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Assessment of operational changes in the maritime transport with the introduction of the EU ETS

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Abstract

While the European Union is implementing new environmental measures, this thesis explores the segment-specific impacts of the European Union Emissions Trading System (EU ETS) on the shipping industry. By examining data from the Automatic Identification System, this study details the policy's short-term environmental effects across different shipping segments, focusing on the first quarter following its implementation in January 2024. To do so, our observations are mainly based on visual representation of the data and on difference-in-differences analysis. The most important observation we make is that the EU ETS has been responsible for a decrease per voyage of 15.38 tonnes of CO_2 equivalent since its introduction. Furthermore, we demonstrate that this impact has been larger on small-sized vessels as they show more significant reduction in speed and pollution levels. Further we show that the market is very sensitive to carbon allowances prices as, since 2024, voyages display a reduction of 15.16 tonnes of CO_2 equivalent per euro increase in the prices of allowances, meaning that policymakers can optimize the efficiency of the measure by monitoring prices. Finally, we looked for carbon leakage by observing the evolution of emissions in ports situated close the European Economic Area but found no significant evidence of rerouting. However, all these observations are based only on the initial response of the sector to the new measure. Therefore, it is important to continue measuring the effectiveness of the system in the upcoming months. This assessment will help estimate its long-term influence and adjust the system if the results deviate from the objectives of the European Union concerning environmental protection.

Keywords — EU Emissions Trading System, Shipping industry policy, Carbon pricing, Sustainable shipping practices, Carbon leakage, AIS, Vessel type, Difference-in-Differences analysis, Regression analysis

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List of abbreviations

Abbreviation	Definition
EU	European Union
EEA	European Economic Area
ETS	Emissions Trading System
EU ETS	European Union Emissions Trading System
EUA	European Union Allowance
GHG	Greenhouse Gas
IMO	International Maritime Organization
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalent
CH_4	Methane CH_4
NOx	Nitrogen oxides
N_2O	Nitrous oxide
LNG	Liquefied Natural Gas
OPEX	Operational expenditure
AIS	Automatic Identification System
GT	Gross tonnage
MRV	Monitoring, Reporting, and Verification
GWP	Global Warming Potential
GTP	Global Temperature Potential

IPCC	Intergovernmental Panel on Climate Change
DiD	Difference-in-Differences
ARMA	Autoregressive Moving Average
AR	Autoregressive
MA	Moving Average
ACF	Autocorrelation Function
PACF	Partial Autocorrelation Function

1. Introduction

The need of addressing climate change has encouraged the adoption of various environmental regulations worldwide, with the European Union (EU) acting as a leader in integrating ambitious climate policies. Among these, the European Union's Emissions Trading System (EU ETS) represents an important market-based mechanism that aims to reduce greenhouse gas (GHG) emissions through a cap-and-trade mechanism. Until recently, EU ETS focused on sectors like energy and manufacturing. However, the inclusion of the shipping industry in the EU ETS in January 2024 marks a step towards achieving the EU's environmental objectives. Indeed, the shipping industry is a significant source of emissions and thus requires specific policies to mitigate its environmental impact. As a matter of fact, in 2018, the shipping industry was accountable for 2.89% of all anthropogenic GHG emissions which represents 1,076 million tonnes of CO_2 equivalent (CO_2-eq) each year (IMO, 2020). This represents a share of 10% of all the emissions related to the transport sector (Statista, 2024).

This study aims to bring insights into the dialogue on sustainable shipping practices and the role of emissions trading schemes in facilitating the transition towards a low-carbon economy.

The rest of our thesis is organized as follows: Section 2 presents a background analysis describing the main environmental policies in the shipping sector as well as the most important trading schemes currently implemented. In section 3, we present our literature review and identify the literature gaps. Section 4 includes the methodology, explore the data and describe how we extract information from it about the impacts of the EU ETS across different segments of the shipping industry during the first few months of the policy's implementation. In section 5 we present the results derived from our methods. In section 7, we discuss the implications of our findings. Finally, Section 8 concludes and propose future research.

2. Background

This section provides a background analysis of general environmental policies within the shipping sector, examining their objectives, methodologies, strengths, and limitations. Additionally, it introduces emissions trading schemes as a tool for reducing emissions, with a focus on comparing the EU ETS with other trading schemes.

2.1 Existing environmental policies in shipping

First, Dong et al. (2022) review of environmental legislation in shipping provides an overview of maritime environmental policies. This analysis includes the International Maritime Organization's (IMO) initiatives, such as the Energy Efficiency Design Index (EEDI) for new ships, the Ship Energy Efficiency Management Plan (SEEMP) for all ships, and the expansion of MARPOL Annex VI to tackle sulfur oxides and nitrogen oxides (NOx) through Tier III emission control areas. Furthermore, it delves into the EU's 'Fit for 55' package, which integrates shipping into the EU ETS with the goal of cutting net GHG emissions by at least 55% by 2030, alongside initiatives like the FuelEU Maritime to regulate the GHG content of fuels and the inclusion of maritime transport in the Renewable Energy Directive.

Additional measures such as the Ship Fuel Consumption Data Collection System (DCS), the Energy Efficiency Existing Ship Index (EEXI), and the Carbon Intensity Indicator (CII) mandate reporting and adherence to carbon intensity metrics for ships over 5000 gross tonnage (GT). The document also highlights the inclusion of methane (CH_4) and nitrous oxide (N_2O) in GHG emissions analysis, indicating an expanded focus on a broader spectrum of GHGs beyond CO_2 (Don et al., 2022).

In the evolving field of maritime environmental regulations, the European Union's 'Fit for 55' initiative and the IMO's sulfur cap represent significant milestones aimed at reducing the shipping industry's carbon footprint. These regulations have triggered various market responses, ranging from operational adjustments to strategic investments in technology. Malloupas et al. (2022) examines the economic and operational effects of the EU's 'Fit for 55' initiative on the maritime sector through the MSF455 model. Authors describe a significant competitive gap between intra- and extra-EU trade, predicting a rise in operational expenditure (OPEX) due to carbon pricing and fuel taxes. Furthermore, the paper describes a top-down methodology for estimating emissions based on market data, such as fuel sales, contrasting

with a bottom-up approach that calculates emissions using Automatic Identification System (AIS) data. The latter, detailed in the fourth IMO GHG Study Report, estimates emissions based on specific vessel characteristics like size and speed. This bottom-up method, which we adopt in our thesis, enables the precise collection of GHG emissions data for individual ships. (Mallouppas et al., 2022). However, although the bottom-up approach is commonly used to estimate the emissions of vessels, the study of Chen and Yang (2024) highlights some limitations to this method. Indeed, the paper identifies three sources of uncertainty in the data collected. First, the collection and processing of AIS data can introduce errors, as this process involves complex data handling and interpretation steps. Second, inaccuracies can come from the information related to ship characteristics and the calculation of engine load. Lastly, the computation of emissions intensity factors adds a layer of uncertainty in the results (Chen and Yang, 2024). Despite the limitations, the bottom-up approach remains the most accurate method for measuring vessel emissions and is therefore the literature standard. As a result, this thesis is based on this method.

Mallouppas et al. (2022) quantifies OPEX increases across vessel types, emphasizing the differential impacts on shipping segments such as bulkers, tankers, and container ships. It notes shipping companies' adaptive strategies, like investing in fuel efficiency and alternative fuels, to mitigate 'Fit for 55' regulatory costs. This investigation into the economic and environmental outcomes of EU maritime policies offers insights into the regulatory challenges and adaptation pathways for the shipping industry. It also describes the sector's efforts towards sustainability.

In addition, Zisi et al. (2021) provide an evaluation of the IMO's sulfur cap regulation, focusing on the dual effects of sulfur emission reductions and CO_2 emission increases by exhaust gas cleaning systems (scrubbers) and low-sulfur fuels. A cost-benefit analysis assesses the viability of these strategies amid fluctuating fuel prices and describe the economic and environmental trade-offs of compliance methods.

As a result, investments in scrubbers showcase the industry's initial response, balancing the cost-savings of continuing Heavy Fuel Oil (HFO) use against the higher operational expenses of low-sulfur fuels. This analysis also gives an idea of the complex decision-making process for ship operators regarding fuel strategy, influenced by immediate cost implications and long-term operational savings (Zisi et al., 2021).

The study then explores the potential for modal shifts due to increased shipping costs, examining the market dynamics and the effectiveness of regulatory measures. Case studies

across various shipping segments reveal economic impacts and indicates a need for planning and innovation in compliance to answer financial and environmental challenges (Zisi et al., 2021).

2.2 Emissions Trading Schemes

2.2.1 EU Emissions Trading System (EU ETS)

In January 2024, the EU ETS was extended to include the shipping industry. This cap-and-trade system sets a limit on GHG emissions, allowing companies to buy or trade emission allowances. The EU ETS, evolving through four phases since 2005, aims to reduce the GHG emissions by making them financially impactful for businesses.

- Phase 1 (2005-2007): Test of the system's mechanisms through a pilot phase.
- Phase 2 (2008-2012): Implementation of more stringent emission reductions to align with the Kyoto Protocol.
- Phase 3 (2013-2020): Introduction of auctioning as the main method for allocating allowances.
- Phase 4 (2021-2030): Alignment with the EU's goal of a 55% net reduction in emissions by 2030.

Figure 1: Timeline of Emissions Reduction Phases

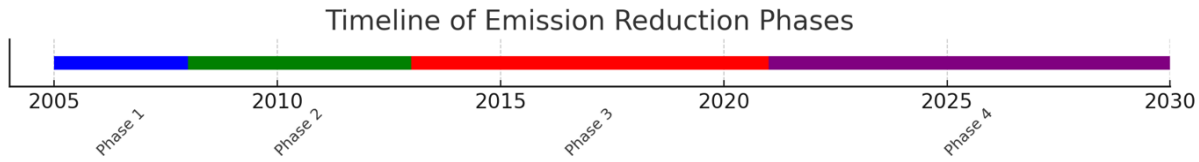

Figure 1

To estimate how efficient this regulation is within each phase, several authors, including Vlachou (2014) and Wrake et al. (2012) have measured the global EU ETS's impact during its first two phases and described the system's effectiveness. However, few research has already been done regarding the system's recent expansions and particularly on the specific implications for shipping, a gap that our thesis will explore.

2.2.2 Comparative analysis of emissions trading schemes

As previously mentioned, this work focuses on the EU ETS. However, examining other cap-and-trade regimes, such as the Regional Greenhouse Gas Initiative (RGGI), the Californian,

and the Quebec cap-and-trade systems, Borghesi and Montini (2016) bring information about the EU ETS's comparative strengths and weaknesses. Despite differences, all systems cover a wide range of GHG and are structured around distinct compliance periods, showcasing similarities in the approach to emissions reduction.

However, the EU ETS sets itself apart by implementing a fixed monetary sanction for non-compliance, unlike other systems which penalize with the requirement of additional allowances in future periods. Furthermore, in terms of ambition, the EU ETS and the Quebec system stand out as the most stringent and aim for significant GHG emissions reductions, whereas the RGGI and Californian systems are considered less demanding (Borghesi and Montini, 2016).

Incorporating observations from Zhang et al. (2017), our analysis extends to compare the EU ETS with China's seven ETS pilots launched in 2011. Both systems share similarities in how the emissions caps are set and which gases are included.

Differences emerge in allowance distribution and trading mechanisms, showing that the choice of implementation strategy depends on each region's economic and environmental goals. Although the comparison is based on information preceding the introduction of China's national ETS, the core observations remain relevant. Indeed, many features of the pilot programs are consistent with the national system (Zhang, 2017).

2.3 Introduction of EU ETS in Shipping

2.3.1 Scope of the EU ETS in shipping

The integration of the shipping industry into the EU ETS in 2024 is a significant extension of the EU's climate policy framework. Under this system, 100% of emissions from between EU ports must be accounted for by companies, while 50% of the emissions must be reported for voyages that either start or end outside the EU. Responsibility for reporting emissions lies with the shipowner, although there is an option to designate this duty to the International Safety Management (ISM)-responsible company, which is tasked with managing safety onboard. Concretely, shipping companies must report their emissions through THETIS-MRV, a platform run by the European Maritime Safety Agency (EMSA) where emissions are reported following Monitoring, Reporting, and Verification (MRV) regulations.

Furthermore, the scope of the EU ETS initially includes CO_2 emissions only, with an expansion to cover CH_4 and N_2O emissions from 2026. The range of ships subject to these regulations is

also set to broaden as it first targets cargo and passenger ships over 5,000 GT from 2024 and expanding to include large offshore service ships from 2027, with the potential inclusion of smaller offshore and general cargo ships based on future assessments by the European Commission (European Union, 2023). The implications of these regulatory choices for the shipping industry are examined in a policy brief by Zetterberg et al. (2021), which explain how these features shape and influence the policy's design and effectiveness.

In addition to the progressive inclusion of a broader set of vessels, the proportion of emissions that are considered also follows progressive implementation schedule. In 2024, companies must cover 40% of their declared emissions with allowances, which increases to 70% in 2025, and finally reaches 100% by 2026. This progressive increase allows maritime businesses to prepare for full compliance, showing the EU's commitment to combating climate change while considering the operational and economic challenges faced by the sector (Directive (EU) 2023/959, 2023).

Critical to the directive is the phased timeline for emissions reporting. While maritime companies must begin accounting for their emissions starting in 2024, the formal reporting of these emissions to the EU authorities will start in January 2025. This delay grants companies a period to adapt to the new requirements, establish accurate emissions tracking mechanisms, and ensure full compliance with the EU ETS. This step-by-step approach to reporting obligations reflects a consideration of the logistical challenges involved in implementing emissions monitoring and reporting systems within the maritime sector (Directive (EU) 2023/959, 2023).

Another important aspect is to understand the environmental impact of the different greenhouse gases included in the policy. The U.S. Environmental Protection Agency’s (EPA) highlights the economic costs of emissions, showing that emitting one tonne of CO_2 costs $120, while CH_4 and N_2O costs soar to $1,700 and $38,000 per tonne, respectively. (EPA, 2023).

The distribution of GHG emissions in the EU further stress the need for their inclusion in the EU ETS analysis. In 2019, CO_2 represented 80% of emissions, CH_4 11%, and N_2O 6%, according to a study by the European Parliament[1]. Despite their varying volumes, each gas's

[1] The rest of the emissions includes hydrofluorocarbons (2%) and other gases (perfluorocarbons, hexafluoride, nitrogen trifluoride)

impact is critical in the overall analysis of the EU ETS's effectiveness. (European parliament, 2019).

Considering the complex legal and technical framework outlined, our thesis will take this context into account. Specifically, we will include the impacts of various GHG (CO_2, CH_4, and N_2O) within our results, considering their distinct environmental effects as recommended by the European parliament.

2.3.2 Allowance allocation

To better understand its impact on companies, we are interested in how the system caps the total amount of GHG emissions. This cap gradually decreases to align with the EU's goal of reducing emissions by 55% by 2030 compared to 1990 levels. In this system, EU allowances (EUAs) represent the right to emit one tonne of CO_2-eq, allowing companies flexibility in managing their emissions through buying, selling, and trading these allowances on the market (European Commission, 2024).

For the maritime industry, specifically ships over 5,000 GT operating in the European Economic Area (EEA), a MRV process has been mandated since 2018. It involves data collection on fuel consumption, distances travelled, and cargo carried per voyage, resulting in an annually aggregated and verified emissions report for each ship. This report is then submitted to the European Commission (European Commission, 2024).

In addition to the existing mechanisms, recent discussions and proposed amendments aim to improve the EU ETS's effectiveness and alignment with global climate goals. A first suggestion is to broaden the range of greenhouse gases accounted for by shipping companies, potentially from 2026, to ensure coherence with the objectives of the Paris Agreement. Another proposal is the creation of an 'Ocean Fund', envisioned to be funded through the auctioning of allowances and penalties under the EU ETS, dedicated to financing research and development in maritime decarbonization, cleaner fuels, and infrastructure improvements for short-sea shipping and ports (European Commission, 2024).

This global framework ensures compliance with emission caps and incentivizes shipping companies to adopt cleaner technologies and more efficient operational practices. By establishing a market for carbon through the trading of EUAs, the EU ETS exploits economic mechanisms to encourage reductions in GHG emissions, driving the maritime sector towards a more sustainable future.

2.3.3 Comparative Analysis with other regulatory mechanisms

To compare the EU ETS's impact on shipping with other regulations, we explore the system's design and its wider implications for the maritime industry. Indeed, the EU ETS requires emissions accountability for voyages both within and into/out of the EU, a shift from previous global and regional frameworks. Indeed, this policy does not only define emission reporting obligations but also phases in the inclusion of various gases and ship categories, showcasing a new approach to emission reduction via financial incentives and technological innovation (Dong, 2022).

Expanding upon this, we want to compare the EU ETS with other international maritime policies, especially those under the IMO, to observe similarities or differences. First, the EU ETS is a market-based mechanism, which incentivizes emissions reductions directly through financial penalties or rewards, contrasting with the IMO's technology-focused standards that lack direct economic incentives (Don, 2022).

Moreover, the EU ETS's phased inclusion of emissions, starting at 40% in 2024 and escalating to full coverage by 2026 differs from the immediate application of the IMO's sulfur cap in 2020 and the varied pace of national policies (Don, 2022).

On one hand, this comparison allows us to observe complexities in harmonizing global shipping practices with regulations. On the other hand, regulations on shipping practices and market-based incentives, like the EU ETS, complement each other and make it possible to achieve decarbonization in a fair and efficient manner.

3. Literature review

3.1 General implications of the EU ETS in shipping

3.1.1 SWOT Analysis

To evaluate the main aspects of the policy, Christodoulou and Cullinane (2023) provide a SWOT analysis of applying the ETS to the shipping sector. Strengths identified include the flexibility it offers to companies as they choose between pollution and abatement strategies, the fairness of the system, and the effectiveness of cap-and-trade mechanisms in other sectors. However, it highlights several weaknesses, such as the challenges in setting an appropriate emissions cap, the administrative burden of the system, and its limited geographic scope, only accounting for ships arriving or departing from Europe. On the opportunities front, the ETS could reduce GHG emissions and generate revenue for policymakers, potentially reinvested in further system improvements. The main threat it identifies is the risk of carbon leakage, that the European Commission (2021) describe as "the situation that may occur if, for reasons of costs related to climate policies, businesses were to transfer production to other countries with laxer emission constraints. This could lead to an increase in their total emissions". During this thesis, we will therefore inspect if this threat has materialized so far.

3.1.2 Technological innovations in emission reduction

In response to decarbonization regulation, Mallouppas and Yfantis (2021) review how the shipping sector adopts a variety of technological innovations for emission reduction. The study observes the deployment of advanced fuels (such as methanol, hydrogen, ammonia, and LNG). Each of these fuels brings distinct CO_2 reduction potentials and operational challenges. Hydrogen and ammonia, for instance, could bring emissions potential down to zero when used in fuel cells or innovative propulsion systems, even if they face hurdles related to storage and safety. LNG, while reducing SOx (Sulfur oxides), NOx and particulate matter, still emits CO_2 and CH_4, even if at lower levels than conventional marine fuels (Balcombe et al., 2022).

