encouraging inclusive decarbonisation also shielding poorer homes from higher energy prices. This is especially salient considering how income levels correlate, how intensely energy is used, and how vulnerable people are to energy poverty.

Results highlight EU ETS2 harmonisation with existing national policies as a necessity. A number of Member States have already moved to implement carbon pricing domestically or put regulations in place that happen to be sector-specific and cover transport and buildings. Without proper coordination, regulatory overlap, compliance confusion, or even competitive distortions across national markets could result. So full EU ETS2 integration will therefore be needed within EU climate governance. A solid MRV framework across sectors and jurisdictions needs digital infrastructure plus institutional capacity-building support.

The model confirms EU ETS2 environmental success relies much on implementation's credibility as well as quality from a governance point of view. Provided allowances get auctioned in a timely and transparent manner and compliance mechanisms get properly enforced and strong MRV procedures get established, the system is effective. If they inadequately do implement, they would erode market confidence also diminish environmental gains. This also may pose risk of weakening of the broader agenda for decarbonisation.

The projected reductions via ETS2 are meaningful, amounting to more than 210 $MtCO_2$ eq cumulatively from 2027 to 2030. Importantly, they must be interpreted inside the larger context of the EU’s climate strategy. EU ETS2 can play an important but not exhaustive role as it achieves the 55% emissions reduction target by 2030 toward climate neutrality by 2050. For sectors that are currently outside of the emissions trading framework, such as agriculture, waste, and land use, they will require additional contributions. EU ETS2 should in this sense be viewed more as a stimulus for change than a separate answer.

Hypothesis 2's developed model gives compelling empirical support to extending carbon pricing's environmental rationale into sectors once excluded. An EU ETS2 that is properly implemented and also well-designed shows how it can generate emission reductions in transport and buildings that are statistically meaningful and policy-relevant while it is improving the economic efficiency and coherence of the EU’s climate policy mix. However, these same benefits hinge instead on policies that can be effectively coordinated and also institutions that can be strongly framed. Deliberate efforts also ensure social equity coupled with acceptance among the public. For decarbonisation, carbon pricing must function as a planned tool. We can realise its full potential only then.

4.3 Research Limitations and Directions for Future Studies

While the findings presented in this thesis provide substantial empirical support for the effectiveness of EU ETS2 in both price formation and emissions reduction, the research also presents a number of methodological and structural limitations that must be acknowledged. These limitations do not invalidate the results; rather, they clarify the analytical boundaries within which these findings should be interpreted. In this section, three major limitations are discussed in depth: (1) the temporal and structural constraints of the dataset used in the emissions model (Hypothesis 2), (2) the issue of multicollinearity and functional form stability across sectors and time, and (3) the assumption of uniform behavioural and policy responsiveness across Member States. Each limitation is presented with reference to its implications for inference, as well as concrete suggestions for future empirical extensions.

(1) Temporal and Structural Constraints of the Emissions Dataset

One of the primary limitations of this study relates to the emissions model dataset's aggregated annual frequency along with a relatively short temporal window. For analysis, Hypothesis 2 uses a long-format panel with annual observations spanning over 16 years (from 2008 to 2023), broken down by transport and buildings sector. This structure permits an understandable simple modelling framework, but key limits exist regarding results' generalisability and statistical power.

Yearly data smooth variation within the year and might mask key seasonal dynamics since emissions are temperature-sensitive particularly in heating and mobility. Because of the lack of higher-frequency data the model cannot capture short-run responses to sudden carbon price spikes or climatic anomalies (e.g. quarterly or monthly emissions by sector). This is particularly problematic since one of the key mechanisms through which carbon pricing operates is behavioural change that is near-term. Estimation's available degrees of freedom are reduced by the observations' relatively limited number. By this limitation, investigation of non-linearities or structural breaks or else of time-varying coefficients is also hampered. The dataset's aggregation of energy with activity variables is a structural limitation. It is further a structural limitation of the dataset. For instance, the model includes data for building energy consumption in GWh and Vehicle Kilometres for freight and for passengers. Yet, such variables feature as yearly averages for the EU overall. This implies a loss of important within-EU heterogeneity, particularly because energy mixes as well as building insulation standards in addition to modal transport structures are vastly different among Member States. The model is better viewed as capturing average marginal effects, not identifying policy responsiveness or country-specific dynamics. Future research should address these issues through panel datasets. Higher temporal frequency plus greater sectoral and geographical granularity are needed in these datasets. More precise estimates in terms of policy impact could be enabled via the integration of Eurostat NUTS2 regional statistics coupled with smart-metered or satellite-based emissions tracking. For future studies, econometric forecasting combined with structural energy models or with agent-based simulations might offer benefits, thus allowing for the analysis to account for dynamic policy feedbacks and for intertemporal substitution effects.

(2) Multicollinearity and Model Specification Trade-offs

A second limitation of this research lies in the multicollinearity that exists among key explanatory variables when modelling emissions. Strong linear associations exist among several independent variables like GDP, VKM_freight, building energy use, also electricity prices as is shown in the Variance Inflation Factor (VIF) analysis and the Pearson correlation matrix. For example, the VIF value with respect to GDP exceeded the commonly accepted threshold of 10, while GDP correlated with VKM_freight to reach $\rho = 0.91$, and also with electricity prices to reach $\rho = 0.93$. Multicollinearity does not bias coefficient estimates in and of themselves, but it increases variance for them, which makes it more difficult to isolate the individual effect of each predictor as well as to assess just how they truly contribute to emissions variation. It also can lead to instability in the estimated coefficients across model specifications. Out-of-sample forecasts along with policy simulations are thus less trustworthy. Notwithstanding statistical concerns, all theoretically relevant variables were retained in this study. This choice shows a wider balancing act between statistical efficiency and theoretical completeness, often present when macro-environmental models reveal variable interdependence as typical rather than atypical. Multicollinearity still be present, might skew our view of some findings, most notably those about income variables and pricing. For example, the small and unstable coefficients for electricity price and energy taxes may partly reflect their collinearity with broader economic variables, rather than genuinely lacking influence on emissions behaviour. For future studies, alternative modelling techniques should be explored because of the fact that these techniques are stronger to multicollinearity. These could well include principal component analysis which is to help reduce dimensionality. Ridge regression or lasso regularisation are other possibilities for penalising overparameterisation or Bayesian estimation frameworks incorporating prior information on expected effect sizes. Transformations with careful pre-modelling may help one reduce the redundancy. Examples of improving coefficient stability are using first-differences, logarithmic forms, or normalised indices.

(3) Uniform Behavioural and Policy Response Assumptions

A third and arguably more structural limitation concerns within it the assumption embedded into the simulation model that each of EU Member States must respond uniformly to carbon pricing signals since behaviour also shows demand elasticity and since policy also implements energy taxation and investment incentives. Within the emissions simulation under Hypothesis 2, forecast inputs such as vehicle kilometres and building energy use were each uniformly adjusted downward by 10% in the ETS2 scenarios for the reason that it reflected assumed behavioural responses to higher EUA prices. However, this assumption overlooks how income levels, infrastructure readiness, energy dependency, and political will vary vastly across the EU. Across the EU, this huge heterogeneity exists. For example, rich countries having greater average incomes and more built energy systems such as Germany, the Netherlands, or the Nordics may respond to carbon prices more quickly and thoroughly by changing fuels, improving buildings, or shifting transport modes. Even with equivalent price signals, lower-income Member States could face affordability constraints that might limit their adoption of cleaner technologies. This heterogeneity can have impacts that are regressively inclined, can reduce responsiveness in the aggregate, and can even backfire in political terms if managers are not being careful. Policies overlap then policies conflict causing difficulty. These happen nationally and cause additional problems. For buildings and transport, some Member States already apply national carbon taxes or efficiency mandates. Other Member States rely more heavily upon public subsidies or price caps. With these policies, the EU ETS2 may interact in non-linear and jurisdiction-specific ways. The current model cannot capture all the spillovers along with distortions and any redundancy that results from such an interaction. For focusing on the average EU-wide effect also to maintain internal consistency, the simplifying assumption of homogeneity was justified throughout this study. Realism and policy specificity are sacrificed, however, then. In an attempt to move beyond this limitation, future empirical efforts will seek to vary dependent and explanatory variables across countries and ideally construct multi-country panel datasets. Interaction terms between carbon pricing as well as national characteristics such as median income, building age, or vehicle fleet composition could help uncover heterogeneous treatment effects because these terms are used. In order to validate the realism of modelled policy responses and also to contextualise behavioural assumptions, complementary qualitative research or case studies may then be necessary.