Then, renewable energy sources including wind, solar, and biofuels are identified as promising alternatives for powering shipping operations. Technologies such as Flettner rotors (wind-assisted propulsion) and solar panels on ships exemplify how renewable energy can be harnessed at sea, each contributing to the reduction of reliance on fossil fuels (Mallouppas and Yfantis, 2021).

Finally, technical improvements further illustrate how the industry could get more efficient and reduce fuel consumption. Practices like ‘slow steaming’ where vessels operate at lower speeds to significantly cut fuel use, alongside hull design optimizations that reduce water resistance, can lower emissions significantly. Air lubrication systems, which introduce a layer of air bubbles beneath the hull to reduce drag, and waste heat recovery systems that convert exhaust gas heat into electric power, can also improve efficiency of vessels (Mallouppas and Yfantis, 2021).

This overview outlines the environmental benefits of these technologies and describe their economic and operational implications. By showing the industry's capacity for environmental impact mitigation through innovation, the author describes considerable potential toward decarbonization (Mallouppas and Yfantis, 2021).

3.1.3 Legal and regulatory challenges

In addition to the complexity of the abatement solutions, several legal and regulatory challenges arise with the integration of shipping into the EU ETS. The first challenge is to identify the responsible party for EU ETS administration, which is defined as the “shipping company”, which can be the shipowner or the Document of Compliance (DOC) holder (Norton Rose Fulbright, 2023).

Another challenge involves the impact of the EU ETS on chartering arrangements, as it requires precise data exchange between shipowners and charterers to manage compliance costs and allocate EUAs. The document suggests contractual solutions, like the BIMCO “ETS - Emissions Trading Scheme Allowances Clause for Time Charterparties”, to handle the complexities of passing EUAs between parties (Norton Rose Fulbright, 2023).

Specifically, the BIMCO ETS Clause[2] links the cost of emissions to the operational activities of ships by defining responsibilities for emissions allowances. It tackles the challenge of fluctuating carbon permit prices by allowing shipowners and charterers to adjust their contractual responsibilities in real-time.

The clause requires charterers, who supply and pay for the fuel, to also cover the corresponding emissions allowances at the price of allowances at the moment the contract is signed, in line with the “polluter pays” principle. This clause thus allows for short-term adjustments based on actual ship operations, which is needed given the volatility of carbon market prices. Each

[2] https://www.bimco.org/contracts-and-clauses/bimco-clauses/current/etsa_clause

month, shipowners are required to report their actual emissions, and charterers must then transfer the appropriate quantity of allowances to the shipowner's account. This process ensures that the cost of carbon emissions is directly included into the operational costs. By aligning the emission allowance adjustments closely with the vessel's operational realities, the BIMCO ETS Clause helps mitigate financial risks for shipowners associated with carbon price fluctuations.

If the estimated allowances for the final month of charter differ from actual usage, either party is obligated to rectify the difference. In periods of off-hire, where the charterers are not using the ship, they can adjust the emissions allowances proportionally. This maintains fairness and enhances compliance flexibility, adapting to the operations of the vessel. Also, the right of shipowners to suspend contractual obligations if charterers fail to transfer required allowances acts as a strong compliance incentive, ensuring that environmental responsibilities are taken seriously and integrated into the commercial operations of shipping.

Finally, the EU ETS legislation's annual calculation of vessel emissions introduces complexities in handling mid-period changes in ownership or chartering, requiring clear agreements on how emissions are accounted for, and allowances are transferred or compensated (Norton Rose Fulbright, 2023).

These challenges underscore the interplay between the EU ETS and existing maritime practices, showing the importance of planning and legal advice to navigate the new regulatory landscape effectively.

3.2 Environmental implications

3.2.1 EU ETS in general

In their paper, Dechezleprêtre et al. (2023) adopt a comprehensive approach to assess the EU ETS' effectiveness. Using a Difference-in-Differences (DiD) methodology, the authors compare the outcomes of entities subject to the EU ETS with those that are not, both before and after the system's implementation. This analytical framework helps to quantify the ETS's real-world impacts. Particularly, their findings underscore the environmental efficacy of the EU ETS. The study reveals that the system is associated with a significant reduction in emissions, quantified at approximately 10%. This figure provides empirical support to the argument that the EU ETS effectively incentivizes entities to lower their carbon footprint.

However, the paper does not delve into the shipping sector as it was published before the introduction of the measure in January 2024. This omission highlights a gap in the literature, showing that there is need for research on how the EU ETS influences this sector. To address this literature gap, our thesis will quantify the EU ETS's effectiveness using a similar methodology as it is tailored to observe the effects of a policy introduction. This comparison will provide clear evidence of the policy's impact on reducing the shipping industry's carbon emissions compared to other sectors.

3.2.2 EU ETS in the field of shipping

As the extension of the EU ETS in shipping is very recent, the literature on the subject is sparse and existing documents can therefore be considered as pioneers. These studies provide interesting insights into the complex impacts of the EU ETS on maritime transport, setting the stage for further research.

Among those studies, Ben-Hakoun et al. (2016) give a good overview of the environmental impact of this new policy by exploring the potential of a simulated Marine Emissions Trading System (METS) specifically adapted for the shipping industry. The findings suggest that the METS could achieve an annual reduction rate of 7% or more in CO_2 emissions in the scenario of a low growth rate in fuel demand. This simulation provides an optimistic view of the potential for emissions abatement through an ETS in Europe's shipping sector. However, the study does not include a review of the challenges that could diminish the system's efficiency, such as technological barriers or international compliance issues.

Furthermore, a study from Garrido et al. (2023) describes the operational adjustments and potential unintended consequences of integrating the shipping industry into the EU ETS. It highlights how the extension of the EU ETS could bifurcate maritime routes into two segments: one from America/Asia to North Africa, and another from North Africa to Europe. This division raises concerns over carbon leakage and evasion of the EU ETS, as operators might only pay for emissions in the latter half of their voyages. Moreover, this adaptation could lead to increased emissions due to the selection of less efficient, shorter routes and potentially stimulate expansion projects in North African ports, while increasing the lead time for the delivery of goods.

Finally, Lagouvardou and Psaraftis (2022) presents a more in-depth analysis of the risk of carbon leakage, a phenomenon where efforts to reduce emissions within the EU could be offset by increased emissions outside its jurisdiction. Through a cost-benefit analysis, the study

concludes that container vessels might opt to load and unload cargo outside the EEA to avoid higher costs when the price of carbon permits exceeds €25.

To mitigate the risk of carbon leakage, strategies may include a better collaboration with non-EU nations to ensure that emissions reduction efforts are globally aligned and do not encourage carbon leakage strategies. Additionally, refining the EU ETS to include measures that counteract the incentives for such emissions-intensive route adjustments is another proposed solution. Adjustments could involve expanding the coverage of the system to ensure that emissions for entire voyages are accounted for regardless of intermediary stops. A last solution is to introduce adjusted taxation rates that more accurately reflect the environmental impact of different segments of a voyage (Harilaos and Lagouvardou, 2022).

The interconnection between these documents illustrates the complexity of environmental policy implementation within the shipping industry. While the simulated ETS offers a theoretical foundation for emissions reduction potential, real-world analyses provide pragmatic insights into the operational and economic challenges that may arise. These include the risk of carbon leakage, strategic route adjustments, and the broader implications of these changes on global shipping efficiency and environmental integrity. To build on the information provided by the existing literature, our thesis will contribute to this area of research by manipulating data from the first months of the EU ETS implementation. By conducting a real-world analysis, we aim to validate the forecasts of previous studies against actual emissions and operational data. This approach will allow us to assess whether the expected outcomes, such as emissions reduction rates and the strategic adjustments predicted by simulations and reports, align with the early impacts observed following the policy's introduction.

3.3 Economic implications

As exemplified by the problematic of carbon leakage, the ETS system can also affect the economy of both shipping companies and countries. These implications are complex and must be considered when observing the impact of such policy on each stakeholder involved.

3.3.1 EU ETS in general

Using again Dechezleprêtre et al. (2023), some other results are relevant to this discussion. Section 6 of their study uses again DiD to explore the system's influence on the financial performance of companies. From the regression, the authors measured that, in the long run,

revenues of firms regulated under the ETS were about 15% higher during the ETS period compared to those without regulation. Authors attribute this intriguing increase to several factors linked with ETS regulation, such as the ability to sell free EUAs and the potential enhancements in product quality or diversification coming from investments in abatement technologies.

However, the significance of carbon allowance prices on this impact must be considered. As prices has been rising in the past decades, the pressure increased on major polluters to innovate or cut emissions. This upward price trajectory, however, reached a peak in January 2022 and stopped increasing since then, as observed in Figure 2.

Figure 2: Monthly EU-ETS carbon pricing from April 2005 to March 2024

Source: TRADING ECONOMICS, 2024 [3]

Figure 2

When looking at the reasons behind the price increases up to January 2022, Friedrich et al. (2019) highlight the 2018 reform of the EU ETS as a key driver. Moreover, the 2023 World Bank's Carbon Pricing Report sheds light on recent dynamics, noting that the global energy crisis and high inflation rates have led governments to stabilize carbon prices since 2022. This intervention, aimed at providing economic relief, showcases the delicate balance between achieving environmental objectives and maintaining economic stability (World Bank, 2023).

Therefore, even if the allowance system can increase revenue in the long run, firms must deal carefully with the short-term dynamics and the high prices currently observed.

[3] https://tradingeconomics.com/commodity/carbon

3.3.2 EU ETS in the field of shipping

When narrowing down the analysis to the emissions of vessels, Christodoulou et al. (2021) present an analysis of the economic impact of the EU ETS on the shipping industry. This study leverages MRV data to estimate the costs imposed by the ETS on ships exceeding 5000 GT.

By distinguishing the shipping sector into distinct market segments, the study breaks down how the ETS costs will affect each segment differently. As a matter of fact, it identifies that while the ETS will lead to increased costs across all market segments, certain segments like Roll-on/Roll-off (RoRo) and Roll-On/Roll-Off/Passenger (RoPax) vessels are expected to face disproportionately higher costs. This variation underscores the complexity of the ETS's impact on the shipping industry, where different types of vessels and operational models will experience varied economic repercussions (Christodoulou et al., 2021).

Yet, the study is not without its limitations. One significant oversight is the lack of consideration for the size of the vessels. Larger vessels, generally more energy-efficient, are less affected by the ETS, a factor not adequately addressed in the analysis. Additionally, the reliance on historical data, from a period before the shipping sector's inclusion in the ETS, means that the study does not fully capture the potential economic side effects of the regulation, such as carbon leakage (Christodoulou et al., 2021).

In addition to this article, the European Commission's study on the integration of the shipping and aviation sectors into the EU ETS provides information about the system's economic impacts. It describes the need for equitable cost distribution of ETS credits across all actors of the sector to ensure fair competition and prevent a decrease in voyages coming into the EU from outside. Aside of the challenge of import, the competitiveness of companies exporting goods outside the EU is also concerning as this competitiveness could be affected by the increased costs associated with the ETS. Finally, the study once again highlights the risk of carbon leakage as positive effects of emission reductions in the EU may be compensated by increases elsewhere due to relocation of the activities.

Comparing this study with the paper of Christodoulou et al. (2021), a common observation is that the ETS has various impacts on different shipping segments, which underlines the need for an analysis that distinguish the different segment of the market. While the report offers a broad view of potential risks, it lacks specificity in quantifying these risks and their precise impacts, suggesting a need for more detailed research.

4. Methodology

In the previous section, we highlighted the importance of evaluating the EU ETS's effectiveness. In this section, we will explain our data collection and analysis methods. Additionally, we will introduce the main analyses that constitute our thesis.

4.1 Data collection

The main dataframe used comes from the AIS data that provides detailed information of the maritime movements and allows to build a list of the voyages each vessel has undertaken. It provides complete voyage information, including the identification of the operating ship, its port of origin, destination, and the trajectory of its movement. This level of detail enables good understanding of shipping activities, forming the basis for the emissions calculations phase.

From this AIS data, emissions associated with each voyage were computed based on the voyage-based bottom-up approach outlined in the Fourth IMO GHG Study (2020). This method uses AIS data for each voyage to assess emissions accurately. To do so, it starts by collecting AIS information and matching it with the technical specifications of each vessel[4]. Then, the AIS data is cleaned and information regarding the operation of each vessel is collected to distinct between domestic and international emissions. Thereafter, an estimation of each voyage fuel consumption is computed based on voyage information. Finally, the method uses these consumption figures to compute emissions using emission related factors. Concretely, the methodology we employed mirrors the one used by Fuentes and Ådland (2023) in their case. A specificity of this approach is that while it calculates the emissions of GHGs, it does not account for other gases like nitrogen oxides (NOx). Indeed, even if NOx is not considered a GHG as it does not contribute to global climate change, it can harm population living close to the emission source by causing respiratory issues, acid rain and nutrient pollution in coastal waters (US EPA, 2023). This approach ensures thus that GHG emissions estimations are based on the actual operational patterns of the vessels, making that data robust for analysing the environmental impact of the shipping industry under the EU ETS framework.

[4] This is done by matching vessels in the AIS database with their IHS technical specifications database based on the IMO number or the Maritime Mobile Service Identity (MMSI) number.

Utilizing the bottom-up approach for analysing AIS data has resulted in a substantial data structure, containing approximately 5,000,000 records from January 2022 to March 2024. Each record within this dataset corresponds to a specific voyage $(v \in V)$, where V is a set of voyages, capturing movements either between two ports or between a port and open sea. The latter occurs when chartering contracts commence or conclude while the vessel is not docked. Concerning the structure of the dataframe, it is detailed in Table 1.

In conjunction with the voyage data, our research utilizes a dataframe containing information about each vessel engaged in those voyages ($s \in S$), where S is a set of vessels. This vessel-specific dataset helps to differentiate the effects of the EU ETS across various groups of vessels (see Table 2).

To maintain the clarity in the following tables, a more detailed description of the sets and the corresponding indices is available in Appendix 1.

Table 1: Description of the dataframe of voyages

Column	Description	Data type	Representative Set
imo	The International Maritime Organization number uniquely identifying each vessel	Char(7)	$i \in I \subseteq \mathbb{N}$
segr	The segment of the voyage	Int	$g \in G \subseteq \mathbb{R}_+ \mid \forall s \in S, \exists\, g : \big((d_{v1} < d_{v2}) \cap (i_{s1} = i_{s2})\big) \Rightarrow g_{s1} < g_{s2}$
start_datetime	The date of departure of the vessel	Datetime	$d \in D$
end_datetime	The date of arrival of the vessel	Datetime	$e \in E \mid \forall v \in V, \exists\, e: e_v > d_v$
port_fr	Name of the port of departure	String	$f \in F$
port_to	Name of the port of arrival	String	$t \in T$
co2_t	Amount of CO_2 emitted during the voyage	Float	$c \in C \subseteq \mathbb{R}_+$
ch4_t	Amount of CH_4 emitted during the voyage	Float	$m \in M \subseteq \mathbb{R}_+$
n2o_t	Amount of N_2O emitted during the voyage	Float	$n \in N \subseteq \mathbb{R}_+$

Table 1

Table 2: Description of vessel dataframe of vessels

Column	Description	Data type	Representative Set
imo	The International Maritime Organization number uniquely identifying each vessel	Char(7)	$i \in I \subseteq \mathbb{N} \mid \forall s \in S, s1 \neq s2, \exists\, i: i_{s1} \neq i_{s2}$
ShipName	Name of the vessel	String	$h \in H$
ExName	Previous name of the vessel, if applicable	String	$x \in X$
mmsi	Maritime Mobile Service Identity, used in identification during incidents	Char(9)	$a \in A \subseteq \mathbb{N} \mid \forall s \in S, s1 \neq s2 \Rightarrow \exists a: i_{s1} \neq i_{s2}$
RegisteredOwner--CountryOfRegistration	Country where the vessel is registered	String	$r \in R$
GrossTonnage	Total volume of the ship measured in gross tonnage	Float	$b \in B \subseteq \mathbb{R}_+$
Deadweight	Maximal carrying capacity of the ship in tonnes	Float	$w \in W \subseteq \mathbb{R}_+$
LengthOverallLOA	Total length of the vessel from bow to stern	Float	$o \in O \subseteq \mathbb{R}_+$
NumberofMainEngines	Number of main engines on the vessel	Int	$u \in U \subseteq \mathbb{N}$
Powerkwmax	Maximum power output of the engines, measured in kilowatts	Float	$p \in P \subseteq \mathbb{R}_+$
MainEngineModel	Model of the main engine	String	$j \in J$

Speed	Recommended operating speed of the vessel	Float	$k \in K \subseteq \mathbb{R}_+$
SummerDraught	Maximum draught of the vessel during the summer	Float	$q \in Q \subseteq \mathbb{R}_+$
FlagName	Name of the flag the vessel is registered under	String	$y \in Y$
FlagCode	ISO 3166-1 alpha-3 code of the flag under which the vessel operates	Char(3)	$l \in L \mid y = y_{s1} \Rightarrow l_{v1} = l_{s1}$
MainEngineType	Type of the main engine (Oil/Gas/Turbine/Reciprocating)	String	$z \in Z$
ShiptypeLevel5	Specific type of the vessel, categorized into 217 types, with a focus on major types	String	$\varepsilon \in \mathrm{E}$

Table 2

Note: the most important variables are highlighted in bold

Finally, we used a dataframe providing the prices of the EUAs. The data used was sourced from the International Carbon Action Partnership. The dataset contains the daily spot prices of emissions allowances, expressed in Euros per metric ton (€/metric ton). This information on the EUA prices is used further in the analysis to measure the economic dynamics influencing the shipping industry's response to environmental regulations.

4.2 Data analysis

4.2.1 Introduction

In this section, we focus on the data analysis process, the most important part of our work that is based on a Python notebook in a Google Colab environment, with pandas for data handling.

Our analysis starts with data cleaning, addressing any inconsistencies to build a reliable dataset. Then comes the data enrichment part, where we generated 11 new columns to provide

additional insights into our data. The exploratory data analysis (EDA) follows, where we employ descriptive statistics and visualizations to transform our data into clear information. We conclude with an overview of our network design model, a section where we identify and plot the most important routes and ports relevant to this analysis.

4.2.2 Data cleaning

Data cleaning is an important step in our analysis process that involves a series of checks and corrections to ensure the dataset is fit for use. This stage is essential for establishing a solid foundation for subsequent analyses, as it directly influences the reliability of our findings.

The first aspect of data cleaning are the straightforward data integrity checks. In our case, we verify that each identifier is unique and ensure that dates are correctly formatted. These checks prevent potential issues related to data duplication or misinterpretation due to incorrect date formats.

However, some verifications are more complex and provide significant insights. Our investigation into missing values revealed that departure and, notably, arrival ports were frequently absent (7.33% of the observation for departure port were missing and 99.85% of the arrival ports were missing). Further analysis showed that many missing arrivals port values were due to ongoing voyages at the end of a month. To address this, we annotated the corresponding entries to indicate that the ship was still at sea. In addition, we combined the rows which reported on the same journey over several months by adding up the emissions values.

Another check was to verify the continuity between voyage segments. We ensured that the arrival port of one voyage segment (recorded in the 'segr' column) matched the departure port of the subsequent segment. This check in the consistency is important for maintaining a coherent and complete representation of each voyage as it allowed to reduce dramatically the number of missing values for ports information.

Finally, we checked the dataset for extreme values of GHG emissions. Some records displayed implausibly high GHG emission values, forcing us to eliminate data corresponding to observation where the hourly emissions (in 100 years carbon dioxide equivalent (CO_2-eq)) were higher than the 95^{th} percentile value. Indeed, extreme emission values can often be attributed to AIS errors as a low signal can create transmission gaps. Therefore, we removed entries where CO_2-eq emissions exceeded 6.98 tonnes of CO_2-eq per hour (i.e. the 95^{th}

percentile), thereby mitigating the influence of potential outliers or erroneous data on our environmental impact assessment.

Through these data cleaning processes, we have significantly enhanced the dataset's quality, enabling a more accurate and reliable exploration of the EU ETS's impact on maritime transportation.

Finally, we segmented our voyage dataset into three subsets. This segmentation allows us to distinguish between voyages that do not visit Europe and those that do, that are then segmented depending on whether the voyage occurred under the active EU ETS (after January 2024) or not. It is important to note that voyages straddling the years 2023 and 2024 are subject to the ETS only for the emissions produced within 2024. However, this detail is of minimal significance in our context since voyages spanning both years are treated as separate entries in our initial dataframe.

4.2.3 Data enrichment

Once our dataset is clean, data enrichment is another important step in data analysis, where we transformed raw data into relevant information. The goal is to add information based on the data we already have, to be able to analyse it. In this section, we will describe the information we built concerning the CO_2-eq emissions, the locations of ports and the types of vessels.

The first columns we created were aimed at transforming the emissions of CO_2, CH_4, and N_2O into their CO_2-eq. This conversion allows us to compare different voyages on a uniform scale, focusing solely on one metric.

To achieve this result, we use conversion factors that express the impact of CH_4, CO_2 and N_2O in terms of long-term CO_2's impact. The most common measures to operate this conversion are the Global Warming Potential (GWP) and the Global Temperature Potential (GTP). On one hand, the GWP is a metric that quantifies the heat a greenhouse gas traps over a specific period to illustrate its warming potential. On the other hand, the GTP measures the effect that a gas has on the global temperatures at the end of a particular period. Both these measures are detailed by the Intergovernmental Panel on Climate Change (IPCC) (2013) and provide conversion factors for various gases over different time spans. Below is a summary of a conversion table showing the GWP and GTP values calculated in the IPCC report using the gases included in the carbon credit calculations.

Table 3: GWP values for 20 and 100 years and GTP values for 20, 50 and 100 years

Acronym, Common Name or Chemical Name	Chemical Formula	Lifetime (years)	GWP 20-year	GWP 100-year	GTP 20-year	GTP 50-year	GTP 100-year
Carbon dioxide	CO_2	See*	**1**	**1**	1	1	1
Methane	CH_4	12.4	**84**	**28**	67	14	4
Nitrous Oxide	N_2O	121	**264**	**265**	277	282	234

Table 3

* No single lifetime can be given

Source: IPCC[5]

Among these, the GWP is the most used metric as it is easy to compute and offers transparent results (IPCC, 2014). It compares the warming effect of a specific mass of a GHG to that of the same mass of CO_2 over a chosen time frame, giving a standardized evaluation of different gases' contributions to global warming. Therefore, we focussed on the GWP to ensure our findings are aligned with global standards. Consequently, we generate two additional columns: one representing the CO_2-eq of a voyage over the next 20 years ($y20_co2_t_eq = \alpha \in A \subseteq \mathbb{R}_+ | \forall v \in V, \eta_v = c_v + 84m_v + 264n_v$) and another for the next 100 years ($y100_co2_t_eq = \beta \in B \subseteq \mathbb{R}_+ | \forall v \in V, \beta_v = c_v + 28m_v + 265n_v$). This distinction is needed as long-term impacts of greenhouse gases vary. Indeed, methane has a more pronounced effect in the short term, which diminishes over time, whereas the impacts of N_2O and CO_2 are more stable.

Despite these considerations, it is important to note that within the shipping industry, CO_2 emissions predominantly drive the CO_2-eq figures, with CH_4 and N_2O contributing minimally to the overall emissions profile. However, our whole analysis is based on the 100 years GWP equivalent as this measure is the most used in existing literature.

Following the establishment of CO_2-eq emissions columns, we further enriched our data. A limitation in our raw data is that the emissions per voyage alone provide an incomplete picture of the vessel's environmental efficiency due to variability in the voyage lengths. Therefore, our analysis requires that this emission data is put in relation with the amount of time of each

[5] https://www.ipcc.ch/report/ar5/wg1/

voyage. To this end, we aimed to calculate emissions on a per-hour basis, facilitating a more accurate comparison across different voyages.

To achieve this, we first calculated the duration of each voyage. By subtracting the time of departure from the time of arrival, we derived the duration of each trip ($duration_hours = \delta \in \Delta \subseteq \mathbb{N}||\forall v \in V, \delta_v = e_v - d_v$), representing the voyage duration in hours.

From there, we created two columns: $y20_co2_t_eq_per_hour = \gamma \in \Gamma \subseteq \mathbb{R}_+|\forall v \in V, \gamma_v = \frac{\alpha_v}{\delta_v}$ and $y20_co2_t_eq_per_hour = \zeta \in Z \subseteq \mathbb{R}_+|\forall v \in V, \zeta_v = \frac{\beta_v}{\delta_v}$. These columns were computed by dividing the tonnage of CO_2-eq emissions by the voyage duration in hours. This straightforward transformation provides us with a better perspective on emissions, as they are now expressed as an average per hour spent at traveling, thus offering a standardized measure to evaluate the effectiveness of the EU ETS in incentivizing emission reductions across diverse voyage durations.

Following the emissions related data, the enrichment of the dataframe includes the geographical classification of ports. This process enables us to examine the impact of the EU ETS on European ports solely. To achieve this, we employed the GeoNames database, a geographical database that provides information about locations worldwide, including cities which correspond to our ports of departure and arrival.

The classification process begins with extracting the names of ports from the port of departure and the port of arrival of our dataset. Then, for each port listed, we query the GeoNames database to associate the port with its corresponding country. This association enables us to discern the global distribution of maritime traffic and identify whether a port is located within Europe or not. This determination is important given our focus on the EU ETS and its implications for European maritime activities. Therefore, by associating each port with its continent, we categorize them into 'European' and 'Non-European'.

Through this process, we enrich our dataframe by adding four new columns, which represent the countries of the departure and arrival ports, and whether these ports are located within Europe or not.

Despite the use of the GeoNames database, we encounter instances where certain ports are not found or not accurately classified. In these cases, we verified the location manually, researching each unmapped port to determine its geographical location and European status. This

meticulous process ensures that our dataset remains robust and comprehensive. As a result, we found 185 countries in total with 2771 different ports.

Then, we used information regarding ports to include the percentage of emissions that fall under European legislation. Therefore, we introduced the 'portion_eu' column, which gives the proportion of emissions for which companies are mandated to acquire carbon permits (0%, 50% or 100% of them). To ensure comprehensive data integrity, we also noted whether all or part of the data on ports was missing.

In addition to the changes in the dataframe of voyages, we also included two other columns in our dataframe of vessels by transforming the vessel type information. Indeed, this information is based on the StatCode 5 Shiptype Coding System standard that provides five levels of vessel type, each one being aggregated to a certain level. For our analysis, we decide to compute from the ship type of level five[6] the vessel type of vessel three and two by grouping the categories according to the standards (ShiptypeLevel3$= \kappa \in \mathrm{K} | \forall s_1, s_2 \in S, \varepsilon_{s1} = \varepsilon_{s2} \Rightarrow \kappa_{s1} = \kappa_{s2}$ and ShiptypeLevel2$= \lambda \in \Lambda | \forall s_1, s_2 \in S, \varepsilon_{s1} = \varepsilon_{s2} \Rightarrow \lambda_{s1} = \lambda_{s2}$). By doing so, we can analyse patterns across different vessel types with a smaller number of vessel type as types have been grouped together.

4.2.4 Data analysis

With our dataset ready, we can start analysing the effectiveness and impact of the EU ETS. First, we observe the evolution of emissions since January 2024 to identify any immediate trends resulting from the policy implementation. Then, we extend our analysis period from January 2022 to March 2024 to observe long-term trends in emissions. To do so, we use linear and Autoregressive Moving Average (ARMA) models to represent the relationship between time and emissions. Additionally, we implement a DiD analysis to test whether the introduction of the ETS has significantly influenced emission reductions.

We also examine how vessel speeds have evolved over the same period. Indeed, speed is an important operational parameter that greatly influences fuel consumption and, consequently, GHG emissions. Studies, such as Faber et al. (2017), have shown that reducing vessel speed, commonly referred to as 'slow steaming,' can lead to substantial decreases in fuel usage and emissions. In addition, speed reduction is relatively simple to implement as it does not require any technological change. Therefore, observing potential speed reductions is a good indicator

[6] The most precise level

of the first response of vessel to a change in legislation. We graphically represent this evolution and employ again a DiD approach to assess the impact of the policy on vessel speeds.

Furthermore, we conduct a comparative study of different vessel types. By graphically representing emissions and speed data across various categories of ships, we interpret the differences in impacts of the ETS between these groups.

Next, we explore the relationship between the price of EUAs and emissions levels. Using the Pearson correlation coefficient, we measure the correlation between these variables. To confirm the causal relationship, we apply a Granger causality test, that check whether fluctuations in ETS prices can predict changes in emissions.

Finally, based on network analysis we created a network design that utilizes a directed graph-based model to represent international maritime transportation and analyse CO_2-eq emissions related to each route and each country. In this model, countries are depicted as nodes connected by edges representing maritime voyages. Node size varies with the total emissions of each country, offering a visual indicator of their environmental impact, while node colour distinguishes European countries in blue and other countries in green.

Edges are also weighted by the emissions of all the voyage using the route and are colour-graded from lighter to darker red to highlight the emission intensity of the routes. This visual differentiation aids in identifying important corridors for targeted environmental policies under the EU ETS framework.

We employ the Python library NetworkX to construct the graph of aggregated emissions data. This network can adapt to focus on various segments like EU to EU or Non-EU to EU maritime traffic.

The detailed explanation and the interpretation of the results for each of these analyses can be found in the following section.

5. Results

We now move to the analytics and observations of how the EU ETS has influenced maritime journeys. This section begins with a comparative analysis of emissions between voyages that include ports within the EU's jurisdiction against those that do not in the early months of 2024. Subsequently, we delve into the core of the carbon market's influence, examining the introduction of the EU ETS and its consequences on GHG emissions across different routes by comparing emissions levels in 2024 compared to before. Finally, we assess the extent to which the EU ETS has potentially reshaped the significance of ports and routes and explore the occurrence of carbon leakage as a response to regulatory pressures.

5.1 Short term analysis

To evaluate the initial response to the carbon market introduction, we start by determining whether there is a discernible influence on emission trends within the first month of the EU ETS's application. To this end, the first approach is to observe emissions data from three first months of 2024, and compare voyages based on the proportions of their emissions subject to reporting under the EU ETS framework.

5.1.1 Descriptive statistics

To observe how emissions level evolve across different groups of voyages, we create distinct clusters based on the degree to which each voyage is required to provide EUA. We achieved this by grouping our dataframe according to the 'portion_eu' column, which reflects the proportion of the voyage occurring within ports under the jurisdiction of the EU.

The outcome of this classification places all voyages into six mutually exclusive categories. Firstly, we have voyages that both originate and conclude outside of Europe, and those that start and finish within Europe. We also account for voyages that either begin in Europe and end beyond its borders or vice versa. Additionally, the great number of voyages with incomplete port data forces us to consider three other categories: voyages starting or ending in Europe with missing counterpart information, voyages starting or ending outside of Europe with missing counterpart information, and voyages for which we have no port information at all.

After establishing these groups, we then turn to a descriptive analysis to discern how pollution levels are distributed within each category by specifically observing CO_2-equivalent emissions

over 100-year. We assess the central tendency and dispersion measures to provide a clear statistical overview of emissions within each distinct group.

In the following table (see Table 4), we see a reassuring trend: around 80% of our voyages have complete port data. In addition, voyages that start and end either within or outside of Europe exhibit the lowest GHG emissions. This could reflect the effectiveness of regional shipping practices and environmental policies.

However, voyages with missing port information tend to show higher pollution levels. It is likely that these figures represent longer, possibly ongoing voyages, explaining why they show higher levels of emissions compared to the typically shorter, complete voyages.

Groups with incomplete data also present a greater variance in emissions, hinting at their diverse nature, possibly due to long-haul routes or data entry errors. Therefore, to maintain the integrity of our analysis, we will omit these less uniform groups from certain future evaluations.

Among voyages with complete information, those with European ports as destinations or origins report significantly higher emissions. This is because the data reflects total voyage emissions without considering the length of the trip, and voyages involving Europe tend to be longer.

Table 4: Descriptive statistics of 100-years CO_2-eq emissions

Proportion of the voyage in an EU port	Number of observations	Mean (tonnes)	Standard deviation	Min	25th percentile	50th percentile	75th percentile	Max
Voyage between non-EU ports	378023	119.324	473.704	0	0.331437	2.367731	33.276	14989.415
Voyage between EU and non-EU ports	8839	699.370	1102.5	0.189	61.406	256.171	847.297	11275.822
Voyage between EU ports	44553	111.275	345.926	0	0.491	3.293	82.562	12158.332
No information about the ports	11892	3981.66	3415.901	0	1161.145	3343.451	5729.301	15231.925
One port in the EU, other is unknown	8023	1226.25	1792.343	0	141.061	497.188	1535.922	14795.201
One port outside the EU, other is unknown	37518	1551.90	1899.934	0	235.922	849.052	2190.931	15026.991

Table 4

Even if these insights help us to understand how voyage specifics correlate with emissions in the context of the EU ETS, observing voyage emissions alongside their respective durations and observe average hourly pollution levels is more relevant. It allows for a standardized comparison across different voyages, regardless of their length.

Table 5: Descriptive statistics of 100-years CO_2-eq emissions per hour

Proportion of the voyage in an EU port	Number of observations	Mean (tonnes)	Standard deviation	Min	25th percentile	50th percentile	75th percentile	Max
Voyage between non-EU ports	378023	1.125	1.297	0	0.296	0.587	1.436	6.978
Voyage between EU and non-EU ports	8839	2.477	1.591	0.163	1.263	2.042	3.362	6.977
Voyage between EU ports	44553	1.641	1.502	0	0.481	1.157	2.21	6.978
No information about the ports	11892	2.171	1.531	0	1.012	1.84	2.953	6.977
One port in the EU, other is unknown	8023	2.02	1.462	0	0.933	1.626	2.69	6.972
One port outside the EU, other is unknown	37518	2.215	1.506	0	1.062	1.86	3.005	6.978

Table 5

These standardized measures can be plotted to visualise the differences between the different groups we consider. We represent each distribution in a boxplot that allows to observe the dispersion of each group (see Figure 3).

When reviewing this figure, we note that distinguishing between intra-European and extra-European voyage pollution levels is not straightforward. This lack of disparity could come from the early stage of the carbon market system's implementation. The shipping industry has, presumably, not yet had sufficient time to adapt technologically or operationally to the costs associated with the regulation. Consequently, the emission levels from voyages within Europe

remain comparable to those from the rest of the world, given that both are still driven by similar economic incentives.

However, an observation of note is that the category of voyages with exactly one port in Europe tends to have the highest emissions. These voyages are predominantly intercontinental, spending a substantial portion of their journey on the high seas. In contrast, voyages entirely within or outside Europe are often intracontinental, spending a relatively greater amount of time within territorial waters. The discrepancy between the intercontinental category and the others is to be expected. As highlighted by Li et al. (2022), the lack of regulation on the high seas leads to higher pollution levels compared to territorial waters. Furthermore, this gap is likely to widen as territorial regulations become more stringent. With emissions on the high seas increasing by an estimated 7.26% annually, compared to a 2.23% annual increase in the global maritime sector, the difference in pollution levels between these areas is increasing. The role of environmental policies such as the EU ETS is therefore decisive, as it aims to provide an economical incentive for reducing emissions while departing from or going to the European Union, even when being on the high seas (Li et al., 2022).

Figure 3: Distribution of 100-years CO_2-eq emissions per hour

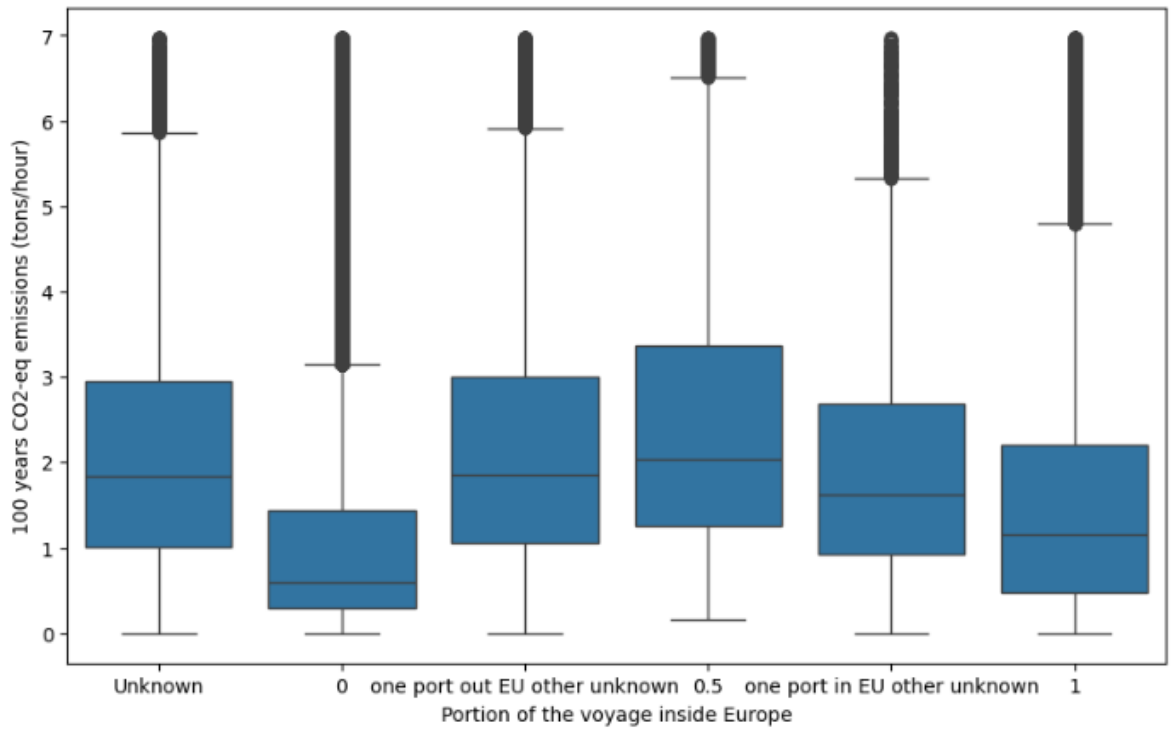

Figure 3

5.1.2 Preliminary findings

While assessing the dispersion measures of voyages during the initial three months of the year provides a good overview of the general state of emissions, it does not offer insight into the dynamics of ship emissions since the start of the year. To gain a better understanding of emission trends, we examine the trajectory of pollution levels over these three months.