Directions for Future Studies

Given the limitations identified, future research can head in directions that could improve how precisely, and practically similar analyses apply. The temporal coverage of the dataset could be extended through one promising avenue that exists. Another option is spatial coverage extension. This thesis did rely on the annual data aggregated by the EU. Data with higher frequency and data that is more granular could be of benefit for studies of the future like statistics on emissions quarterly that are disaggregated by each country or also by regions that are sub-national. This would not only make statistical estimates stronger but additionally allow one to capture seasonal dynamics together with regional policy differences, which happen to be especially relevant in sectors such as heating and transport. Such data are available as well, which may then enable panel models incorporating fixed effects with time trends. These models would offer a bit more in the way of subtle perceptions into how carbon pricing impacts space and time differently. Treatment of variable interdependencies has relation to yet another direction for improvement. This analysis showed multicollinearity namely with energy-related macroeconomic variables. Future studies might explore different model specifications that lessen this problem. Techniques for dimensionality reduction such as principal component analysis or regularised regression methods such as ridge or lasso can isolate emissions' core drivers without any inflating of standard errors. These tools might be augmented since they strongly examine different functional forms like logarithmic or interaction models to assess if the observed relationships persist when assumptions change.

Conclusion

This thesis set out for exploring what the European Union Emissions Trading System 2 (EU ETS2) potentially implies because this landmark policy instrument seeks to improve how effectively the EU prices carbon. EU ETS2 shows structural changes within Europe's climate policy design via expanded market decarbonisation methods for buildings plus road transport two very carbon-heavy previously unregulated sectors. Through its analysis structured around two empirically testable hypotheses, this thesis has strongly assessed how this extension might influence carbon pricing dynamics along with the volume of greenhouse gas (GHG) emissions in the European Union.

The initial portion of that empirical investigation focused upon how carbon prices did evolve after the EU ETS2 was introduced. The model used with a multivariate regression model. Key variables like energy demand, fossil fuel prices, temperature, GDP, and a proxy for market tightness were accounted for, and monthly EUA prices from 2008 to 2024 calibrated it, revealing carbon prices should moderate slightly under an EU ETS2 regime. The expanded market scope does not automatically imply higher prices in contrast to initial expectations; rather, the results show that abatement signal is still maintained while prices are stabilized by decarbonisation trends integrated with improved allowance supply controls. In effect, the policy seems able to balance environmental ambition alongside economic predictability now. It does also give support to market efficiency and has controls for emissions, so achieving a dual objective. Excessive price volatility weakens investor confidence and long-term low-carbon capital deployment, a particularly relevant policy result.

The second hypothesis has yielded such equally compelling findings now. It explored whether emissions trading's extension to buildings with transport could yield meaningful GHG emissions reductions. Panel-style data from 2008 to 2023 disaggregated by sector received a strong linear regression model. Key drivers were included for prediction of emissions outcomes, and these drivers included EUA prices, heating and cooling demand, vehicle kilometres, building energy use, electricity prices, taxation, and GDP. Two policy scenarios ETS2 Low and ETS2 High were simulated by the analysis. The analysis projected emissions levels from 2027 to 2030. Confirming results show higher EUA prices correlate to substantial emission reductions especially in the building sector that is characterized through a higher emissions baseline together with greater responsiveness to price signals. ETS2 High scenario projects emissions should drop more than 210 $MtCO_2$ eq by 2030 versus the baseline. This contribution goes toward both the EU's Fit-for-55 and climate neutrality objectives and is of high importance.

A credible, economy-wide price on carbon can reallocate emissions reductions toward the most cost-effective sectors as these empirical outcomes reinforce the core theoretical premise of cap-and-trade systems. The thesis findings do thus validate the policy logic since it can support the ETS2 reform which namely pursues environmental integrity with economic rationality. Emissions trading offers a decentralized adaptive framework that is unlike command-and-control approaches using market forces for climate goals. For sectors such as transport and buildings, this feature becomes more valuable, because emissions sources are fragmented, and behavioural changes are important in short-run abatement.

Still and all, the results can spotlight some key caveats that do restrain highly hopeful forecasts. Firstly, the models assume full institutional actors implement the ETS2 framework, for systems accurately monitor, report, and verify, auctions are uncorrupted, and policy consistently enforces. In actuality, a lot of these different administrative prerequisites are yet still developing or do vary greatly across different Member States. EU ETS2's actual performance will in this way depend heavily within national institutions responsible for sectoral compliance, also at just the EU level, on governance capacity. Secondly, the models can simulate behavioural responses to carbon pricing, and they can also simulate technological responses that are based on policy announcements plus historical elasticities. This necessary common methodological approach does intrinsically rely on assumptions concerning responses by businesses as well as households to future price signals. The projected emissions outcomes here may not be fully realised in case fuel-switching or energy-efficiency investments slow down because of policy delays, public resistance, or financial constraints. This shows why carbon pricing needs assistance from tools like heat pump subsidies, combustion vehicle scrappages schemes, and inefficient housing stock renovation.

Thirdly, justice is a key issue, so the distributional concerns are central. Carbon pricing in buildings and transport is intrinsically regressive because energy consumption among lower-income households is a necessity and less elastic. This thesis does not conduct a formal welfare analysis. However, the literature along with institutional guidance does strongly stress the need for revenue recycling mechanisms such as for the Social Climate Fund. Political backlash risk can weaken the ETS2 framework's effectiveness as well as legitimacy without these schemes. The model underscores this tension so that it projects emissions reduction contingent not only on prices but also on the public and politicians who then sustain support for the broader decarbonisation agenda. The thesis furnishes key quantitative results. It also gives some critical perceptions on the planned positioning of EU ETS2 inside European climate policy. The policy does act as a lever that is for emission reductions. Also, the policy is a signal toward green investment. By creating a forward price signal, the ETS2 has the potential to influence capital decisions in buildings, mobility, and energy infrastructure sectors well before formal compliance periods begin. That indication might mold such choices. This aspect of carbon markets anticipating EUA price divergence before 2027 reinforces the need for communication from EU institutions that is credible, timely, and transparent. Price expectations are shaped via policy announcements, political stability, and consistency in regulatory implementation. Thus expectations are not formed in such a vacuum. Its methodological architecture counts as another meaningful contribution. This thesis unites the separation of policy design and evaluation. Econometric modelling combines in the customary way with scenario-based forecasting to accomplish this. Hypothesis 1's EUA price forecasts filter directly into Hypothesis 2's emission projections, though the two hypotheses are analytically distinct and functionally linked. Reflecting real-world policy feedbacks, this recursive structure improves thesis coherence because market responses to pricing influence environmental outcomes, shaping future regulatory cycles. The thesis contributes in regard to policy relevance to continuing debates on system architecture and market integration. Deciding currently to maintain ETS2 as a market that is separate from EU ETS appears justified because sectors are heterogeneous. The findings do suggest that a move in the direction of market convergence may yield efficiency gains over a period of time, particularly once marginal abatement costs align and behavioural responses mature. So, auctions deserve a link consideration. Future work should harmonize caps to eventually allow allowance fungibility across the two systems. However, such integration must proceed cautiously as well as be informed by granular empirical evidence. More research is needed within this area.

This thesis shows factual evidence now. EU ETS2 has both environmental and economic justification according to the evidence. Though limits remain in place, and though actual results hinge on a tangled mix of structural, human, and technical elements, the plan can greatly reshape the EU's climate resources. Since carbon pricing includes both buildings and transport, it then expands the reach of that market discipline, promotes innovation within lagging sectors, and strengthens the Union's credibility as such a climate leader. At one and the same time, implementation of ETS2 is of great importance. It will then require more than just market mechanics, however. Public trust above all else including administrative capacity policy coherence will be demanded. To align economic efficiency with social legitimacy, revenue recycling, clear communication, and support for vulnerable households are needed. If these same conditions are met, EU ETS2 could mark not just a technical reform, but recalibrate fundamentally how Europe balances growth, also equity, and furthermore ecological responsibility. We cannot overstate just how strong, adaptive, as well as inclusive policy instruments do matter when climate risks accelerate also geopolitics are uncertain. One of these most promising instruments is standing as the EU ETS2, as it is demonstrated here. Its success will depend upon the collective will to realise its potential and the precision of its design.

Appendix A

```r
options(repos = c(CRAN = "https://cloud.r-project.org"))


install.packages(c("readr", "dplyr", "ggplot2", "lmtest", "car", "MASS", "
lubridate"))

## Warning: package 'MASS' is not available for this version of R
##
## A version of this package for your version of R might be available else
where,
## see the ideas at
## https://cran.r-project.org/doc/manuals/r-patched/R-admin.html#Installin
g-packages

##
## The downloaded binary packages are in
##  /var/folders/wq/jm2r5gzx3hdb3_nk86r8z2y40000gn/T//RtmpMFdKNJ/downloade
d_packages

library(readr)
library(dplyr)

##
## Attaching package: 'dplyr'

## The following objects are masked from 'package:stats':
##
##     filter, lag

## The following objects are masked from 'package:base':
##
##     intersect, setdiff, setequal, union

library(ggplot2)

## Warning: package 'ggplot2' was built under R version 4.3.3

library(lmtest)

## Warning: package 'lmtest' was built under R version 4.3.3

## Loading required package: zoo

## Warning: package 'zoo' was built under R version 4.3.3

##
## Attaching package: 'zoo'

## The following objects are masked from 'package:base':
##
##     as.Date, as.Date.numeric

library(car)

## Warning: package 'car' was built under R version 4.3.3
```

```
## Loading required package: carData

##
## Attaching package: 'car'

## The following object is masked from 'package:dplyr':
##
##     recode

library(MASS)

##
## Attaching package: 'MASS'

## The following object is masked from 'package:dplyr':
##
##     select

library(lubridate)

## Warning: package 'lubridate' was built under R version 4.3.3

##
## Attaching package: 'lubridate'

## The following objects are masked from 'package:base':
##
##     date, intersect, setdiff, union

# Historical Data
file_path <- "~/Desktop/Dataset/Dataset1.csv"
dataset <- read_csv(file_path)

## Rows: 207 Columns: 7

## ── Column specification ──────────────────────────────────────────────
──────────

## Delimiter: ","
## dbl  (5): EUA Price, Brent Crude Oil, Natural Gas Price, Temperature, G
DP_EU...
## num  (1): Energy_Demand_GWh
## date (1): Date
##
## ℹ Use `spec()` to retrieve the full column specification for this data.
## ℹ Specify the column types or set `show_col_types = FALSE` to quiet thi
s message.

dataset <- dataset %>% mutate(Date = as.Date(Date, format = "%Y-%m-%d"))

# Historical Allowances
allowances_data <- data.frame(
  Year = 2008:2024,
  Allowances_Mt = c(1785.468, 1788.800, 1810.305, 1832.595, 1895.051, 1928
.669,
                    1407.086, 1357.159, 1395.178, 1561.520, 1494.544, 1223
.020,
                    1245.244, 1111.529, 1005.581, 1036.292, 987.905)
```

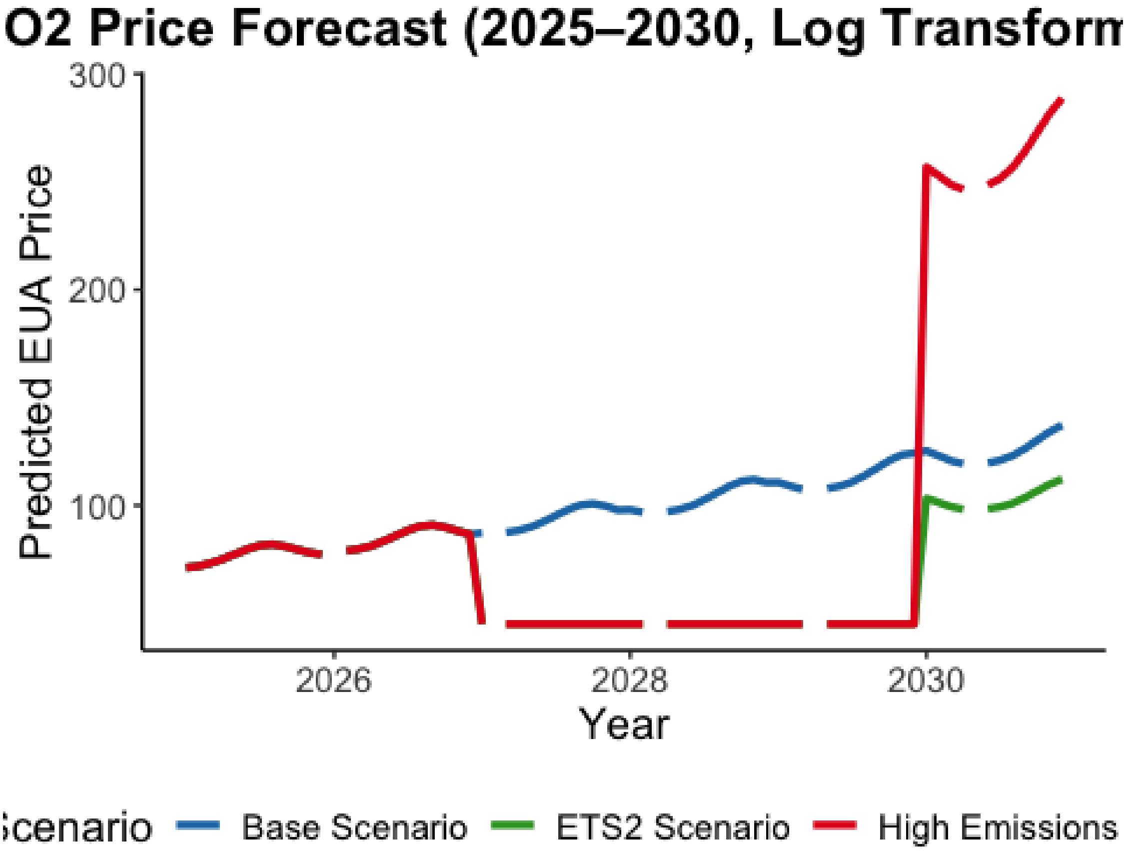
```
)

allowances_monthly <- allowances_data %>%
  mutate(Date = as.Date(paste0(Year, "-01-01"))) %>%
  slice(rep(1:n(), each = 12))

allowances_monthly$Date <- seq.Date(from = as.Date("2008-01-01"), to = as.
Date("2024-12-01"), by = "month")

dataset <- dataset %>% left_join(allowances_monthly, by = "Date")

# Compute Expected variables 2025-2030
brent_expected <- dataset %>% filter(Date >= as.Date("2019-01-01")) %>% su
mmarise(mean_value = mean(`Brent Crude Oil`, na.rm = TRUE)) %>% pull(mean_
value)
energy_lm <- lm(`Energy_Demand_GWh` ~ as.numeric(Date), data = dataset)
energy_expected <- predict(energy_lm, newdata = data.frame(Date = as.numer
ic(seq(as.Date("2025-01-01"), as.Date("2030-12-01"), by = "month"))))
gas_expected <- dataset %>% filter(Date >= as.Date("2019-01-01")) %>% summ
arise(mean_value = mean(`Natural Gas Price`, na.rm = TRUE)) %>% pull(mean_
value)
temperature_expected <- dataset %>% mutate(Month = format(Date, "%m")) %>%
group_by(Month) %>% summarise(Mean_Temp = mean(Temperature, na.rm = TRUE))
gdp_start <- dataset %>% filter(Date == as.Date("2008-01-01")) %>% pull(GD
P_EU27_MillionEUR)
gdp_end <- dataset %>% filter(Date == as.Date("2024-12-01")) %>% pull(GDP_
EU27_MillionEUR)
years <- 2024 - 2008
gdp_cagr <- (gdp_end / gdp_start)^(1 / years) - 1
gdp_expected <- gdp_end * ((1 + gdp_cagr)^(seq(1, 6, by = 1)))

# Dataset base future
future_dates <- seq.Date(from = as.Date("2025-01-01"), to = as.Date("2030-
12-01"), by = "month")
future_data <- data.frame(
  Date = future_dates,
  `Brent Crude Oil` = brent_expected,
  `Energy_Demand_GWh` = energy_expected,
  `Natural Gas Price` = gas_expected,
  Temperature = rep(temperature_expected$Mean_Temp, length.out = length(fu
ture_dates)),
  GDP_EU27_MillionEUR = rep(gdp_expected, each = 12)
)

# Average of allowances
avg_allowances <- mean(allowances_data$Allowances_Mt[allowances_data$Year
>= 2020], na.rm = TRUE)

# Scenario BASE
base_data <- future_data %>%
  mutate(Allowances_Mt = avg_allowances)

# Scenario ETS2 - Low
ets2_low <- future_data %>%
```

```r
  mutate(
    `Energy_Demand_GWh` = ifelse(Date >= as.Date("2027-01-01"), `Energy_De
mand_GWh` * 0.90, `Energy_Demand_GWh`),
    Allowances_Mt = ifelse(Date >= as.Date("2027-01-01"), avg_allowances *
1.00, avg_allowances)
  )

# Scenario ETS2 - High
ets2_high <- future_data %>%
  mutate(
    `Energy_Demand_GWh` = ifelse(Date >= as.Date("2027-01-01"), `Energy_De
mand_GWh` * 1.05, `Energy_Demand_GWh`),
    Allowances_Mt = ifelse(Date >= as.Date("2027-01-01"), avg_allowances *
0.90, avg_allowances)
  )

# Prepara training set e modello
training_data <- dataset %>%
  filter(!is.na(`EUA Price`), !is.na(`Brent Crude Oil`), !is.na(`Energy_De
mand_GWh`),
         !is.na(`Natural Gas Price`), !is.na(Temperature), !is.na(GDP_EU27
_MillionEUR), !is.na(Allowances_Mt)) %>%
  mutate(Log_EUA_Price = log(`EUA Price`))

colnames(training_data) <- make.names(colnames(training_data))

model_log <- rlm(Log_EUA_Price ~ poly(Brent.Crude.Oil, 2) +
                                   Energy_Demand_GWh +
                                   Natural.Gas.Price +
                                   Temperature +
                                   GDP_EU27_MillionEUR +
                                   I(Energy_Demand_GWh / Allowances_Mt),
                 data = training_data)

smearing_factor <- mean(exp(resid(model_log)))

# Forecast for the 3 scenarios
base_data <- base_data %>%
  mutate(
    Predicted_Log_Price = predict(model_log, newdata = base_data),
    Predicted_Price_Base = exp(Predicted_Log_Price) * smearing_factor
  )

ets2_low <- ets2_low %>%
  mutate(
    Predicted_Log_Price = predict(model_log, newdata = ets2_low),
    Predicted_Price_Low = exp(Predicted_Log_Price) * smearing_factor
  )

ets2_high <- ets2_high %>%
  mutate(
    Predicted_Log_Price = predict(model_log, newdata = ets2_high),
    Predicted_Price_High = exp(Predicted_Log_Price) * smearing_factor
  )
```

```r
ets2_low <- ets2_low %>%
  mutate(
    Predicted_Log_Price = predict(model_log, newdata = ets2_low),
    Predicted_Price_Low = exp(Predicted_Log_Price) * smearing_factor,
    Predicted_Price_Low = ifelse(Date >= as.Date("2027-01-01") & Date < as
.Date("2030-01-01") & Predicted_Price_Low > 45, 45, Predicted_Price_Low)
  )

ets2_high <- ets2_high %>%
  mutate(
    Predicted_Log_Price = predict(model_log, newdata = ets2_high),
    Predicted_Price_High = exp(Predicted_Log_Price) * smearing_factor,
    Predicted_Price_High = ifelse(Date >= as.Date("2027-01-01") & Date < a
s.Date("2030-01-01") & Predicted_Price_High > 45, 45, Predicted_Price_High
)
  )

# Annual Average
base_data <- base_data %>% mutate(Anno = format(Date, "%Y"))
ets2_low <- ets2_low %>% mutate(Anno = format(Date, "%Y"))
ets2_high <- ets2_high %>% mutate(Anno = format(Date, "%Y"))

media_base <- base_data %>% group_by(Anno) %>%
  summarise(Media_Scenario_Base = mean(Predicted_Price_Base, na.rm = TRUE)
)
media_ets2 <- ets2_low %>% group_by(Anno) %>%
  summarise(Media_Scenario_ETS2 = mean(Predicted_Price_Low, na.rm = TRUE))
media_high <- ets2_high %>% group_by(Anno) %>%
  summarise(Media_Scenario_High = mean(Predicted_Price_High, na.rm = TRUE)
)

media_annuale <- media_base %>%
  left_join(media_ets2, by = "Anno") %>%
  left_join(media_high, by = "Anno")

print(media_annuale)

## # A tibble: 6 × 4
##   Anno  Media_Scenario_Base Media_Scenario_ETS2 Media_Scenario_High
##   <chr>               <dbl>               <dbl>               <dbl>
## 1 2025                 77.3                77.3                77.3
## 2 2026                 85.8                85.8                85.8
## 3 2027                 94.3                45                  45
## 4 2028                104.                 45                  45
## 5 2029                114.                 45                  45
## 6 2030                125.                103.                261.

# Quarterly Means
base_data <- base_data %>% mutate(Trimestre = paste0(format(Date, "%Y"), "
-Q", quarter(Date)))
ets2_low <- ets2_low %>% mutate(Trimestre = paste0(format(Date, "%Y"), "-Q
", quarter(Date)))
ets2_high <- ets2_high %>% mutate(Trimestre = paste0(format(Date, "%Y"), "
-Q", quarter(Date)))
```