To do so, we focus on the evolution of average daily pollution levels for the three most relevant groups. These are voyages mandated to report 100% of their emissions, those required to report 50%[7], and those not required to report any. The decision to concentrate on these categories comes from their direct relevance to the EU ETS's impact, while other groups were excluded due to their less informative nature regarding hourly pollution levels.

Fig. 4 presents an interesting trajectory for GHG emissions from voyages during the first quarter of 2024. As we might expect from our earlier observations, voyages that are obligated to report 50% of their emissions not only start off with higher pollution levels but also show a more pronounced decrease over time.

More unexpectedly, we see that extra-European voyages are experiencing a downward trend in pollution levels that is steeper than the trend of intra-European voyages. A possible explanation for this development came on February 15, 2024, when the European Commission revised its economic forecasts upwards, anticipating a faster-than-expected decline in inflation. This optimistic economic outlook could be driving a surge in shipping activity within Europe, leading to more emissions than in the rest of the world. However, this figure is difficult to read due to a huge difference between the pollution level observed in the different groups. Therefore, Fig. 5 represents the trend of emissions by plotting the daily average pollution level compared to the monthly average.

In Fig. 5, we observe more clearly that, while the voyages outside of Europe seem to follow a downward trend, the voyages that visit at least one European port seem to experience an exponential decrease. This observation shows that voyages occurring in Europe are subject to other factors that pushes them to diminish their emission faster. Whether this increasingly important factor is the consideration of the new ETS system is difficult to assess at the moment.

[7] We acknowledge that in 2024, they report only 40 and 20% of their emissions respectively. The formulation used here and later in the work refers to the relative proportion of emissions that must be reported compared to the maximum amount that can be reported this year.

These first results show, nevertheless, that emissions of vessels visiting EU ports are subject to an increasing pressure.

Figure 4: Evolution of daily average 100-years CO_2-eq emissions

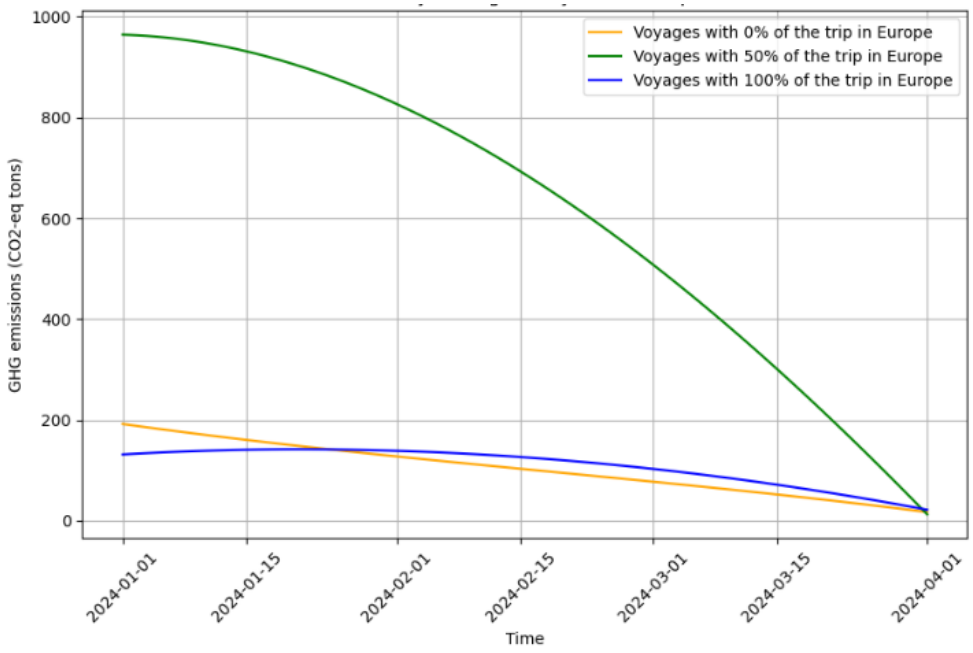

Figure 4

Figure 5: Evolution of daily average 100-years CO_2-eq emissions compared to 2024 average within each group

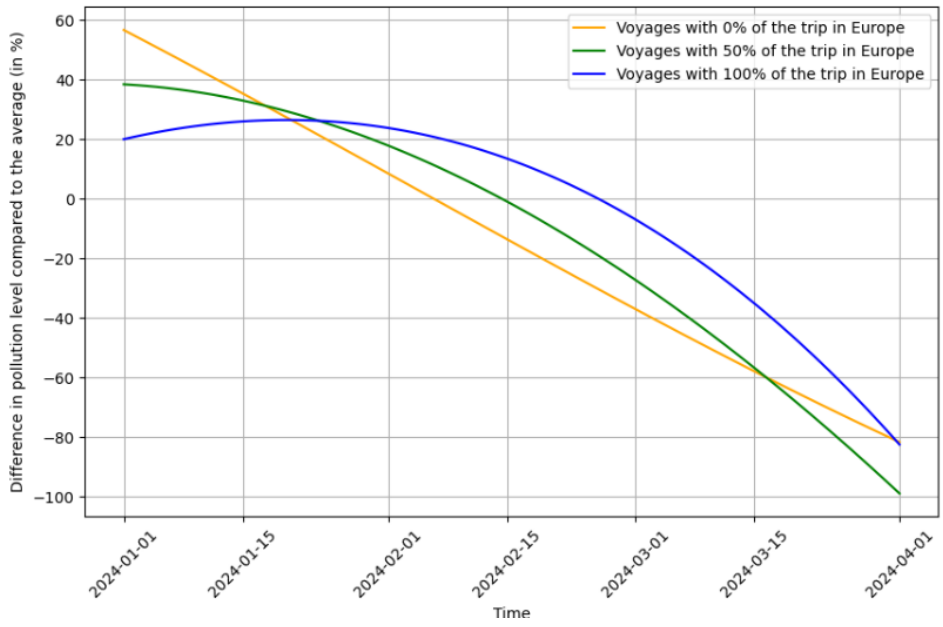

Figure 5

In the following sections, we will extend our analysis to previous years to determine if there were any anticipatory changes in the industry that could indicate a more subtle influence of the EU ETS leading up to 2024.

5.2 Long term analysis

5.2.1 Analysis of the vessels' GHG emissions

In this examination of emissions, our focus now shifts beyond short-term fluctuations to concentrate on a broader perspective. By doing so, we want to observe the long-term trends as well as the efficacy of the EU ETS over a more extended period. In addition, we want to confirm the observations of Faber et al. (2017) that vessel speed is one of the main drivers of vessels' GHG emissions. Indeed, the authors estimated that reducing speed by 10% reduces the GHG emissions by 13%. Therefore, we make the hypothesis that the trend of GHG emissions is strongly correlated with the one of speed and that potential breaks in the emissions could also be found in speed levels.

The first step is to observe the evolution of emissions and speed as well as their trends since January 2022 (See Figure 6). The aim is to get a first idea of what might be driving the speed of vessels and if these variations impact the GHG emissions. To do so, we analyse the evolution of the weekly average speed and emissions of CO_2 equivalent over 100-year tonne for all voyages occurring within each respective week. Given the variability in the number of voyages taking place on different date, we focus on average values. Furthermore, to mitigate the influence of short-term fluctuations, we opt to examine average speeds and emissions on a weekly basis. This approach helps in smoothing out any transient anomalies.

As expected, Figure 6 shows the relationship between vessel speed and GHG emissions. Despite some deviations where emission peaks do not correspond to increases in speed, the general trend supports the utility of speed adjustments as a method for controlling emissions. This demonstrates industry practices in which companies primarily manage emissions through speed regulation.

In a recent study of Kouzelis et al. (2022), the evolution of maritime fuels is examined with a focus on how some alternative fuels (methanol, upgraded bio-oil, Fischer–Tropsch diesel and liquefied bio-methane) can be economically viable, and how they can help maintaining high speeds while reducing emissions. As these technologies mature, we expect that their adoption

will decouple the link between higher speeds and increased emissions, suggesting high speeds and environmental efficiency may coexist.

Furthermore, we observe a distinct pattern of peaks and troughs occurring both for the speed observation and the emissions. Fig. 6 depicts a significant increase in both speed and emissions during the winter months, as highlighted by the trendlines' upward movement during these periods. This seasonal rise can be attributed to increased shipping activity due to a higher demand for commodities used for heating. The demand surge for shipping services naturally drives up freight prices, which in turn appears to correspond with higher speed levels and thus higher emissions, suggesting that shipping companies may ramp up operations to capitalize on favourable market conditions.

As mentioned above, spikes in emissions happen each January, April and August while not particularly being related to speed variations. However, the spike observed at the end of March 2024 is particularly pronounced, warranting a deeper dive to understand whether this is due to data accumulation at year's end, an actual spike in shipping emissions, or an anomaly within the data collection process itself.

Indeed, concerning this recent trend, we see that the correlation between speed and emissions is more difficult to discern. On one hand, the emissions long-term trend does not present a strong downward trajectory after the introduction of the EU ETS in January 2024. This could suggest that any potential impacts of the EU ETS on reducing emissions are not yet apparent from the data at hand. Indeed, the figure's seasonality may mask any immediate effects of the regulatory measure.

On the other hand, speed data have plunged since January 2024, indicating that the EU ETS has indeed been considered by companies. A reason why the trend curves no longer follow the same trajectory could be due to a time lag between the reduction in the speed and the level of emissions. Therefore, we conclude that the EU ETS seems to have incentivized companies to reduce their speed but that this speed reduction cannot yet be observed in the emissions level of vessels.

Figure 6: Weekly average of speed and 100-year CO_2 equivalent emissions

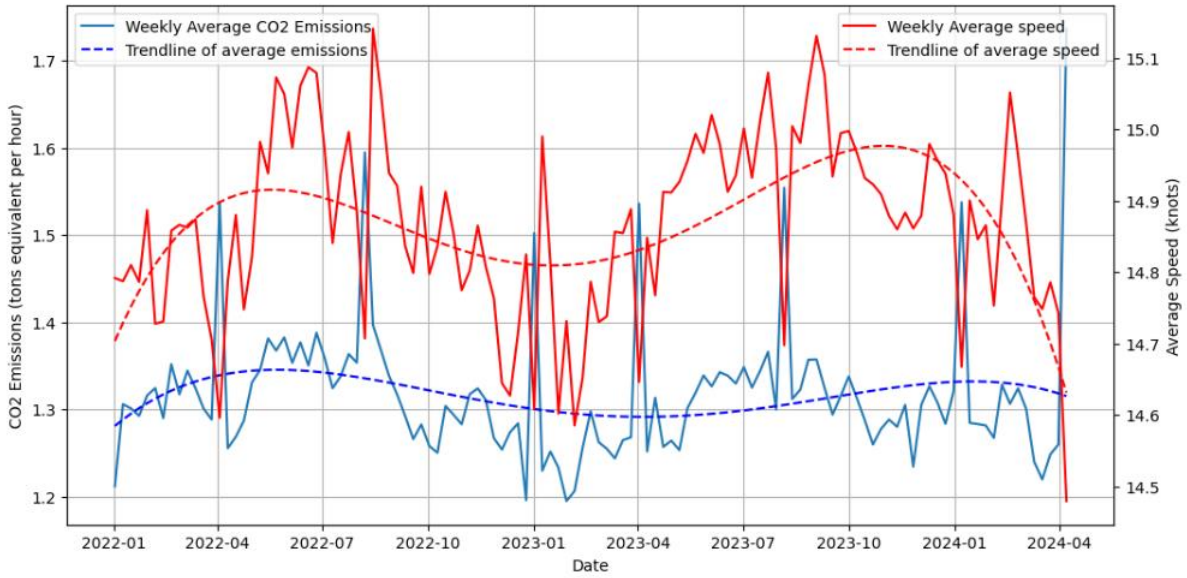

Figure 6

To better see the impact of the carbon market on emissions, we focus on voyages visiting at least one European port, as these are the trips directly influenced by the EU ETS. This focus will help clarify the policy's effect on shipping emissions. To do so, we start by plotting the trend of emissions depending on the proportion of European ports within the voyage.

Fig. 7 shows that each of the groups follow the same seasonal pattern. In addition, we see that, since the official announcement in January 2023 of the introduction of the shipping sector in the EU ETS system, the emissions of trips visiting EU ports has not decreased and follows the same seasonal pattern as before. A reason therefore might be that since the announcement in January 2023, prices of carbon permits have decreased, and so did the anticipated pressure on shipping companies. In short, we see that the announcement as well as the introduction of a carbon market in Europe does not seem to have had a significant impact, highlighting the slow speed at which the shipping industry can adapt their practices.

Figure 7: Trend curve of weekly weighted average of CO_2 equivalent

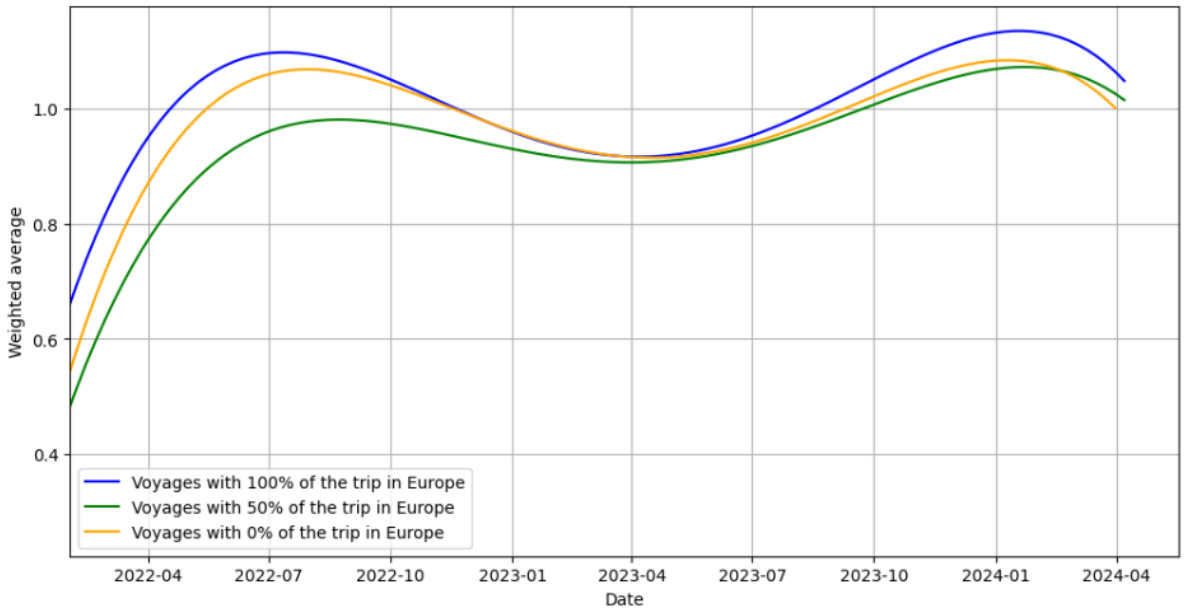

Figure 7

After this brief overview, we adopt a more sophisticated approach through statistical modelling. Specifically, we employ linear models and ARMA models.

Linear models are used to quantify the strength and direction of relationships between time and emissions. They allow us to estimate the average change in emissions for each time unit and to assess whether this change is significant. In addition, ARMA models are suited to time series data like ours because they can capture and adjust for patterns that are not immediately apparent in the data. These models consider the possibility of autocorrelation, where past data points influence future ones, and they integrate seasonal trends that linear models might overlook.

When focusing on voyages that occur within the EU (whether partly or fully) we find that time can serve as a significant explanatory variable for emissions. First, we checked that our timeseries were stationary through an Augmented Dickey-Fuller Test and concluded that both the timeseries of emissions withing the EU and of emissions partly within the EU were stationary, an important precondition for ARMA modelling. Then, after plotting the Autocorrelation Function (ACF) and the Partial Autocorrelation Function (PACF) for both groups, we find that both our Auto Regressive (AR) models should be of order 1 and the Moving Average (MA) models of order 2 (See Appendix 2). As a result, the performance indicators of our ARMA (1,2) models are more robust than the one in the linear model (See Appendix 3). This suggests that, as expected, emissions can partly be explained simply by previous pollution levels.

Figure 8: Emissions of intra-European voyages over time with predictive models

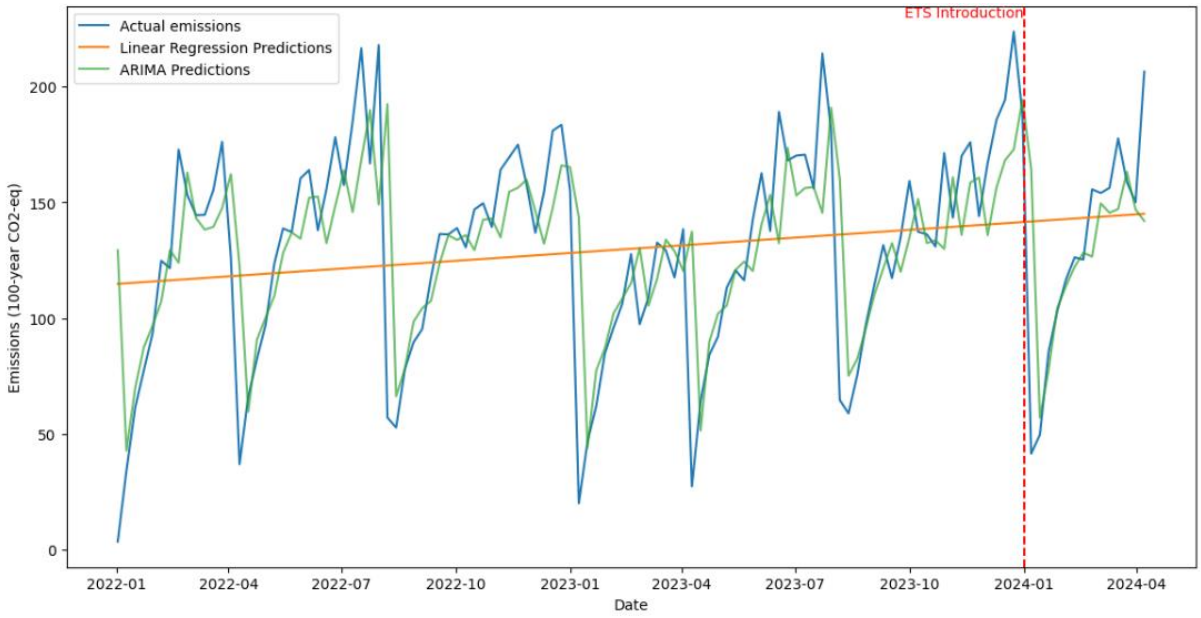

Figure 8

Figure 9: Emissions over time with predictive models for voyages with one port in Europe

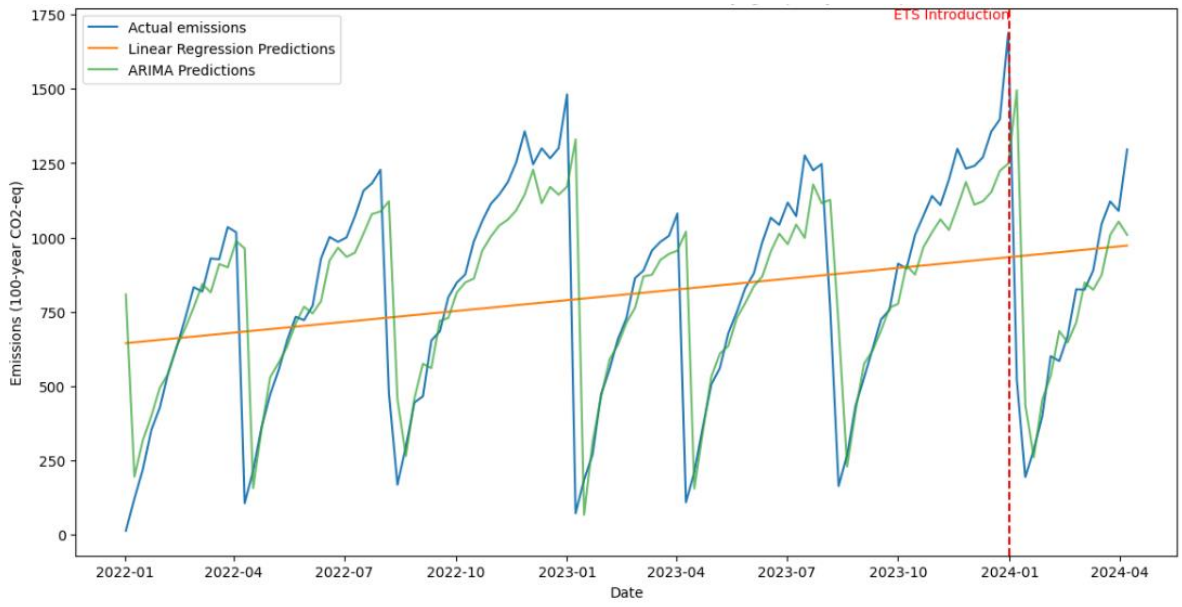

Figure 9

To go further into the analysis of the evolution of emissions since the introduction of the EU ETS, we try to observe if January 2024 marks a clear break in the emission levels. Therefore, we represent the situation using graph theory and we then conduct a DiD analysis.