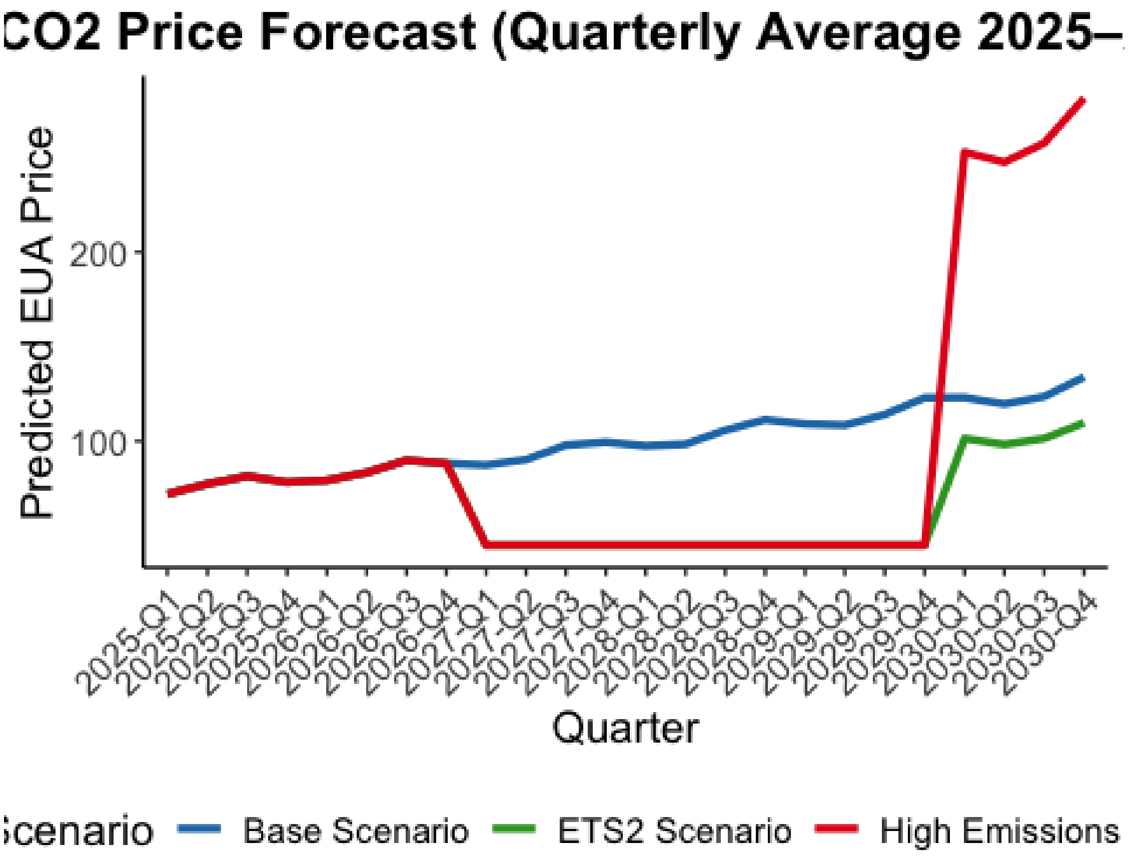
```
media_base_trim <- base_data %>%
  group_by(Trimestre) %>%
  summarise(Media_Scenario_Base = mean(Predicted_Price_Base, na.rm = TRUE)
)
media_ets2_trim <- ets2_low %>%
  group_by(Trimestre) %>%
  summarise(Media_Scenario_ETS2 = mean(Predicted_Price_Low, na.rm = TRUE))
media_high_trim <- ets2_high %>%
  group_by(Trimestre) %>%
  summarise(Media_Scenario_High = mean(Predicted_Price_High, na.rm = TRUE)
)

media_trimestrale <- media_base_trim %>%
  left_join(media_ets2_trim, by = "Trimestre") %>%
  left_join(media_high_trim, by = "Trimestre")

print(media_trimestrale)

## # A tibble: 24 × 4
##    Trimestre Media_Scenario_Base Media_Scenario_ETS2 Media_Scenario_Hig
h
##    <chr>                   <dbl>               <dbl>               <dbl
>
##  1 2025-Q1                  72.1                72.1                72.
1
##  2 2025-Q2                  77.4                77.4                77.
4
##  3 2025-Q3                  81.5                81.5                81.
5
##  4 2025-Q4                  78.3                78.3                78.
3
##  5 2026-Q1                  79.3                79.3                79.
3
##  6 2026-Q2                  83.4                83.4                83.
4
##  7 2026-Q3                  89.9                89.9                89.
9
##  8 2026-Q4                  88.3                88.3                88.
3
##  9 2027-Q1                  87.4                45                  45
## 10 2027-Q2                  90.3                45                  45
## # ℹ 14 more rows

# Graph for the 3 Scenarios
library(ggplot2)

ggplot() +
  geom_line(data = base_data, aes(x = Date, y = Predicted_Price_Base, colo
r = "Base Scenario"), linewidth = 1.2) +
  geom_line(data = ets2_low, aes(x = Date, y = Predicted_Price_Low, color
= "ETS2 Scenario"), linewidth = 1.2) +
  geom_line(data = ets2_high, aes(x = Date, y = Predicted_Price_High, colo
r = "High Emissions Scenario"), linewidth = 1.2) +
```

```r
  labs(
    title = "CO2 Price Forecast (2025-2030, Log Transformation)",
    x = "Year",
    y = "Predicted EUA Price",
    color = "Scenario"
  ) +
  scale_color_manual(values = c("Base Scenario" = "#1f78b4",
                                "ETS2 Scenario" = "#33a02c",
                                "High Emissions Scenario" = "#e31a1c")) +
  theme_classic() +
  theme(
    text = element_text(size = 14),
    plot.title = element_text(hjust = 0.5, face = "bold"),
    legend.position = "bottom"
  )
```



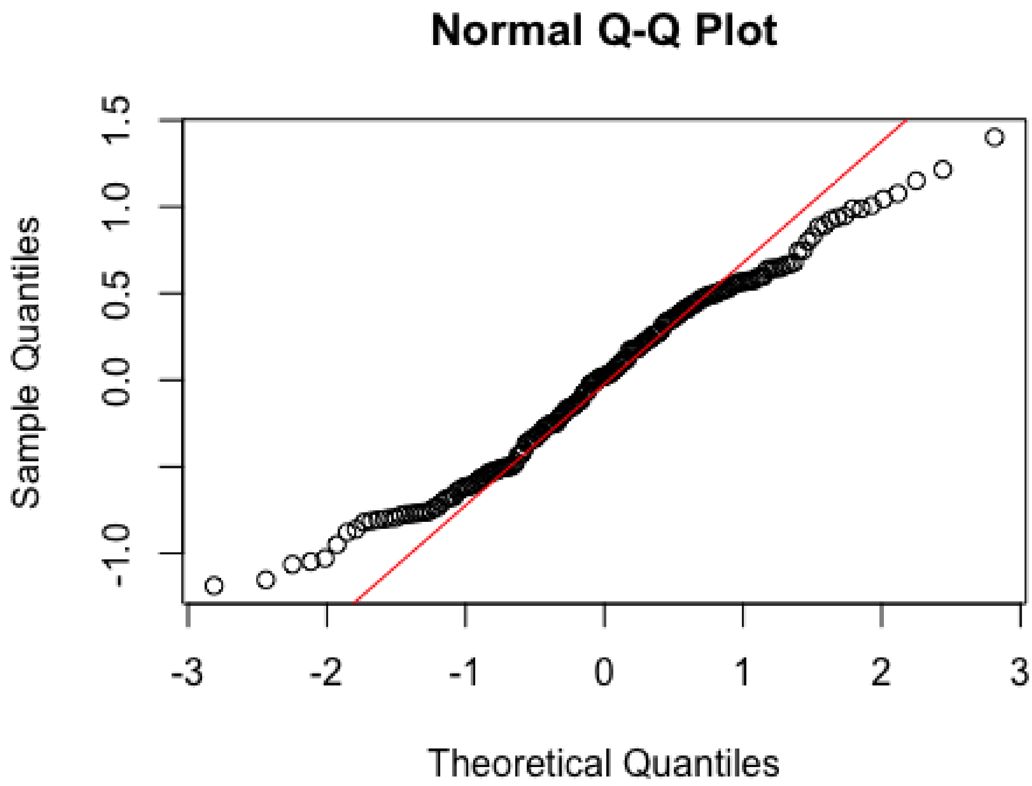

```r
ggplot(media_trimestrale, aes(x = Trimestre)) +
  geom_line(aes(y = Media_Scenario_Base, color = "Base Scenario"), linewid
th = 1.2, group = 1) +
  geom_line(aes(y = Media_Scenario_ETS2, color = "ETS2 Scenario"), linewid
th = 1.2, group = 1) +
  geom_line(aes(y = Media_Scenario_High, color = "High Emissions Scenario"
), linewidth = 1.2, group = 1) +
  labs(
    title = "CO2 Price Forecast (Quarterly Average 2025-2030)",
    x = "Quarter",
    y = "Predicted EUA Price",
```

```r
    color = "Scenario"
  ) +
  scale_color_manual(values = c("Base Scenario" = "#1f78b4",
                                 "ETS2 Scenario" = "#33a02c",
                                 "High Emissions Scenario" = "#e31a1c")) +
  theme_classic() +
  theme(
    text = element_text(size = 14),
    axis.text.x = element_text(angle = 45, hjust = 1),
    plot.title = element_text(hjust = 0.5, face = "bold"),
    legend.position = "bottom"
  )
```

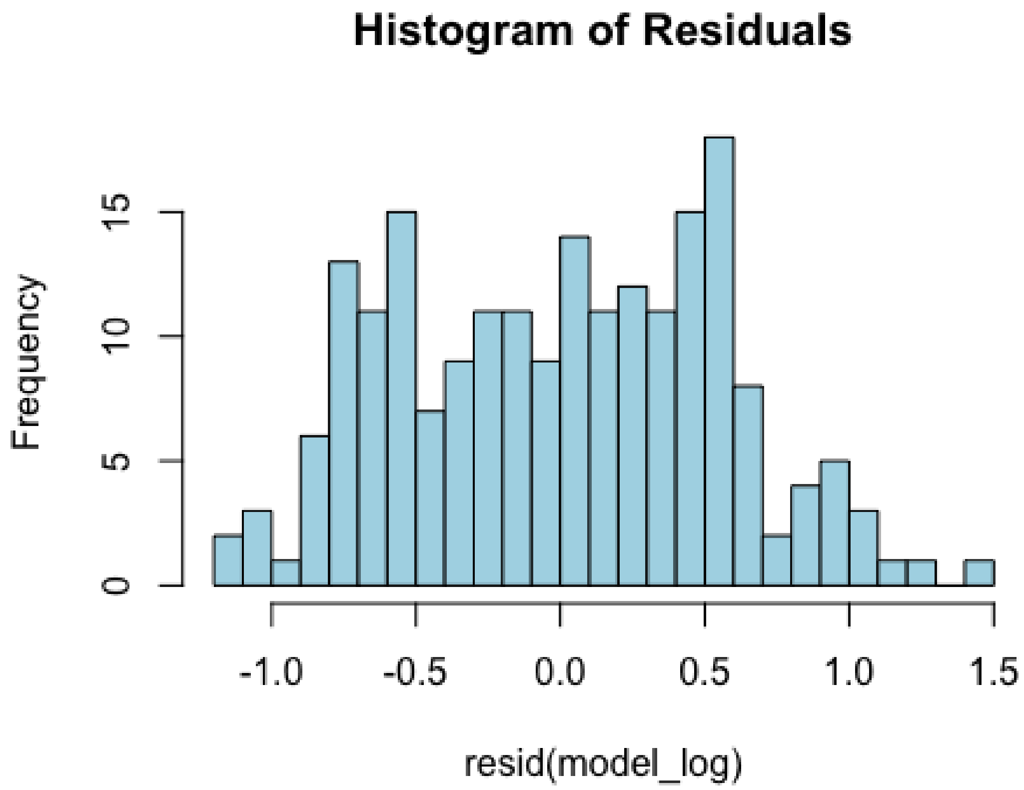



```r
# Diagnostic Test for the model
library(lmtest)
bptest(model_log)  # Test di Breusch-Pagan per l'eteroschedasticità

##
##  studentized Breusch-Pagan test
##
## data:  model_log
## BP = 45.905, df = 7, p-value = 9.122e-08

library(car)
vif_values <- vif(model_log)
print("VIF Test Results:")

## [1] "VIF Test Results:"
```

```r
print(vif_values)

##                                         GVIF Df GVIF^(1/(2*Df))
## poly(Brent.Crude.Oil, 2)            2.700017  2        1.281863
## Energy_Demand_GWh                  22.978050  1        4.793543
## Natural.Gas.Price                   1.993281  1        1.411836
## Temperature                         1.041199  1        1.020392
## GDP_EU27_MillionEUR                 3.670333  1        1.915811
## I(Energy_Demand_GWh/Allowances_Mt) 29.152932  1        5.399346

# Test for normality of residuals
shapiro.test(resid(model_log))

##
##  Shapiro-Wilk normality test
##
## data:  resid(model_log)
## W = 0.98211, p-value = 0.01071

# Log-Likelihood, AIC e BIC
log_likelihood <- logLik(model_log)
print("Log-Likelihood:")

## [1] "Log-Likelihood:"

print(log_likelihood)

## 'log Lik.' -167.9434 (df=9)

AIC(model_log)

## [1] 353.8867

BIC(model_log)

## [1] 383.7498

qqnorm(resid(model_log))
qqline(resid(model_log), col = "red")
```




```
hist(resid(model_log), breaks = 30, main = "Histogram of Residuals", col =
"lightblue")
```




```
summary(model_log)

##
## Call: rlm(formula = Log_EUA_Price ~ poly(Brent.Crude.Oil, 2) + Energy_D
emand_GWh +
##     Natural.Gas.Price + Temperature + GDP_EU27_MillionEUR + I(Energy_De
mand_GWh/Allowances_Mt),
##     data = training_data)
## Residuals:
##      Min       1Q   Median       3Q      Max
## -1.18752 -0.49523  0.02219  0.44937  1.40110
##
## Coefficients:
##                                     Value   Std. Error t value
## (Intercept)                          0.9235  1.0101     0.9143
## poly(Brent.Crude.Oil, 2)1            0.5608  0.8686     0.6457
## poly(Brent.Crude.Oil, 2)2           -1.2206  0.6612    -1.8459
## Energy_Demand_GWh                    0.0000  0.0000    -5.6380
## Natural.Gas.Price                    0.0169  0.0069     2.4650
## Temperature                          0.0064  0.0078     0.8230
## GDP_EU27_MillionEUR                  0.0000  0.0000     1.0483
## I(Energy_Demand_GWh/Allowances_Mt)  0.0192  0.0026     7.3024
##
## Residual standard error: 0.6992 on 196 degrees of freedom
```