First, graph theory is used to test our hypothesis that from 2024, emissions were reduced regarding ports in Europe.

Fig. 10 shows that emissions are concentrated around a few global shipping hubs. Particularly, the importance of countries such as China, the United States, and India is seen in the larger percentage of emissions concerning these countries and the thicker edges to EU countries, indicating that routes connected by these countries contribute significantly to maritime emissions. Within Europe, the Netherlands emerges as an important actor, indicating a dense web of intra-EU trade.

Figure 10: Voyages prior to 2024 and visiting at least one European port

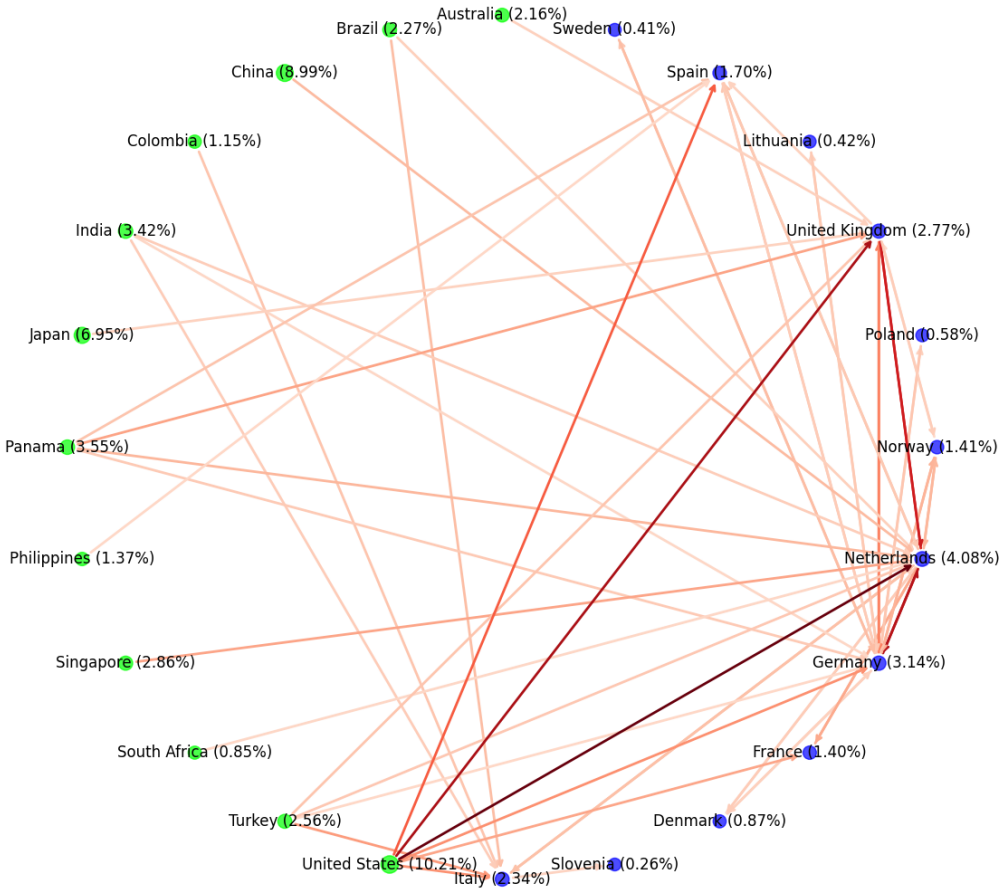

Figure 10

In Fig. 11, we expected to observe some deviation from the previous years, but the obtained result does not seem to confirm this hypothesis. Indeed, with only a three-month window into the post-EU ETS era, the anticipated reduction of emissions in European ports did not happen, and the overall network topology appears unaltered.

To sum up, this graph representation showed that changes in the behaviour of shipping companies is not easy to observe as many factors may influence the decisions of these companies. Furthermore, it suggests that the actual impact of the EU ETS on maritime traffic

patterns is complex as it involves economic, logistical, and regulatory factors that may not lead to immediate changes as initially thought. However, as the industry continues to adjust to the EU ETS, future data may show clear shifts in which ports and which routes are selected.

Figure 11: Voyages posterior to 2024 and visiting at least one European port

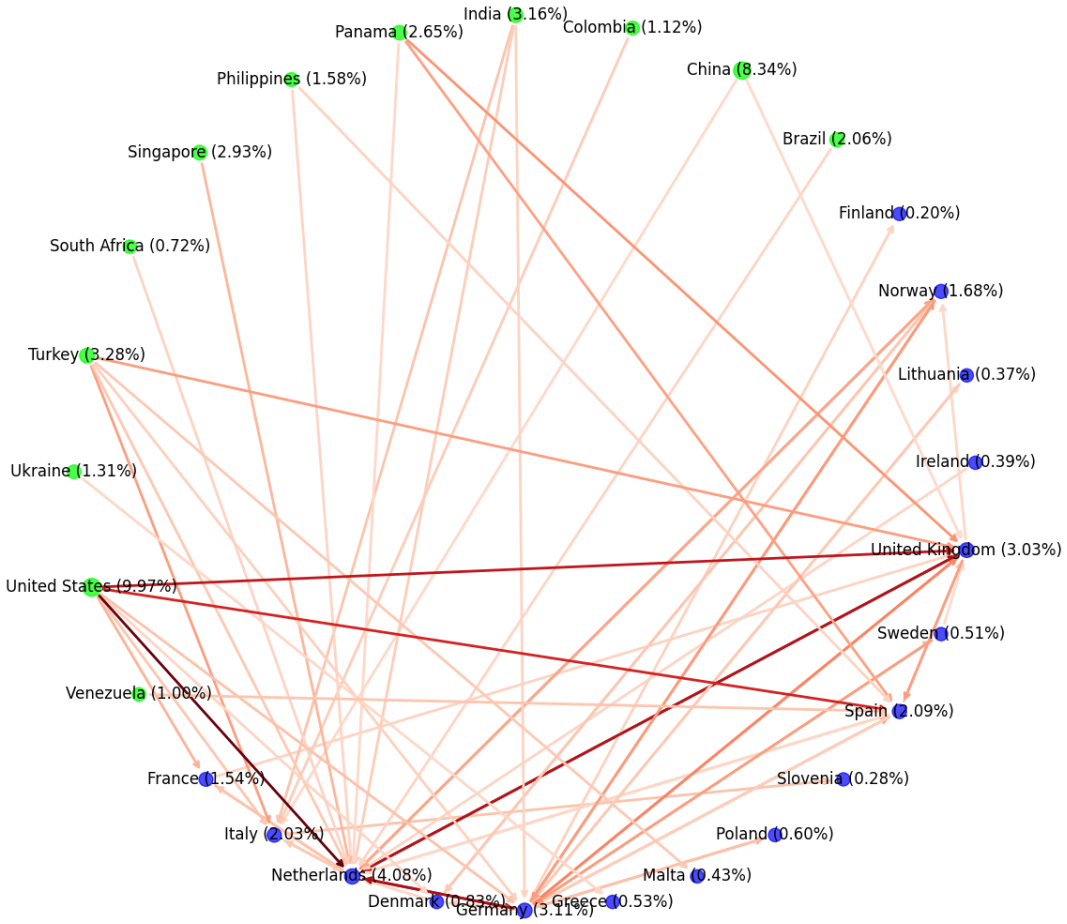

Figure 11

Secondly, the DiD method measures the effect of a specific intervention or treatment by comparing the changes in outcomes over time between a group that is exposed to the intervention (the treatment group) and a group that is not (the control group). DiD starts with the identification of the treatment and control groups, as well as the pre-intervention and post-intervention periods.

In our context, the treatment group are the voyages that must report emissions fully or partially under the ETS, with the post-intervention period spanning from January to March 2024. The control group consists of non-EU voyages not subject to the ETS, with comparable pre-intervention periods established from January 2022 to December 2023 for a balanced comparison.

The DiD is computed by taking the difference in the average change in emissions (measured by the 100-year CO_2-eq emissions) for the treatment group before and after the ETS implementation and then subtracting the average change in emissions for the control group over the same time frame.

This approach is relevant here as it allows to observe the shock due to the introduction of policy while considering the common trends between the treated and untreated groups. Through the DiD analysis, we aim to observe whether there is a statistically significant reduction in the average emissions of vessels that could be attributed to the operational and economic adjustments coming from the ETS regulation.

When observing the results (see Table 6), we observe first that there has been a decrease in the level of emissions per voyage in both groups of 15.8823 tonnes CO2-eq on average since 2024 (variable post). However, this coefficient is not significant, showing that there is a 12.1% chance to observe such results while the level of emissions has remained constant. Nevertheless, we see that the global level of emissions is likely to have dropped since the introduction of the EU ETS.

In addition, the model shows that the trips concerned by the ETS measure show an additional decrease of 15.3762 tonnes of CO_2-eq compared to the voyages outside of Europe (variable treatment_post). When compared to other sectors[8] for which Dechezleprêtre et al. (2023) estimated, using a DiD, that EU ETS contributed to reducing the emissions by 10%, this already represents a decrease of 5.8% of emissions in the EEA, showing that shipping companies, while probably not abating emissions enough for the moment, start showing results that are similar to other sectors. However, once again, the level of significance is too low and we cannot conclude surely that the ETS has indeed reduced the level of emissions, as there is a 28.8% chance to observe such result while the ETS has had no effect on emissions levels.

In conclusion, these results go in the expected direction even if the lack of statistical significance prevent us from concluding formally that the EU ETS has reduced the level of emissions. This limitation might be caused by the relatively low amount of data we have for our post-treatment group due to the recent implementation of the policy. Therefore, the results we obtain should be tested again with a larger set of data to be confirmed.

[8] The observed sectors are the food, beverage, tobacco, chemicals, pharma., rubber, plastic, minerals, electricity, gas, steam and other manufacturing sectors.

Table 6: Summary of the DiD model for emissions

Variable	Coefficient	Std. Error	t-Statistic	Probability
constant	124.67	3.4	36.71	0
treatment	110.58	4.8	23.02	0
post	-15.88	10.25	-1.55	0.12
treatment_post	-15.38	14.46	-1.06	0.29

Dependant Variable	emissions	Jarque-Bera	831.814
Method	Least Squares	Durbin-Watson stat	0.403
No. Observations	1641	Akaike info criterion	1.949e+04
R-squared	0.265	Bayesian information criterion	1.951e+04
Adjusted R-squared	0.263	F-statistic	196.4
Log likelihood	-9742.4	Prob(F-statistic)	8.72e-109

Table 6

5.2.2 Analysis of the vessels' speed

With the introduction of the ETS system in Europe, we are interested in observing the effect the policy can have on the practices of shipping company. The previous section acknowledged the fact that emissions are strongly linked with the speed of vessels and that while the time since the implementation of the carbon market is too short to observe a significant change in emissions, it seems that companies already took action in response to the policy by reducing their speed and thus their emissions. However, we want to verify if this reduction of speed is significant and whether all the industry responds to the ETS policy in the same way. Within our dataset comprising trips concerning European ports, we identified an array of 193 vessel types when observing the 5th and more precise level of StatCode 5 Shiptype Coding System. To make our results easier to read, we therefore base our analysis on the second ship type level that gives a more aggregated image.

To observe the variations in how different vessel groups responded to the implementation of the ETS, we plotted emissions data for each group. We constructed two boxplots for each vessel type under consideration. The first boxplot (in blue) depicts speed from trips made visiting at least one European port before the implementation of the ETS, where carbon certificates were not required yet, even if we only consider trips made by vessels bigger than 5000GT. The second boxplot (in red) illustrates speed from trips occurring after the vessel owners were mandated to deliver EUAs (See Figure 12).

First, it is evident from Fig. 12 that speed levels vary dramatically between different groups, which indicates that vessels' speed is not uniform across vessel types. This diversity suggests that the impact of environmental measures could vary depending on the type of vessel.

On one hand, some vessel classes exhibit changes in speed levels post-ETS. However, the direction of change is not uniform across all vessel types. Most smaller vessel types, such as offshore and fishing vessels, appear to have reduced their speed. This finding confirms Christodoulou, A. (2021), who suggests smaller vessels should be under greater pressure to reduce emissions and therefore speed following ETS implementation. The figure partially corroborates this, with most small vessels showing a decrease in speed.

On the other hand, larger vessels, including passenger vessels and containerships do not show a significant reduction in speed; in some cases, there seems to be a slight increase. This confirms that regulatory pressures are smaller on larger vessels or that they might be more willing to pay for their emissions via emissions credits, even if they should nevertheless induce a reduction in speed.

Figure 12: Speed distribution by vessel type

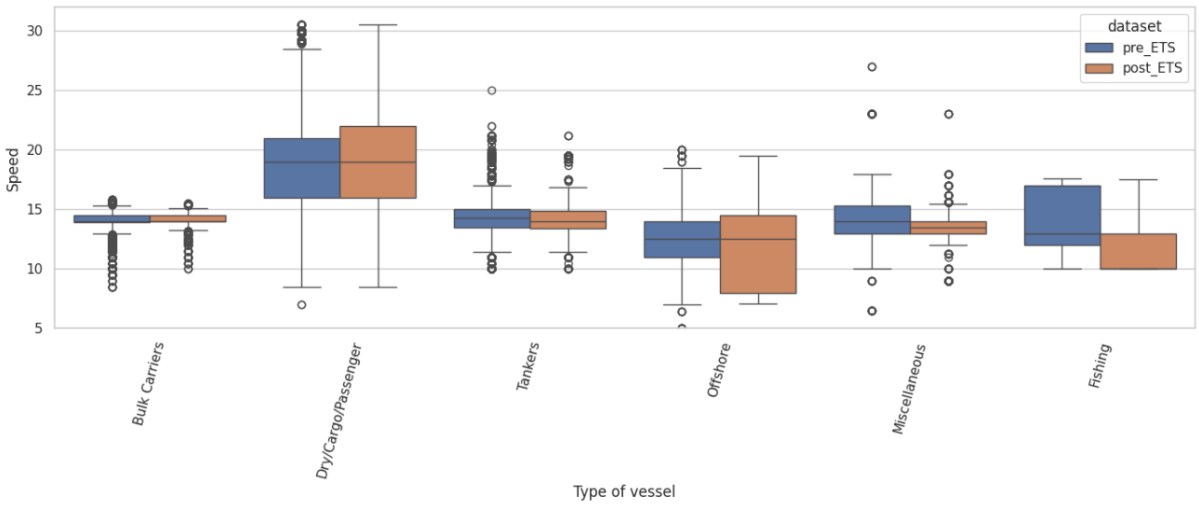

Figure 12

Note: The boxplots are displayed in descending order of the average gross tonnage within each category (Considering only vessel bigger than 5000GT).

To confirm these observations, we conduct DiD analysis of the speed evolution within each vessel type (see Appendix 5). The results of our models tend to confirm our hypothesis that speed may have decreased for small vessels while it might have slightly increased for larger one. Among the six vessel types observed, five of them show a significant change in vessels speed with at least a 95% confidence level.

Among the significant test, two of them, namely the one concerning bulk carriers and Dry cargo/Passenger vessels show a significant increase of 0.12 and 0.19 knots respectively. Interestingly, these two types of vessels are the one with the highest average gross tonnage.

On the opposite, smaller vessel types that are offshore, other types of ships, and fishing vessels show a significant decrease in speed. What's more is that the smaller the average size of the vessels inside the vessel type, the larger this decrease is, with a decrease of 0.26 knot for offshore, 0.64 for others and 1.92 knots for fishing vessels.

Finally, the category of tankers vessels that in our case contain average sized vessels is the only category not displaying a significant change in vessel speed.

These results confirm once again the prediction from Christodoulou, A. (2021) that smaller vessels are more impacted by the ETS. Here, we confirmed that this larger pressure on smaller vessels indeed translates in a reduction speed for those vessels.

5.2.3 GHG emissions evolution across vessel types

After noting a small decrease in emissions across all industry and a substantial decrease in speed from small vessels following the implementation of the ETS, our focus now turns to discerning variations in the emissions across different vessel types.

Once again, we represented the situation using boxplots. As in the previous section, blue boxplots represent voyages before the entry into force of EU ETS while the red ones represent the situation of vessels subject to the measure (See Figure 13).

In this case, we see that some vessel classes exhibit changes in emission levels post-ETS, though these changes do not appear to be substantial. Most smaller vessel types, such as bulk carriers and fishing vessels, appear to have reduced their emissions.

Larger vessels, including Dry cargo/passenger vessels however do not seem to have reduced GHG emissions. These observations corroborate the findings from the previous section,

confirming that the correlation between speed and emissions hold across all groups of vessels as these small sized vessels are also the one identified as the ones having reduced their speed.