Appendix B

```r
options(repos = c(CRAN = "https://cloud.r-project.org"))
install.packages("estimatr")

##
## The downloaded binary packages are in
##  /var/folders/wq/jm2r5gzx3hdb3_nk86r8z2y40000gn/T//RtmpqiKsQb/downloade
d_packages

install.packages("tidyverse")

##
## The downloaded binary packages are in
##  /var/folders/wq/jm2r5gzx3hdb3_nk86r8z2y40000gn/T//RtmpqiKsQb/downloade
d_packages

install.packages("lmtest")        # Per Breusch-Pagan test (bptest)

##
## The downloaded binary packages are in
##  /var/folders/wq/jm2r5gzx3hdb3_nk86r8z2y40000gn/T//RtmpqiKsQb/downloade
d_packages

install.packages("car")           # Per VIF (vif)

##
## The downloaded binary packages are in
##  /var/folders/wq/jm2r5gzx3hdb3_nk86r8z2y40000gn/T//RtmpqiKsQb/downloade
d_packages

install.packages("nortest")

##
## The downloaded binary packages are in
##  /var/folders/wq/jm2r5gzx3hdb3_nk86r8z2y40000gn/T//RtmpqiKsQb/downloade
d_packages

library(estimatr)

## Warning: package 'estimatr' was built under R version 4.3.3

library(tidyverse)

## Warning: package 'ggplot2' was built under R version 4.3.3

## Warning: package 'lubridate' was built under R version 4.3.3

## ── Attaching core tidyverse packages ──────────────────────── tidyverse
2.0.0 ──
## ✓ dplyr     1.1.4     ✓ readr     2.1.5
## ✓ forcats   1.0.0     ✓ stringr   1.5.1
## ✓ ggplot2   3.5.2     ✓ tibble    3.2.1
## ✓ lubridate 1.9.4     ✓ tidyr     1.3.0
## ✓ purrr     1.0.2
## ── Conflicts ────────────────────────────────────────── tidyverse_confl
```

```
icts() ──
## ✖ dplyr::filter() masks stats::filter()
## ✖ dplyr::lag()    masks stats::lag()
## ℹ Use the conflicted package (<http://conflicted.r-lib.org/>) to force
all conflicts to become errors

# DATASET BASE

dataset <- data.frame(
  Date = 2008:2023,
  MtCO2_Buildings = c(528.63, 519.01, 546.38, 478.22, 490.62, 494.14, 423.
50, 447.20, 449.10, 448.53, 436.73, 428.83, 423.05, 433.64, 382.31, 352.23
),
  MtCO2_Transports = c(22.24, 21.58, 22.38, 21.73, 21.54, 22.71, 22.01, 22
.48, 23.30, 24.01, 24.12, 24.17, 20.88, 21.66, 20.52, 19.60),
  HDD = c(3036.39, 3113.25, 3497.41, 2968.15, 3237.86, 3160.09, 2815.53, 2
901.23, 3033.05, 3044.85, 2940.90, 2909.29, 2759.16, 3126.31, 2857.63, 282
0.92),
  CDD = c(73.50, 82.81, 96.73, 76.89, 114.81, 85.09, 58.96, 121.61, 93.49,
111.79, 97.85, 110.54, 98.66, 100.15, 139.56, 121.48),
  VKM_freight = c(122349.00, 112201.00, 113561.00, 112740.00, 108449.00, 1
11061.00, 112039.00, 114801.00, 119817.00, 124252.00, 123511.00, 126679.00
, 125536.00, 132739.00, 132779.00, 130296.00),
  VKM_Passengers = c(830.37, 1377.54, 1872.13, 2437.19, 2435.70, 2599.28,
2474.07, 2579.97, 2392.03, 2236.71, 2024.86, 2012.11, 1573.03, 1734.12, 18
36.58, 1366.95),
  GWh_Building_Energy_Use = c(6612135.10, 6612135.11, 6612135.12, 5863276.
13, 6182230.84, 6561821.50, 5550968.16, 9838054.04, 10433863.16, 10532894.
32, 10473188.54, 10410046.43, 10397519.26, 10991184.51, 10153695.87, 10153
695.88),
  Avg_Electricity_Price_EU27_kWh = c(0.1863, 0.1818, 0.1873, 0.1960, 0.207
2, 0.2155, 0.2190, 0.2242, 0.2308, 0.2349, 0.2365, 0.2470, 0.2518, 0.2531,
0.2651, 0.2910),
  Energy_taxes_percent_GDP = c(1.7, 1.8, 1.8, 1.8, 1.9, 1.9, 1.9, 1.9, 1.9
, 1.9, 1.9, 1.8, 1.7, 1.7, 1.7, 1.7),
  GDP = c(12842227.6, 12294382.1, 12556801.4, 12797331.5, 12696367.5, 1269
0847.7, 12896241.8, 13198422.5, 13455273.5, 13830622.9, 14114391.7, 143795
04.1, 13580293.8, 14439651.1, 14942824.1, 15009031.1),
  EUA_Price = c(21.96, 13.04, 14.21, 13.73, 7.07, 4.37, 5.88, 6.58, 4.54,
5.99, 6.58, 7.63, 9.55, 24.86, 24.82, 52.76)
)

# Conversion to Long Format
dataset_long <- dataset %>%
  pivot_longer(cols = c(MtCO2_Buildings, MtCO2_Transports),
               names_to = "Sector", values_to = "Emissions") %>%
  mutate(Sector = ifelse(Sector == "MtCO2_Buildings", "Buildings", "Transp
orts"))


# Model Estimation Using lm_robust

model_sectors <- lm_robust(
  Emissions ~ EUA_Price + HDD + CDD + VKM_freight + VKM_Passengers +
```

```r
    GWh_Building_Energy_Use + Avg_Electricity_Price_EU27_kWh +
    Energy_taxes_percent_GDP + GDP + Sector,
  data = dataset_long,
  se_type = "HC1"
)


# 4. Forecast of Future Scenarios

years <- 2025:2030
eua_ets2_low <- c(77.34, 85.78, 45.00, 45.00, 45.00, 103.04)
eua_ets2_high <- c(77.34, 85.78, 45.00, 45.00, 45.00, 260.84)

# Common Base
base_forecast <- expand.grid(
  Date = years,
  Sector = c("Buildings", "Transports")
) %>%
  mutate(
    HDD = mean(dataset$HDD),
    CDD = mean(dataset$CDD),
    VKM_freight = mean(dataset$VKM_freight),
    VKM_Passengers = mean(dataset$VKM_Passengers),
    GWh_Building_Energy_Use = mean(dataset$GWh_Building_Energy_Use),
    Avg_Electricity_Price_EU27_kWh = mean(dataset$Avg_Electricity_Price_EU
27_kWh),
    Energy_taxes_percent_GDP = mean(dataset$Energy_taxes_percent_GDP),
    GDP = mean(dataset$GDP)
  )

# Addition of ETS2 Scenarios
forecast_ETS2_low <- base_forecast %>%
  mutate(EUA_Price = rep(eua_ets2_low, each = 2))

forecast_ETS2_high <- base_forecast %>%
  mutate(EUA_Price = rep(eua_ets2_high, each = 2))

# Forecast
forecast_ETS2_low$Emissions_Low <- predict(model_sectors, newdata = foreca
st_ETS2_low)
forecast_ETS2_high$Emissions_High <- predict(model_sectors, newdata = fore
cast_ETS2_high)

# Pooling of the results
results <- forecast_ETS2_low %>%
  select(Date, Sector, Emissions_Low) %>%
  left_join(forecast_ETS2_high %>% select(Date, Sector, Emissions_High), b
y = c("Date", "Sector")) %>%
  mutate(
    Reduction_Absolute = Emissions_Low - Emissions_High,
    Reduction_Percent = 100 * (Reduction_Absolute / Emissions_Low)
  )

#Visualization of Results
```