Figure 13: Hourly emissions distribution by vessel type

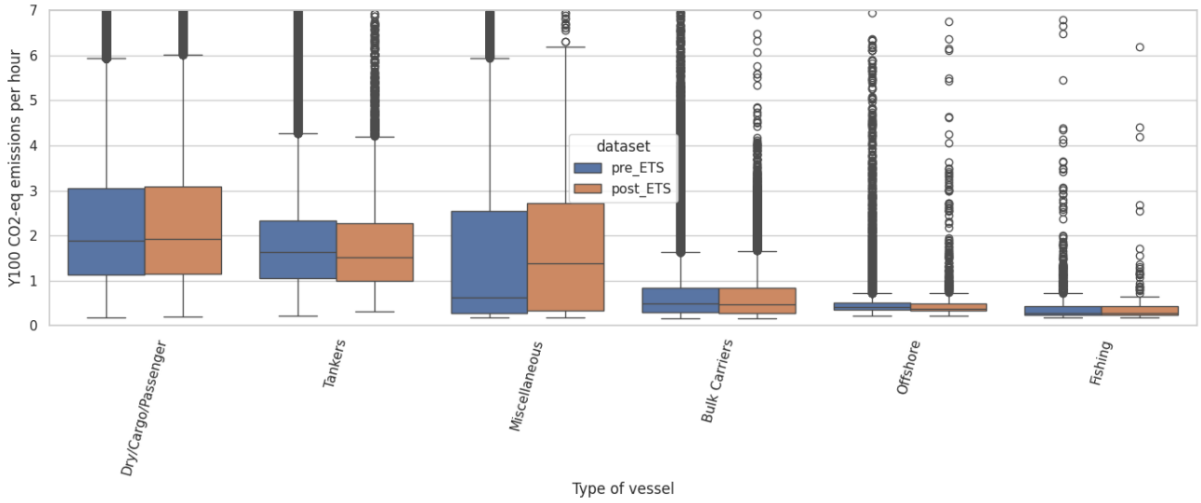

Figure 13

Note: The boxplots are displayed in descending order of the average emissions within each category (Considering only vessel bigger than 5000GT).

However, when analysed using DiD models (see Appendix 6), these fluctuations appear to be too small to be significant within different vessel types. This issue, which arises during the modelling process, suggests the need for further research once the ETS has been implemented over a longer period. This extended timeframe will likely make the differences between vessel types more distinct and statistically significant.

5.2.4 EU ETS general price impact

In this section, we explore the potential relationship between the pricing of the EUAs and the emissions generated within the EU. By examining this correlation, we aim to assess whether fluctuations in ETS prices influence maritime emissions. Identifying a significant link could suggest that adjustments in the price of EUAs may serve as an effective lever to reduce vessel emissions. Such findings would provide valuable insights for policymakers seeking to enhance the efficacy of the ETS as a tool for environmental management, aligning economic incentives with sustainability goals of the measure.

To measure this relation, we calculate the Pearson correlation coefficient. This coefficient measures the degree of linear relationship between two variables. As for the interpretation, a Pearson coefficient near 1 indicates a strong positive correlation, near -1 indicates a strong negative correlation, and around 0 suggests no linear correlation.

In our case, for all trips occurring visiting an EU port prior to the implementation of the ETS, we observed a Pearson correlation coefficient of -0.14, indicating a weak negative correlation between the prices of EUAs and emissions. This suggests that companies may have adjusted their operations in anticipation of the pressures imposed by the ETS.

More significantly, post-implementation of the ETS, this coefficient drops to -0.75. This change underscores a much stronger negative relationship, indicating that higher allowance prices are now more effectively influencing companies to reduce emissions, as they bear the responsibility of providing certificates for their emissions during voyages in Europe.

These trends are illustrated Fig. 14 and 15, which depicts the correlation between ETS prices and emissions, and the evolving trend between these two variables since the ETS's implementation.

Figure 14: Average emissions vs ETS Price with Trend Line before the ETS implementation

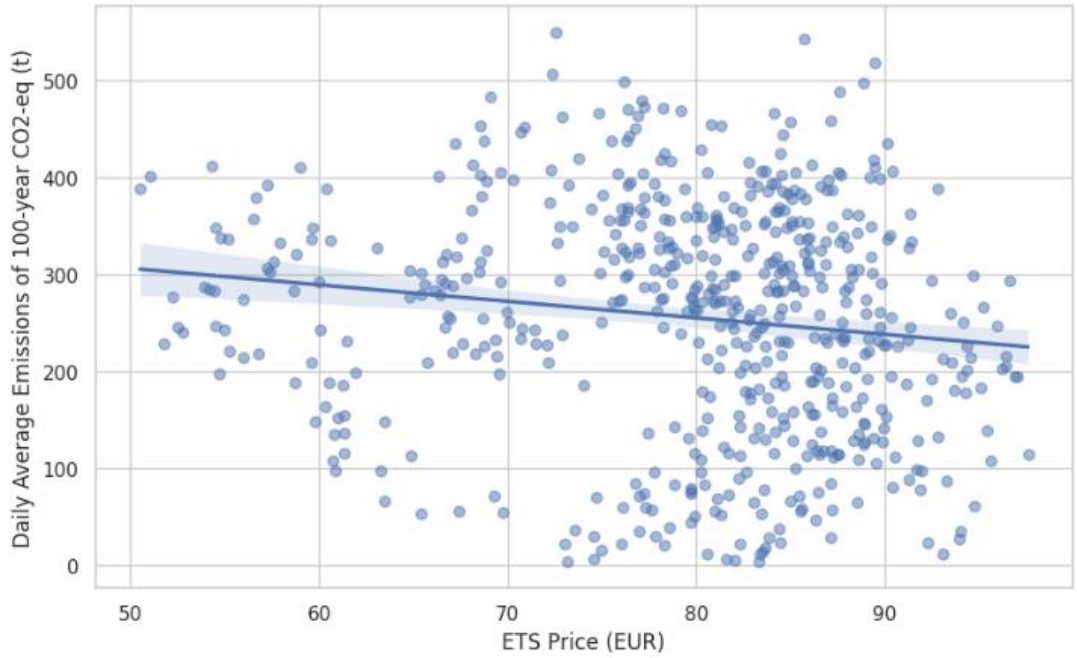

Figure 14

Figure 15: Average emissions vs ETS Price with Trend Line after the ETS implementation

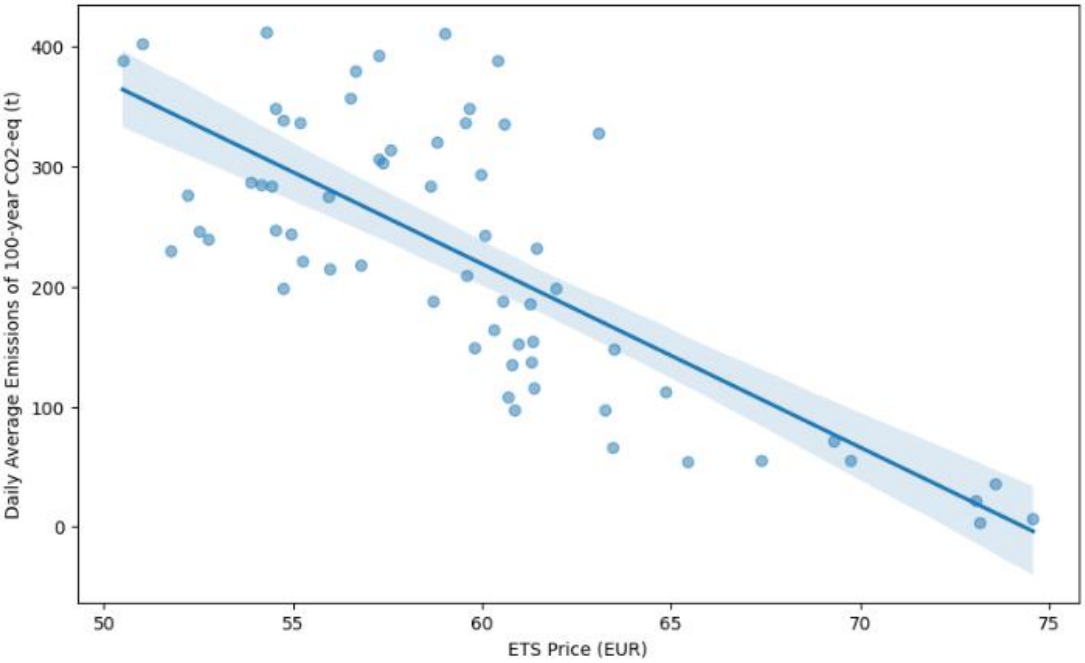

Figure 15

To further quantify the strength of the link between the pricing of EUAs and maritime emissions, we employ a linear regression model, and proceed with the regression analysis.

The regression results indicate a relationship between ETS prices and emissions. Specifically, the analysis reveals that prior to the implementation of the ETS, a €1 increase in the price of allowances led to a decrease in CO_2-eq emissions per voyage by an average of 1.7 tonnes (see Table 7). Remarkably, after the ETS was implemented, the same €1 increase is associated with a much more substantial decrease of 15.16 tonnes of CO_2-eq (see Table 8).

Furthermore, these results are statistically significant, both before and after the implementation of the ETS, with level of significance of 99.9% and more than 99.9% respectively. These high levels of significance show how unlikely it is to observe this data while there is no link between prices and emissions. In addition, the evolution of the R-squared and Adjusted R-squared values from pre-ETS (0.02 and 0.018, respectively) to post-ETS (0.53 and 0.522, respectively) indicates a substantial increase in how good the model can explain the variation in GHG emissions levels. This improvement in the goodness-of-fit suggests that since January 2024, EUA prices became a more precise indicator of emissions levels.

Table 7: Summary of the linear regression of emission on prices pre-ETS

Variable	Coefficient	Std. Error	t-Statistic	Probability
constant	392.01	40	9.8	0
ETS_price	-1.7	0.5	-3.42	0.001

Dependant Variable	y100_co2_t_eq	Jarque-Bera	13.27
Method	Least Squares	Durbin-Watson stat	0.286
No. Observations	575	Akaike info criterion	7121
R-squared	0.02	Bayesian information criterion	7129
Adjusted R-squared	0.018	F-statistic	11.71
Log likelihood	-3558.3	Prob(F-statistic)	6.64e-04

Table 7

Table 8: Summary of the linear regression of emission on prices post-ETS

Variable	Coefficient	Std. Error	t-Statistic	Probability
constant	1129.46	110.03	10.26	0
ETS_price	-15.169	1.846	-8.22	0

Dependant Variable	y100_co2_t_eq	Jarque-Bera	4.216
Method	Least Squares	Durbin-Watson stat	0.363
No. Observations	62	Akaike info criterion	715.9
R-squared	0.53	Bayesian information criterion	720.1
Adjusted R-squared	0.522	F-statistic	67.54
Log likelihood	-355.93	Prob(F-statistic)	2.08e-11

Table 8

However, despite these promising results, it is important to note that the period considered for the analysis after the ETS implementation is relatively short. The observed correlation may be influenced by external factors not accounted for in our model. Therefore, while these findings are indicative, they should be interpreted with caution and verified with a more extensive dataset over a longer period.

To assess the causality between prices and emissions, we conduct Granger causality tests on our two groups of data (before and after the policy introduction). The Granger causality test is used to determine if one time series can predict another, checking if past values of prices help forecast future values emissions.

After conducting the tests, we find that no lag in the prices of EUAs yields a significant result. This indicates that ETS prices do not statistically help to predict emissions as the significance levels are too low to assert a predictive relationship (see Appendix 7).

We conclude that both prices and emissions are perhaps too volatile, and the time required to reflect changes in price within emission levels is too long to observe any significant direct or

lagged causal effect. Therefore, while there might be a trend between ETS prices and emissions, we could not conclude to any causal link.

5.2.5 EU ETS segment specific price impact

Now that we have an idea of the general influence of EUA prices on the GHG emissions, we aim to extend these general findings by observing the dynamics between price fluctuations and emissions across different types of vessels. By doing so, the objective is to confirm the findings from section 5.2.2 and 5.2.3 that the cap-and-trade is affecting small vessels more than large ones. Once again, we employ the second level of the StatCode 5 Shiptype Coding System as it focusses on a small number of vessel types and thus maintain clarity in our analysis.

As in section 5.2.4, we start by computing the Pearson correlation coefficient to assess the relationship between price variations and emissions across different types of ships.

In Table 9, a trend emerges when ordering the results by the average emissions per hour for each vessel type. The main result is that vessel types with higher average emissions per hour (cargo vessels, passenger vessels, and tanker vessels) exhibit a stronger negative correlation between price increases and emissions.

Conversely, vessel types with lower pollution rates (offshore ships and fishing vessels) display a less pronounced negative correlation. This trend indicates that while price increases still influence emissions reductions, the effect is not as substantial as in the higher emitting categories. These results suggests that higher prices under the EU ETS effectively incentivize larger and more polluting vessels to reduce their emissions more than it incentivizes low emitting ships.

Table 9: Pearson correlation coefficient between price and GHG emissions per vessel type

Vessel type (2nd level of StatCode 5 Shiptype Coding System)	Pearson correlation coefficient
Dry cargo/Passenger	-0.757
Tankers	-0.679
Miscellaneous	-0.294
Bulk carriers	-0.502
Offshore	-0.255
Fishing	-0.417

Table 9

To go further in this analysis, we conduct a linear regression analysis after ensuring the stationarity of our time series data. As the time series for Bulk Carriers, Cargo, Passenger, Offshore, Tankers, and the EUA price series were identified as non-stationary, we addressed this by using the first differences for these series.

Following the transformation for stationarity, the regression of emissions (or the first difference in emissions) on the first difference in EUA prices was performed (see Appendix 8). The results from this regression analysis corroborate the intuition from the Pearson correlation coefficients previously discussed. Specifically, the most polluting group, consisting of dry cargo and passenger vessels, displayed a significant reduction in emissions, with a decrease of 2.61 tonnes of 100-year CO_2-eq per trip for each euro increase in EUA prices. This indicates a strong responsiveness to price incentives. Similarly, tanker vessels showed a very pronounced response, with emissions decreasing by 6.6 tonnes per trip for each euro increase in EUA prices. This highlights the substantial impact of EUA pricing on operational adjustments within high polluters.

Other smaller vessel types that are Bulk carriers, offshore ships, and other less polluting classes displayed coefficients of -2.51, -2.43, and -1.51 tonnes of 100-year CO_2-equivalent per euro increase respectively. This trend suggests that less polluting, smaller vessels are less sensitive to price changes. Interestingly, the least polluting group, fishing vessels, showed a dramatic decrease of 23.72 tonnes of CO2-equivalent per euro increase in allowance prices. However, the reliability of this result is questionable due to the very low number of observations available for this group in the year 2024 (29 observations), which could potentially alter the analysis.

In conclusion, while earlier sections of the thesis indicated that smaller, less polluting vessels had adapted more rapidly by reducing their speeds, the regression results present new elements of discussion in the distinction between boat types. Larger, more polluting vessels appear to be more responsive to price changes, suggesting a greater sensitivity to financial incentives due to their higher fuel consumption rates and the significant cost savings achievable through emission reductions. This reason why large vessels have not reduced emissions yet while they are more sensitive to price changes might then be attributed to the recent drop in EUA prices, which may have reduced the regulatory pressure on large polluters, leading to less abatement than expected. Therefore, it suggests that larger vessels may not prioritize emission reductions if they can afford to purchase emissions credits but would likely reduce emissions if the cost of these credits were to increase.

Furthermore, these results may have significant implications for the market changes caused by the EU ETS. Indeed, the observed impact on the operations of large vessels could be substantially amplified if EUA prices were to rise. As a result, the efficacy of price mechanisms as a tool for environmental regulation is a very important component of the measure. If EUA prices increase, it could drive important operational changes among the largest emitters, thereby improving the overall effectiveness of the EU ETS in curbing emissions from the shipping sector.

Thus, this analysis shed light on the sector-specific impacts of the EU ETS but also suggests future adjustments for the policy that could accelerate the decarbonation of the industry by adjusting the prices of the emissions allowances.

5.3 Carbon leakage

After observing the evolution of emissions and what variables help to explain these changes, we acknowledge that the efficiency of the EU ETS measure not only depends on the abatement of GHG emissions inside the EU but also on the ability of the measure to limit carbon leakage.

Carbon leakage in this context refers to an increase in emissions outside the EU due to a policy within the EU. To detect this phenomenon, we started by defining which are the intermediate ports that vessels visit before entering Europe or after leaving it. We chose countries located around Europe that could be used as intermediate port and allow not having to pay for EUA. We found 137 possible intermediate ports spread across nine countries: Morocco, Algeria, Tunisia, Libya, Egypt, Turkey, Lebanon, Israel, and Syria. We also focused solely on voyages that have some segments outside Europe and some other inside of Europe. As a result, we found 833,882 voyages before 2024 (2022 & 2023) and 93,721 voyages in the 1st quarter of 2024.

A visual comparison of the distribution of CO_2-eq before and after the EU was conducted using histograms.

Figure 16: Comparison of CO2 emissions equivalent before and after the EU ETS

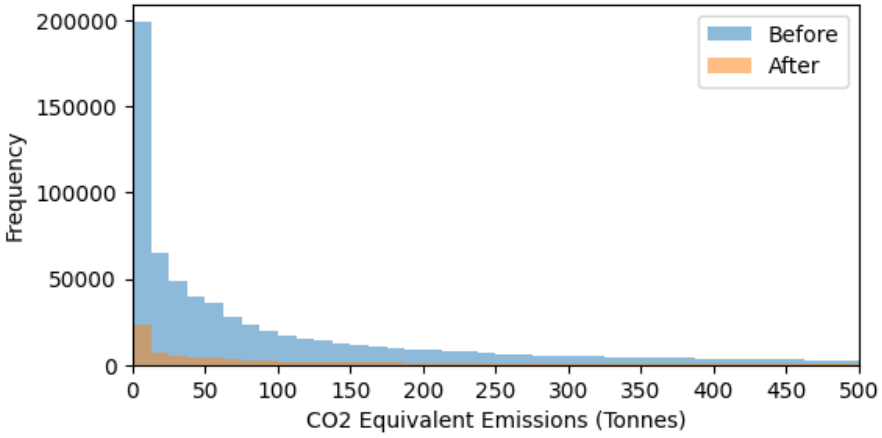

Figure 16

Due to the longer period taken into consideration for the voyages before 2024, we observe a mismatch in the volume of data. To correct this, the "After" dataset (first quarter of 2024) was bootstrapped and the "Before" dataset was down sampled, normalizing the datasets for an impartial statistical analysis.

Bootstrap resampling means that we selected random observations from the dataset with replacement, creating multiple new datasets of equal size to the original. On the other hand, down sampling involves reducing the size of a dataset to match the time frame or sample size of another dataset. These techniques ensure that comparisons between datasets are not biased by differences in observation sizes. (Appendix 9)

We generated some histograms to illustrates the distribution after the data adjustment.

Figure 17: Distribution of the CO2 emissions equivalent after downsampling

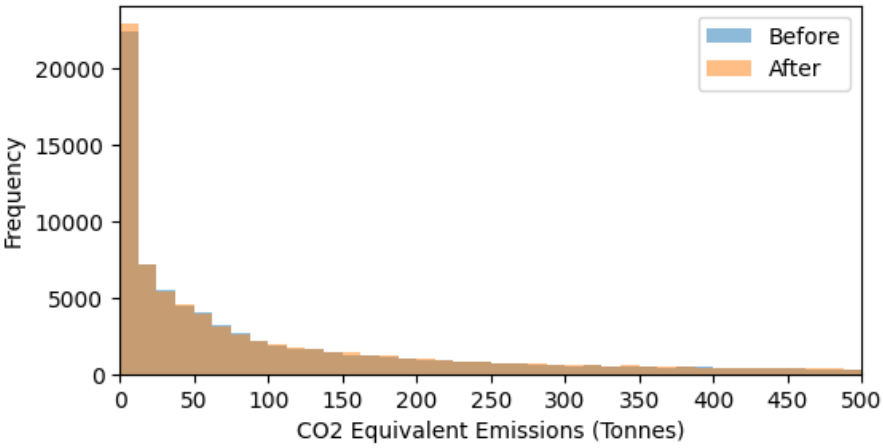

Figure 17

Figure 18: Distribution of the CO2 emissions equivalent after bootstrapping

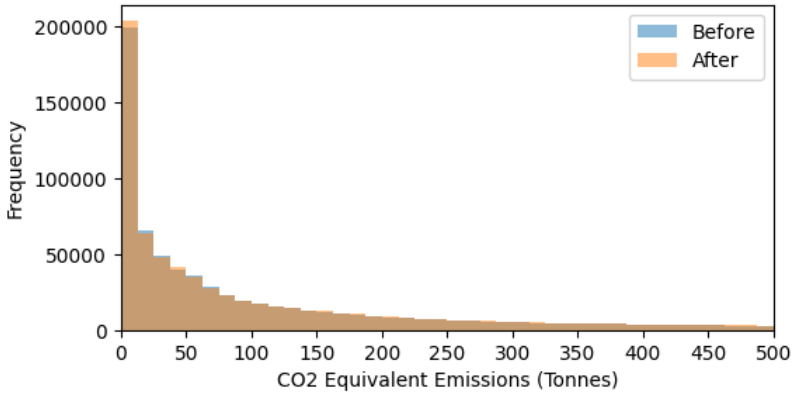

Figure 18

Then, we investigated deeper the distribution and analysed the first quarter of the year 2022, 2023, and 2024. We tested the distribution using a Mann-Whitney U tests we found that that we cannot reject that the distribution are the same with as the p-value of the test is 15%.

Figure 19: Distribution of the CO2 emissions equivalent for the first quarters

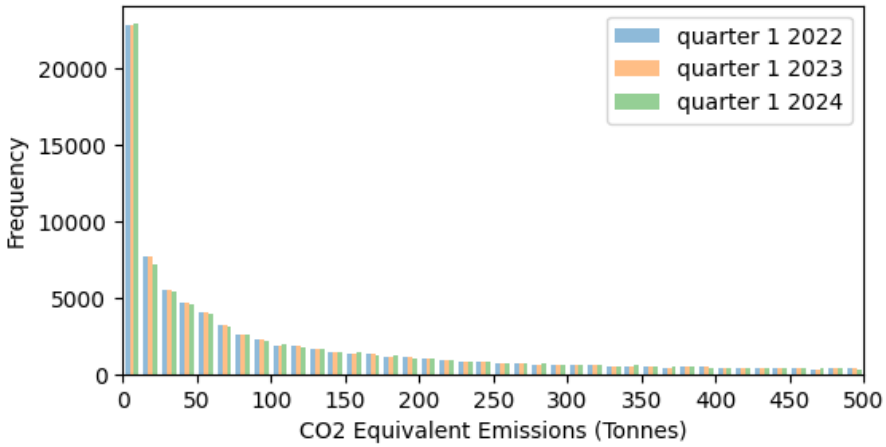

Figure 19

Therefore, we use bootstrap to observe differences in the mean. While the bootstrapping analysis suggested a small average increase of 4.02 tonnes in emissions from 2023 to 2024 (going from 353.02 to 357.09 tonnes). However, our results are not significant, suggesting that any perceived increase in emissions might just be due to natural variability in the data rather than a systematic change. (Appendix 10)

To conclude, we do not observe carbon leakage for the first quarter of 2024, but this does not rule out the possibility of other forms of carbon leakage or the potential for leakage to manifest later. To prevent any possible of carbon leakage, the legislator should refine the definition of a part of call which to capture any leaked emissions in the system (Psaraftis et al., 2021)

6. Discussion

First, we see that the process of reducing emissions is complex as the responses to the EU ETS are contrasted. As a matter of fact, geopolitical instability has impacted this transition to low-carbon alternatives in the maritime sector. For instance, the ongoing conflict between Russia and Ukraine has disrupted global oil supply chains, leading to significant volatility in oil prices. This is consistent with patterns observed in the aviation and heavy industries, where similar economic pressures have resulted in uneven progress toward low-carbon transitions (European Commission, 2021).

On one hand, we observed that smaller vessels, including fishing and offshore vessels, are less sensitive to price changes. As it is a market-based mechanism, the success of the EU ETS in reducing emissions depends on aligning economic incentives with each company's technical and operational capabilities and the broader economic and geopolitical environment. On the other hand, larger vessels, such as passenger ships and containerships, are more sensitive to carbon prices, so increasing EUA prices can impact their operational costs. This economic pressure will drive them to adopt efficiency measures and technological innovations more readily.

Another observation is that vessel speed is a major driver of GHG emissions, as reducing speed by 10% can decrease emissions by 13% (Faber et al., 2017). Our results confirm this correlation between reduced speed and emissions. Concerning how shipping companies adapted their speed to the new EU regulation, smaller vessels have reduced speed by 1.92 knots on average post-ETS implementation, quickly lowering emissions. However, despite their reductions, their overall contribution to total emissions is limited. Concerning larger vessels, they show less significant reductions in speed and emissions, with some even increasing their speed. For example, bulk carriers and dry cargo/passenger vessels increased their speed by 0.12 and 0.19 knots, respectively, indicating slower adaptation to regulatory pressures. Altogether, we see that larger vessels have reacted less significantly to the EU ETS but that they are more sensitive to price changes. As a result, we suggest that EUA prices should be increased to make the policy more impactful across all segments of the shipping sector. Such increase could occur in the upcoming years as companies are currently required to submit allowances for 40% of their emissions, while this proportion will climb to 70% in 2025 and 100% from 2026 onwards, creating scarcity for EUAs and therefore leading to a potential price increase.

Then, our analysis also shows no significant increase in emissions at intermediate ports since 2024, indicating minimal carbon leakage. A comparison of emissions distributions before and after the EU ETS implementation shows that the average CO_2-eq emissions per voyage have not increased substantially. This finding aligns with the assertion by Floden et al. (2024) that the additional cost of emissions allowances under the EU ETS is relatively small compared to the additional costs associated with avoiding EU ports. So, there is little economic incentive for shipping companies to alter their routes to bypass the EU ETS, reducing the likelihood of carbon leakage.

However, the absence of carbon leakage in the short term does not guarantee that it will not become an issue in the future. As regulatory pressures will increase and the costs of emissions allowances should rise, shipping companies might seek new ways to minimize their costs, including route adjustments that could lead to carbon leakage.

To reduce this risk, policymakers should continuously refine the EU ETS framework, and synchronizing it with other regulatory frameworks, such as Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL) and the FuelEU Maritime initiative, which targets pollutants like NOx and SOx, can achieve a more comprehensive approach to maritime environmental management. Harmonizing these regulations ensures consistent environmental standards and closes regulatory gaps that shipping companies might exploit.

As already mentioned, the timing and scope of the EU ETS are crucial. According to the updated EU ETS Directive (2024)[9], the schedule will start in 2024. Cargo and passenger ships of 5000 GT or more are being monitored under the MRV scope. In 2025, the phase-in of surrendering emissions allowances begins, with ships required to surrender 40% of their 2024 emissions. The next year, offshore ships of 5000 GT or more start being considered for inclusion in the EU ETS. By 2026, ships concerned will surrender 70% of their emissions from 2025, and an ETS review will be conducted to potentially include more ship types and sizes. In 2026, The EU ETS expands its scope of the GHG to CH_4 and N_2O. In 2027, ships will surrender 100% of their emissions from 2026, and offshore and general cargo ships of 400-5000 GT will be considered for inclusion based on the ETS review. From 2028 onwards,

[9] https://climate.ec.europa.eu/eu-action/transport/reducing-emissions-shipping-sector/faq-maritime-transport-eu-emissions-trading-system-ets_en

continuous reviews and potential inclusion of additional vessel types and sizes will ensure the EU ETS remains adaptive and comprehensive.

This phased inclusion strategy has several implications. It will pressure shipping companies to invest in fuel-efficient technologies and alternative fuels like hydrogen and ammonia. The 'Ocean Fund' will support these investments, while the expanded MRV scope will improve emissions data accuracy. As observed, smaller vessels have already reduced speed in response to carbon pricing, but larger vessels will face significant cost increases as EUA prices may rise, driving them to adopt more efficient measures or switch to lower-emission fuels. As a result, this anticipated transition must be supported financially to ensure that every company get a fair access to emission reduction technology and clean fuels.

To sum up, the implementation of a carbon pricing mechanism alone may not lead to significant operational shifts in the maritime sector immediately. While the initial cost of compliance with the EU ETS might be manageable, it will increase as the percentage of emissions that need to be covered by allowances increases from 40% in 2025 to 100% by 2027. Operational adjustments, such as reducing vessel speeds or investing in more fuel-efficient technologies, will become more pronounced when non-compliance costs exceed investments needed for operational changes. Our findings align with Mallouppas and Yfantis (2021), who observed slow adoption of innovative technologies like hydrogen and ammonia fuels due to practical and economic challenges.

7. Conclusion

Throughout this thesis on the segment-specific impacts of the integration of the EU ETS in the shipping industry, we confirmed several hypotheses and observed nuanced results across different vessel types. Given that this integration is a relatively new and rapidly evolving area of study, our research answers an urgent need for empirical analysis and stands as a first step in assessing the policy's efficiency.

Among our results, we confirmed the strong link between vessel speed and emissions levels, even if we anticipate that future investments in decarbonization technologies might allow for higher speeds without proportional increases in emissions, suggesting a potential decoupling of these factors. Then, using a difference-in-differences approach, we found that the introduction of the EU ETS caused an average reduction of 15.38 tonnes of CO_2-eq per voyage. However, the lack of statistical significance in these findings suggests the need for more extensive data and studies to validate these trends. When grouping the data by vessel size, we observed that smaller vessels reduced their speeds more than larger vessels, yet these changes did not lead to significant emission reductions across vessel types.

Concerning the influence of EUA prices, a linear regression model showed that each euro increase in prices of allowances leads to a reduction of 1.7 tonnes of CO_2-eq per voyage. Interestingly, larger vessels seem to be more sensitive to these price changes, showing the importance of price management to limit the emissions of the large polluting vessels.

Finally, our investigation of carbon leakage showed no significant route deviations, indicating that shipping routes have remained stable so far.

In conclusion, while these results give a good indication of the trends in the effect of the observed market-based mechanisms, further research is needed to confirm these trends. In addition, we discussed the importance of adjusting these mechanisms to ensure that shipping companies consider the price of carbon in their operations while not pressuring small-sized vessels excessively compared to larger ones.

A first limitation that affects the robustness of these conclusions is the lack of statistical significance in certain results. This absence of significant findings prevents us from making formal conclusion. For example, while reductions in speed and emissions were observed, these changes were not statistically significant.

Additionally, the short time frame of our analysis is also a limitation. Indeed, we focused on the three first months following the implementation of the policy. However, we acknowledge that the shipping industry cannot instantly react to new regulations as it involves operational adjustments and large capital investments in new technologies. As a result, the observed period may be too short to fully capture the policy's impacts. The industry has not yet fully adapted to the new regulatory environment, which could have influenced some of our findings.

Given these limitations, future research would benefit from a longer period of observation and expanded datasets. Observing the evolution of emission levels over a more extended timeframe would allow the shipping industry to adjust operations and integrate new technologies. Such research should provide a clearer picture of the long-term impacts of the EU ETS and could provide results with a greater level of certainty.

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9. Appendices

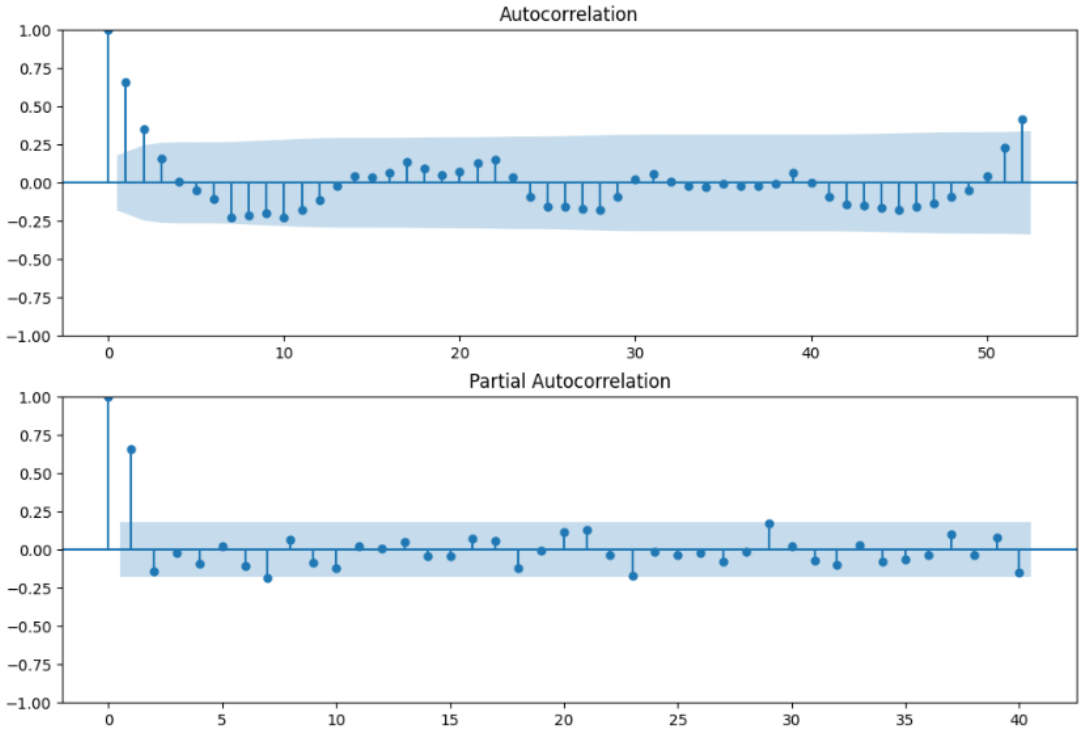
Appendix 1: Description of the sets of data based on the index

Set/Index	Description
I	Set of unique identifiers for vessels, where each element represents the IMO number assigned to a vessel
G	Set of segments of voyages, each segment representing a specific part of a vessel's journey
D	Set of departure times for each voyage, representing when a vessel leaves a port
E	Set of arrival times for each voyage, representing when a vessel arrives at a port
F	Set of departure ports from where vessels begin their voyages
T	Set of arrival ports where vessels end their voyages
C	Set of CO_2 emissions values for each voyage, measured in tonnes
M	Set of CH_4 emissions values for each voyage, measured in tonnes
N	Set of N_2O emissions values for each voyage, measured in tonnes
H	Set of vessels' names
X	Set of previous names of vessels, applicable if a vessel was known by other names
A	Set of Maritime Mobile Service Identities (MMSI)

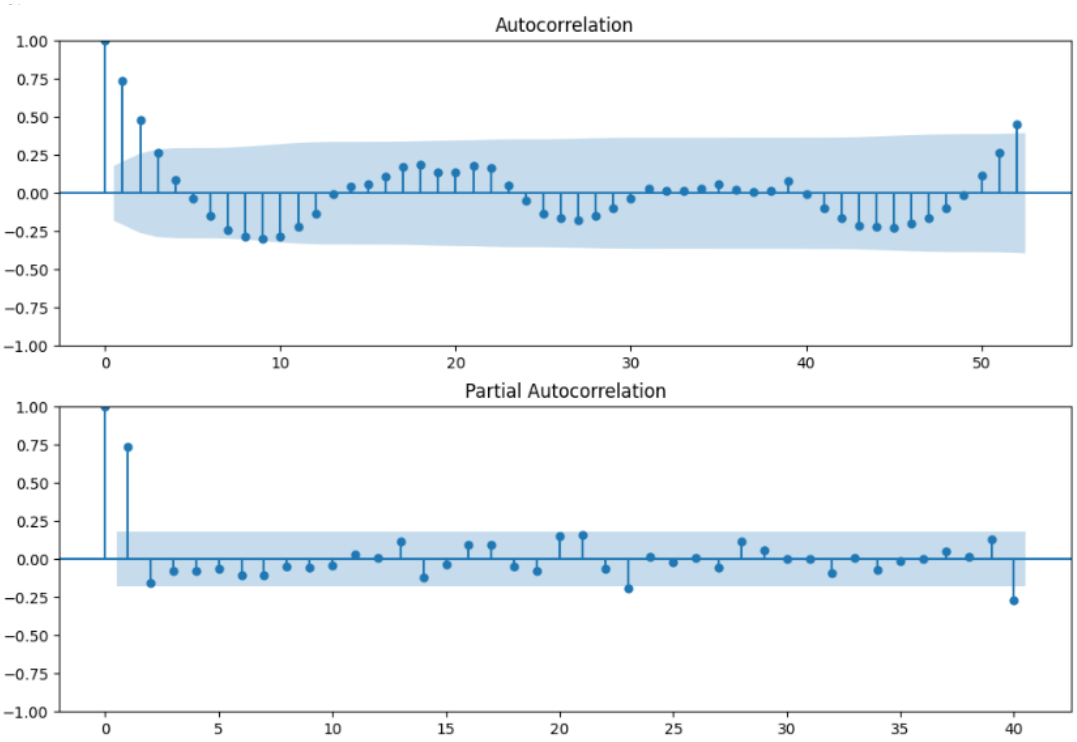
R	Set of countries where vessels can be registered
B	Set of gross tonnage values for vessels
W	Set of deadweight tonnage values for vessels, indicating the maximum weight a vessel can safely carry
O	Set of lengths overall (LOA) for vessels, measuring the length from the bow to the stern
U	Set of counts of main engines on vessels
P	Set of maximum power outputs for the main engines of vessels, measured in kilowatts
J	Set of models of the main engines installed on vessels
K	Set of recommended operating speeds for vessels (in knots)
Q	Set of maximum draughts during summer for vessels, indicating the maximum depth a vessel reaches under water
Y	Set of flag names under which vessels are registered
L	Set of ISO 3166-1 alpha-3 codes for the flags under which vessels operate
Z	Set of main engine types used in vessels, either Oil, Gas, Turbine, or Reciprocating
E	Set of specific ship types, categorized into a detailed classification system used for maritime vessels

Appendix 2: ACF and PACF functions for time-emissions ARIMA models

Appendix 2.1: ACF and PACF functions for intra-European voyages



Appendix 2.2: ACF and PACF functions for voyages partly in Europe



Appendix 3: Model of emissions depending on time summary

Appendix 3.1: Summary of the linear model for intra-European voyages

Variable	Coefficient	Std. Error	z-value	Probability
constant	105.43	7.37	14.3	0
time	0.2328	0.1	2.15	0.033

Dependant Variable	y100_co2_t_eq	Jarque-Bera	6.04
Model	OLS	Prob(JB)	0.05
No. Observations	119	Akaike info criterion	1220
R-squared	0.038	Bayesian information criterion	1226
Adjusted R-squared	0.03	Log likelihood	-608.22

Appendix 3.2: Summary of the ARMA(2,1) model for intra-European voyages

Variable	Coefficient	Std. Error	z-value	Probability
constant	118.45	11.21	10.57	0
AR 1	0.6	0.5	2.55	0.011
MA 1	0.22	0.3	0.74	0.458
MA 2	-0.01	0.25	-0.03	0.979