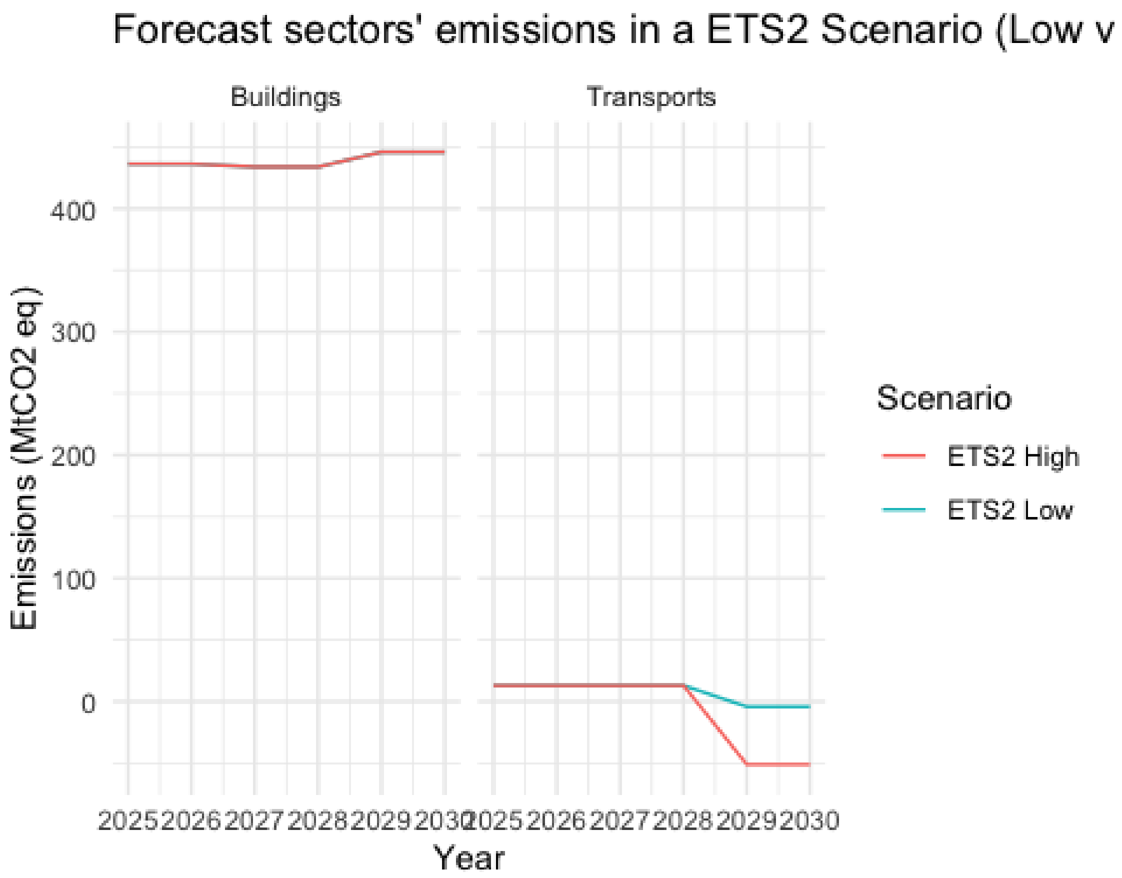
```
knitr::kable(
  results %>% arrange(Sector, Date),
  caption = "Forecasted emissions reduction under ETS2 scenarios"
)

## Warning: 'xfun::attr()' is deprecated.
## Use 'xfun::attr2()' instead.
## See help("Deprecated")

## Warning: 'xfun::attr()' is deprecated.
## Use 'xfun::attr2()' instead.
## See help("Deprecated")
```

Forecasted emissions reduction under ETS2 scenarios

Date	Sector	Emissions_Low	Emissions_High	Reduction_Absolute	Reduction_Percent
2025	Buildings	436.358074	436.35807	0.0000	0.000
2026	Buildings	436.358074	436.35807	0.0000	0.000
2027	Buildings	433.857459	433.85746	0.0000	0.000
2028	Buildings	433.857459	433.85746	0.0000	0.000
2029	Buildings	445.939814	445.93981	0.0000	0.000
2030	Buildings	445.939814	445.93981	0.0000	0.000
2025	Transports	12.990439	12.99044	0.0000	0.000
2026	Transports	12.990439	12.99044	0.0000	0.000
2027	Transports	12.990439	12.99044	0.0000	0.000
2028	Transports	12.990439	12.99044	0.0000	0.000
2029	Transports	-4.205733	-50.95894	46.7532	-1111.654
2030	Transports	-4.205733	-50.95894	46.7532	-1111.654

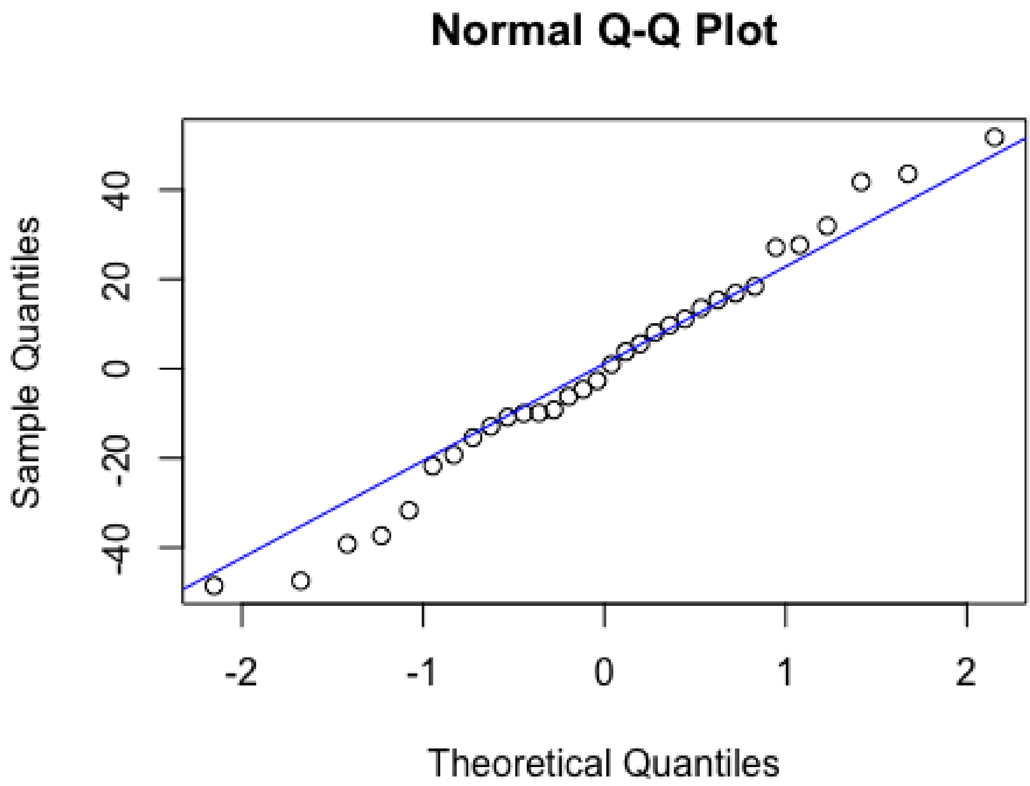
```
# Graph
library(ggplot2)
ggplot(results, aes(x = Date)) +
  geom_line(aes(y = Emissions_Low, color = "ETS2 Low")) +
  geom_line(aes(y = Emissions_High, color = "ETS2 High")) +
  facet_wrap(~ Sector) +
  labs(title = "Forecast sectors' emissions in a ETS2 Scenario (Low vs Hig
h)",
```

```
      y = "Emissions (MtCO2 eq)", x = "Year", color = "Scenario") +
  theme_minimal()
```




```
# Creatyion of the equivalent lm function for diagnostic tests
library(car)

## Warning: package 'car' was built under R version 4.3.3

## Loading required package: carData
##
## Attaching package: 'car'
##
## The following object is masked from 'package:dplyr':
##
##     recode
##
## The following object is masked from 'package:purrr':
##
##     some

lm_equivalent <- lm(
  Emissions ~ EUA_Price + HDD + CDD + VKM_freight + VKM_Passengers +
    GWh_Building_Energy_Use + Avg_Electricity_Price_EU27_kWh +
    Energy_taxes_percent_GDP + GDP + Sector,
  data = dataset_long
)
# VIF
```

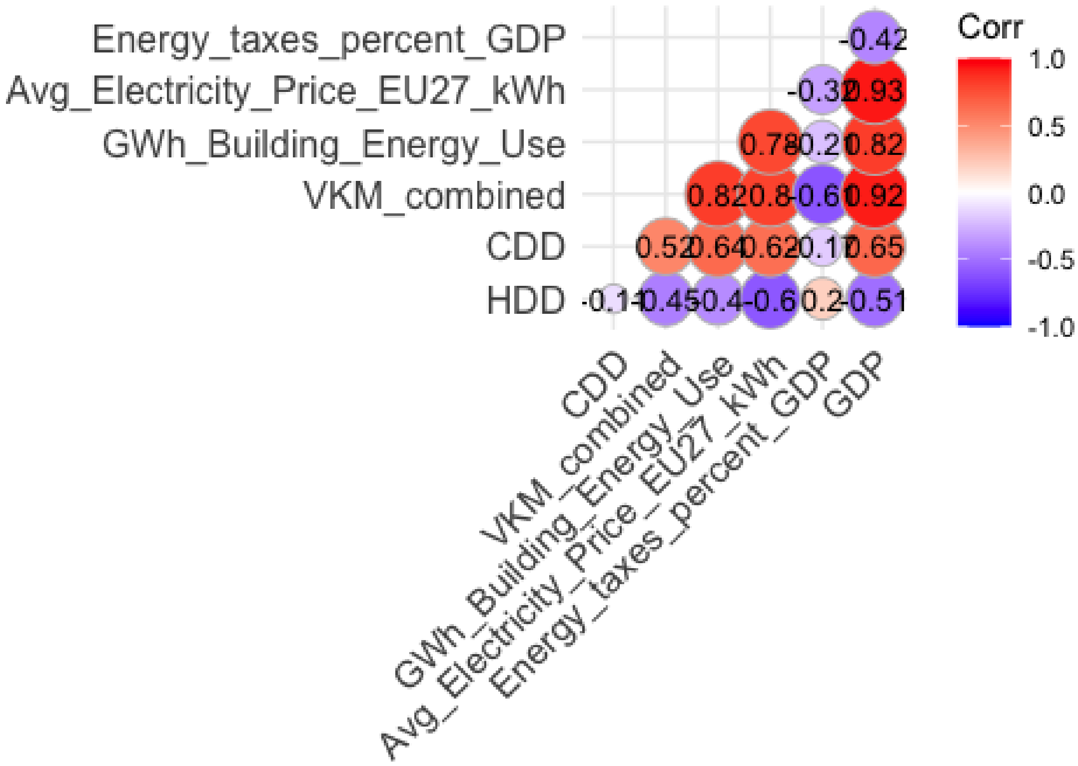
```r
library(car)
vif(lm_equivalent)

##                          EUA_Price                                HDD
##                           5.881461                           2.268408
##                                CDD                        VKM_freight
##                           3.594275                          57.989254
##                     VKM_Passengers           GWh_Building_Energy_Use
##                           5.745984                          10.947395
## Avg_Electricity_Price_EU27_kWh          Energy_taxes_percent_GDP
##                          13.418010                           9.277745
##                                GDP                             Sector
##                          52.020333                           1.000000

# Breusch-Pagan
library(lmtest)

## Warning: package 'lmtest' was built under R version 4.3.3

## Loading required package: zoo

## Warning: package 'zoo' was built under R version 4.3.3

##
## Attaching package: 'zoo'
##
## The following objects are masked from 'package:base':
##
##     as.Date, as.Date.numeric

bptest(lm_equivalent)

##
##  studentized Breusch-Pagan test
##
## data:  lm_equivalent
## BP = 24.933, df = 10, p-value = 0.005473

# Normality of Residuals
library(nortest)

## Warning: package 'nortest' was built under R version 4.3.3

res <- resid(lm_equivalent)
ad.test(res)

##
##  Anderson-Darling normality test
##
## data:  res
## A = 0.14944, p-value = 0.9588

# Visual check
qqnorm(res); qqline(res, col = "blue")
```




```
# AIC e BIC
AIC(lm_equivalent)

## [1] 321.5779

BIC(lm_equivalent)

## [1] 339.1667

independent_vars <- dataset %>%
  select(EUA_Price, HDD, CDD, VKM_freight, VKM_Passengers,
         GWh_Building_Energy_Use, Avg_Electricity_Price_EU27_kWh,
         Energy_taxes_percent_GDP, GDP)

# Pearson Correlation Matrix Calculation
cor_matrix <- cor(independent_vars, use = "complete.obs", method = "pearso
n")
print(round(cor_matrix, 2))

##                                EUA_Price   HDD   CDD VKM_freight VKM_Pa
ssengers
## EUA_Price                           1.00 -0.18  0.31        0.55
-0.61
## HDD                                -0.18  1.00 -0.11       -0.44
0.07
## CDD                                 0.31 -0.11  1.00        0.50
0.02
## VKM_freight                         0.55 -0.44  0.50        1.00
```

```
-0.49
## VKM_Passengers                          -0.61  0.07  0.02        -0.49
1.00
## GWh_Building_Energy_Use                  0.19 -0.40  0.64         0.81
-0.11
## Avg_Electricity_Price_EU27_kWh           0.49 -0.60  0.62         0.78
-0.06
## Energy_taxes_percent_GDP                -0.73  0.20 -0.17        -0.65
0.80
## GDP                                      0.54 -0.51  0.65         0.91
-0.20
##                                  GWh_Building_Energy_Use
## EUA_Price                                           0.19
## HDD                                                -0.40
## CDD                                                 0.64
## VKM_freight                                         0.81
## VKM_Passengers                                     -0.11
## GWh_Building_Energy_Use                             1.00
## Avg_Electricity_Price_EU27_kWh                      0.78
## Energy_taxes_percent_GDP                           -0.21
## GDP                                                 0.82
##                                  Avg_Electricity_Price_EU27_kWh
## EUA_Price                                                  0.49
## HDD                                                       -0.60
## CDD                                                        0.62
## VKM_freight                                                0.78
## VKM_Passengers                                            -0.06
## GWh_Building_Energy_Use                                    0.78
## Avg_Electricity_Price_EU27_kWh                             1.00
## Energy_taxes_percent_GDP                                  -0.32
## GDP                                                        0.93
##                                  Energy_taxes_percent_GDP   GDP
## EUA_Price                                           -0.73  0.54
## HDD                                                  0.20 -0.51
## CDD                                                 -0.17  0.65
## VKM_freight                                         -0.65  0.91
## VKM_Passengers                                       0.80 -0.20
## GWh_Building_Energy_Use                             -0.21  0.82
## Avg_Electricity_Price_EU27_kWh                      -0.32  0.93
## Energy_taxes_percent_GDP                             1.00 -0.42
## GDP                                                 -0.42  1.00

dataset <- dataset %>%
  mutate(VKM_combined = VKM_freight + VKM_Passengers)

install.packages("ggcorrplot")

##
## The downloaded binary packages are in
##  /var/folders/wq/jm2r5gzx3hdb3_nk86r8z2y40000gn/T//RtmpqiKsQb/downloade
d_packages

library(ggcorrplot)

dataset <- dataset %>%
```

```r
  mutate(VKM_combined = VKM_freight + VKM_Passengers)

independent_vars <- dataset %>%
  select(HDD, CDD, VKM_combined, GWh_Building_Energy_Use,
         Avg_Electricity_Price_EU27_kWh, Energy_taxes_percent_GDP, GDP)

# Correlation Matrix
cor_matrix <- cor(independent_vars, use = "complete.obs", method = "pearso
n")

# Visualisation of the Matrix
ggcorrplot(cor_matrix,
           method = "circle",
           type = "lower",
           lab = TRUE,
           lab_size = 3.5,
           colors = c("blue", "white", "red"),
           tl.col = "black",
           tl.srt = 45)
```



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