Dependant Variable	y100_co2_t_eq	Jarque-Bera	234.06
Model	ARIMA(1,0,2)	Prob(JB)	0
No. Observations	119	Akaike info criterion	1151.99
Breush-Pagan stat	0.97	Bayesian information criterion	1165.89
Prob(Heteroskedasticity) (two-sided)	0.09	Log likelihood	-570.994

Appendix 3.3: Summary of the linar model for voyages happening partly in Europe

Variable	Coefficient	Std. Error	z-value	Probability
constant	597.92	60.55	9.87	0
time	2.6	0.89	2.94	0.004

Dependant Variable	y100_co2_t_eq	Jarque-Bera	5.006
Model	OLS	Prob(JB)	0.82

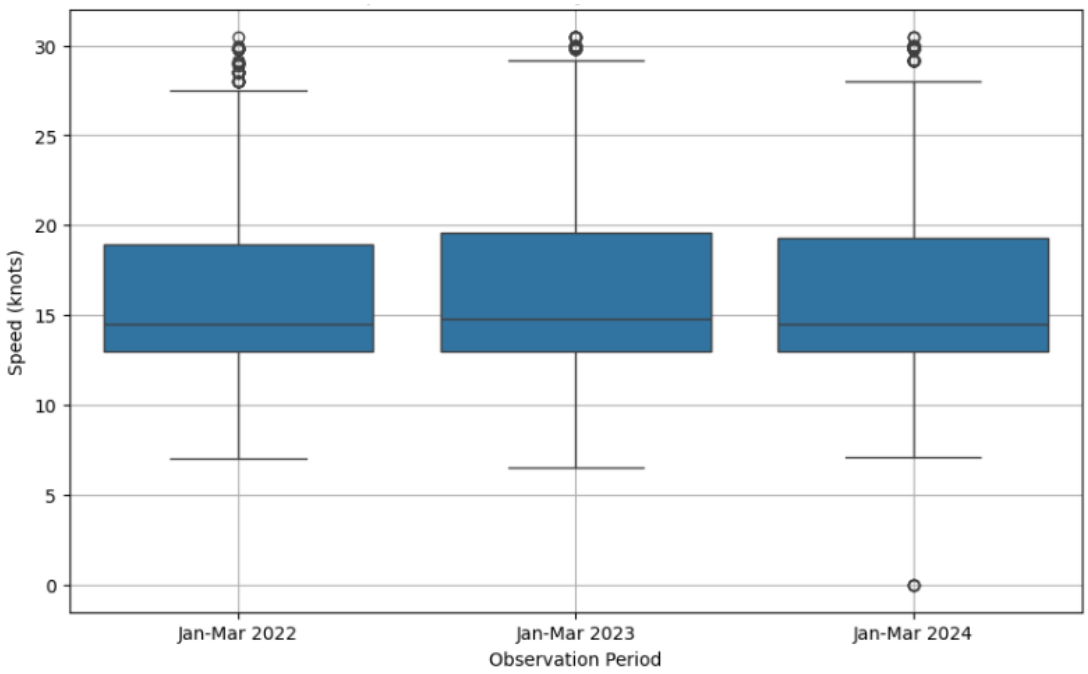
No. Observations	119	Akaike info criterion	1722
R-squared	0.069	Bayesian information criterion	1727
Adjusted R-squared	0.061	Log likelihood	-858.79

Appendix 3.4: Summary of the ARMA(2,1) model for voyages happening partly in Europe

Variable	Coefficient	Std. Error	z-value	Probability
constant	751.41	129.61	5.8	0
AR 1	0.65	0.27	2.39	0.017
MA 1	0.23	0.35	0.7	0.489
MA 2	0.08	0.5	0.16	0.871

Dependant Variable	y100_co2_t_eq	Jarque-Bera	774.95
Model	ARIMA(1,0,2)	Prob(JB)	0
No. Observations	119	Akaike info criterion	1630.5
Breush-Pagan stat	1.28	Bayesian information criterion	1644.4
Prob(Heteroskedasticity) (two-sided)	0.66	Log likelihood	-810.25

Appendix 4: Speed distribution by observation period



Appendix 5: Summary of the DiD model for vessel speed

Results for the DiD model for Bulk Carriers

OLS Regression Results

Dep. Variable:	Speed	R-squared:	0.000
Model:	OLS	Adj. R-squared:	0.000
Method:	Least Squares	F-statistic:	418.7
Date:	Thu, 02 May 2024	Prob (F-statistic):	5.72e-272
Time:	21:31:57	Log-Likelihood:	-1.0498e+07
No. Observations:	3592392	AIC:	2.100e+07
Df Residuals:	3592388	BIC:	2.100e+07
Df Model:	3		
Covariance Type:	nonrobust		

	coef	std err	t	P>|t|	[0.025	0.975]
const	14.6499	0.003	5793.334	0.000	14.645	14.655
treatment	-0.6480	0.019	-33.332	0.000	-0.686	-0.610
post	-0.0701	0.008	-8.978	0.000	-0.085	-0.055
treatment_post	0.1170	0.066	1.780	0.075	-0.012	0.246

Omnibus:	2153788.551	Durbin-Watson:	1.995
Prob(Omnibus):	0.000	Jarque-Bera (JB):	24892464.223
Skew:	2.733	Prob(JB):	0.00
Kurtosis:	14.680	Cond. No.	28.0

Results for the DiD model for Dry/Cargo/Passenger

OLS Regression Results

Dep. Variable:	Speed	R-squared:	0.047
Model:	OLS	Adj. R-squared:	0.047
Method:	Least Squares	F-statistic:	6.313e+04
Date:	Thu, 02 May 2024	Prob (F-statistic):	0.00
Time:	21:32:05	Log-Likelihood:	-1.1131e+07
No. Observations:	3808403	AIC:	2.226e+07
Df Residuals:	3808399	BIC:	2.226e+07
Df Model:	3		
Covariance Type:	nonrobust		

	coef	std err	t	P>|t|	[0.025	0.975]
const	14.6499	0.003	5790.090	0.000	14.645	14.655
treatment	3.8511	0.009	409.884	0.000	3.833	3.869
post	-0.0701	0.008	-8.973	0.000	-0.085	-0.055
treatment_post	0.1935	0.029	6.616	0.000	0.136	0.251

Omnibus:	2154740.313	Durbin-Watson:	1.998
Prob(Omnibus):	0.000	Jarque-Bera (JB):	23150524.863
Skew:	2.553	Prob(JB):	0.00
Kurtosis:	13.946	Cond. No.	12.9

Results for the DiD model for Tankers
OLS Regression Results

Dep. Variable:	Speed	R-squared:	0.000
Model:	OLS	Adj. R-squared:	0.000
Method:	Least Squares	F-statistic:	213.8
Date:	Thu, 02 May 2024	Prob (F-statistic):	1.09e-138
Time:	21:32:11	Log-Likelihood:	-1.0523e+07
No. Observations:	3601682	AIC:	2.105e+07
Df Residuals:	3601678	BIC:	2.105e+07
Df Model:	3		
Covariance Type:	nonrobust		

	coef	std err	t	P>|t|	[0.025	0.975]
const	14.6499	0.003	5796.382	0.000	14.645	14.655
treatment	-0.4030	0.018	-22.076	0.000	-0.439	-0.367
post	-0.0701	0.008	-8.983	0.000	-0.085	-0.055
treatment_post	-0.0477	0.057	-0.838	0.402	-0.159	0.064

Omnibus:	2157991.343	Durbin-Watson:	1.995
Prob(Omnibus):	0.000	Jarque-Bera (JB):	24928774.424
Skew:	2.731	Prob(JB):	0.00
Kurtosis:	14.674	Cond. No.	24.3

Results for the DiD model for Miscellaneous
OLS Regression Results

Dep. Variable:	Speed	R-squared:	0.000
Model:	OLS	Adj. R-squared:	0.000
Method:	Least Squares	F-statistic:	157.1
Date:	Thu, 02 May 2024	Prob (F-statistic):	8.08e-102
Time:	21:32:23	Log-Likelihood:	-1.0397e+07
No. Observations:	3550660	AIC:	2.079e+07
Df Residuals:	3550656	BIC:	2.079e+07
Df Model:	3		
Covariance Type:	nonrobust		

	coef	std err	t	P>|t|	[0.025	0.975]
const	14.6499	0.003	5758.817	0.000	14.645	14.655
treatment	-0.6028	0.035	-17.135	0.000	-0.672	-0.534
post	-0.0701	0.008	-8.925	0.000	-0.085	-0.055
treatment_post	-0.6387	0.132	-4.839	0.000	-0.897	-0.380

Omnibus:	2114420.713	Durbin-Watson:	1.995
Prob(Omnibus):	0.000	Jarque-Bera (JB):	23939435.350
Skew:	2.716	Prob(JB):	0.00
Kurtosis:	14.502	Cond. No.	55.5

Results for the DiD model for Offshore
OLS Regression Results

Dep. Variable:	Speed	R-squared:	0.001
Model:	OLS	Adj. R-squared:	0.001
Method:	Least Squares	F-statistic:	1281.
Date:	Thu, 02 May 2024	Prob (F-statistic):	0.00
Time:	21:32:18	Log-Likelihood:	-1.0387e+07
No. Observations:	3545773	AIC:	2.077e+07
Df Residuals:	3545769	BIC:	2.077e+07
Df Model:	3		
Covariance Type:	nonrobust		

	coef	std err	t	P>|t|	[0.025	0.975]
const	14.6499	0.003	5752.187	0.000	14.645	14.655
treatment	-2.4173	0.042	-57.949	0.000	-2.499	-2.336
post	-0.0701	0.008	-8.914	0.000	-0.085	-0.055
treatment_post	-0.2586	0.139	-1.860	0.063	-0.531	0.014

Omnibus:	2106890.088	Durbin-Watson:	1.994
Prob(Omnibus):	0.000	Jarque-Bera (JB):	23731293.606
Skew:	2.710	Prob(JB):	0.00
Kurtosis:	14.457	Cond. No.	58.4

Results for the DiD model for Fishing
OLS Regression Results

Dep. Variable:	Speed	R-squared:	0.000
Model:	OLS	Adj. R-squared:	0.000
Method:	Least Squares	F-statistic:	45.74
Date:	Thu, 02 May 2024	Prob (F-statistic):	1.50e-29
Time:	21:32:28	Log-Likelihood:	-1.0355e+07
No. Observations:	3533750	AIC:	2.071e+07
Df Residuals:	3533746	BIC:	2.071e+07
Df Model:	3		
Covariance Type:	nonrobust		

	coef	std err	t	P>|t|	[0.025	0.975]
const	14.6499	0.003	5746.491	0.000	14.645	14.655
treatment	-0.6123	0.156	-3.928	0.000	-0.918	-0.307
post	-0.0701	0.008	-8.905	0.000	-0.085	-0.055
treatment_post	-1.9179	0.426	-4.505	0.000	-2.752	-1.084

Omnibus:	2100209.558	Durbin-Watson:	1.995
Prob(Omnibus):	0.000	Jarque-Bera (JB):	23623248.640
Skew:	2.711	Prob(JB):	0.00
Kurtosis:	14.447	Cond. No.	179.

Appendix 6: Summary of DiD models for emission depending on the vessel type

Results for the DiD model for Vehicles Carrier
OLS Regression Results

Dep. Variable:	emissions	R-squared:	nan
Model:	OLS	Adj. R-squared:	nan
Method:	Least Squares	F-statistic:	nan
Date:	Mon, 22 Apr 2024	Prob (F-statistic):	nan
Time:	13:11:17	Log-Likelihood:	nan
No. Observations:	1639	AIC:	nan
Df Residuals:	1635	BIC:	nan
Df Model:	3		
Covariance Type:	nonrobust		

	coef	std err	t	P>|t|	[0.025	0.975]
const	nan	nan	nan	nan	nan	nan
treatment	nan	nan	nan	nan	nan	nan
post	nan	nan	nan	nan	nan	nan
treatment_post	nan	nan	nan	nan	nan	nan

Omnibus:	nan	Durbin-Watson:	nan
Prob(Omnibus):	nan	Jarque-Bera (JB):	nan
Skew:	nan	Prob(JB):	nan
Kurtosis:	nan	Cond. No.	8.47

Results for the DiD model for Bulk Carrier
OLS Regression Results

Dep. Variable:	emissions	R-squared:	nan
Model:	OLS	Adj. R-squared:	nan
Method:	Least Squares	F-statistic:	nan
Date:	Mon, 22 Apr 2024	Prob (F-statistic):	nan
Time:	13:11:22	Log-Likelihood:	nan
No. Observations:	1641	AIC:	nan
Df Residuals:	1637	BIC:	nan
Df Model:	3		
Covariance Type:	nonrobust		

	coef	std err	t	P>|t|	[0.025	0.975]
const	nan	nan	nan	nan	nan	nan
treatment	nan	nan	nan	nan	nan	nan
post	nan	nan	nan	nan	nan	nan
treatment_post	nan	nan	nan	nan	nan	nan

Omnibus:	nan	Durbin-Watson:	nan
Prob(Omnibus):	nan	Jarque-Bera (JB):	nan
Skew:	nan	Prob(JB):	nan
Kurtosis:	nan	Cond. No.	8.48

Results for the DiD model for Container Ship (Fully Cellular)
OLS Regression Results

Dep. Variable:	emissions	R-squared:	0.900
Model:	OLS	Adj. R-squared:	0.899
Method:	Least Squares	F-statistic:	4884.
Date:	Mon, 22 Apr 2024	Prob (F-statistic):	0.00
Time:	13:11:25	Log-Likelihood:	674.13
No. Observations:	1641	AIC:	-1340.
Df Residuals:	1637	BIC:	-1319.
Df Model:	3		
Covariance Type:	nonrobust		

	coef	std err	t	P>|t|	[0.025	0.975]
const	1.1826	0.006	198.900	0.000	1.171	1.194
treatment	0.9486	0.008	112.812	0.000	0.932	0.965
post	-0.0441	0.018	-2.458	0.014	-0.079	-0.009
treatment_post	0.0992	0.025	3.919	0.000	0.050	0.149

Omnibus:	99.411	Durbin-Watson:	1.261
Prob(Omnibus):	0.000	Jarque-Bera (JB):	414.989
Skew:	-0.027	Prob(JB):	7.70e-91
Kurtosis:	5.463	Cond. No.	8.48

Results for the DiD model for Passenger/Ro-Ro Ship (Vehicles)
OLS Regression Results

Dep. Variable:	emissions	R-squared:	0.980
Model:	OLS	Adj. R-squared:	0.980
Method:	Least Squares	F-statistic:	2.703e+04
Date:	Mon, 22 Apr 2024	Prob (F-statistic):	0.00
Time:	13:11:29	Log-Likelihood:	273.98
No. Observations:	1641	AIC:	-540.0
Df Residuals:	1637	BIC:	-518.3
Df Model:	3		
Covariance Type:	nonrobust		

	coef	std err	t	P>|t|	[0.025	0.975]
const	1.1826	0.008	155.859	0.000	1.168	1.198
treatment	2.8772	0.011	268.119	0.000	2.856	2.898
post	-0.0441	0.023	-1.926	0.054	-0.089	0.001
treatment_post	0.0485	0.032	1.501	0.134	-0.015	0.112

Omnibus:	122.236	Durbin-Watson:	1.258
Prob(Omnibus):	0.000	Jarque-Bera (JB):	618.728
Skew:	0.069	Prob(JB):	4.41e-135
Kurtosis:	6.005	Cond. No.	8.48

Results for the DiD model for Other

OLS Regression Results

Dep. Variable:	emissions	R-squared:	0.480
Model:	OLS	Adj. R-squared:	0.479
Method:	Least Squares	F-statistic:	504.2
Date:	Mon, 22 Apr 2024	Prob (F-statistic):	5.17e-232
Time:	13:11:32	Log-Likelihood:	-740.61
No. Observations:	1641	AIC:	1489.
Df Residuals:	1637	BIC:	1511.
Df Model:	3		
Covariance Type:	nonrobust		

	coef	std err	t	P>|t|	[0.025	0.975]
const	1.1826	0.014	83.988	0.000	1.155	1.210
treatment	0.7157	0.020	35.940	0.000	0.677	0.755
post	-0.0441	0.043	-1.038	0.300	-0.127	0.039
treatment_post	0.1242	0.060	2.072	0.038	0.007	0.242

Omnibus:	156.489	Durbin-Watson:	0.887
Prob(Omnibus):	0.000	Jarque-Bera (JB):	427.209
Skew:	0.514	Prob(JB):	1.71e-93
Kurtosis:	5.278	Cond. No.	8.48

Results for the DiD model for Ro-Ro Cargo Ship

OLS Regression Results

Dep. Variable:	emissions	R-squared:	0.919
Model:	OLS	Adj. R-squared:	0.919
Method:	Least Squares	F-statistic:	6207.
Date:	Mon, 22 Apr 2024	Prob (F-statistic):	0.00
Time:	13:11:35	Log-Likelihood:	-224.71
No. Observations:	1641	AIC:	457.4
Df Residuals:	1637	BIC:	479.0
Df Model:	3		
Covariance Type:	nonrobust		

	coef	std err	t	P>|t|	[0.025	0.975]
const	1.1826	0.010	115.015	0.000	1.162	1.203
treatment	1.8694	0.015	128.553	0.000	1.841	1.898
post	-0.0441	0.031	-1.421	0.155	-0.105	0.017
treatment_post	0.0207	0.044	0.472	0.637	-0.065	0.107

Omnibus:	124.167	Durbin-Watson:	1.174
Prob(Omnibus):	0.000	Jarque-Bera (JB):	650.822
Skew:	-0.027	Prob(JB):	4.74e-142
Kurtosis:	6.085	Cond. No.	8.48

Results for the DiD model for Chemical/Products Tanker

OLS Regression Results

Dep. Variable:	emissions	R-squared:	0.792
Model:	OLS	Adj. R-squared:	0.792
Method:	Least Squares	F-statistic:	2080.
Date:	Mon, 22 Apr 2024	Prob (F-statistic):	0.00
Time:	13:11:38	Log-Likelihood:	1109.6
No. Observations:	1641	AIC:	-2211.
Df Residuals:	1637	BIC:	-2189.
Df Model:	3		
Covariance Type:	nonrobust		

	coef	std err	t	P>|t|	[0.025	0.975]
const	1.1826	0.005	259.340	0.000	1.174	1.192
treatment	0.4819	0.006	74.728	0.000	0.469	0.495
post	-0.0441	0.014	-3.204	0.001	-0.071	-0.017
treatment_post	-0.0239	0.019	-1.232	0.218	-0.062	0.014

Omnibus:	71.599	Durbin-Watson:	0.986
Prob(Omnibus):	0.000	Jarque-Bera (JB):	190.649
Skew:	-0.182	Prob(JB):	3.99e-42
Kurtosis:	4.630	Cond. No.	8.48

Results for the DiD model for Trailing Suction Hopper Dredger

OLS Regression Results

Dep. Variable:	emissions	R-squared:	nan
Model:	OLS	Adj. R-squared:	nan
Method:	Least Squares	F-statistic:	nan
Date:	Mon, 22 Apr 2024	Prob (F-statistic):	nan
Time:	13:11:43	Log-Likelihood:	nan
No. Observations:	1641	AIC:	nan
Df Residuals:	1637	BIC:	nan
Df Model:	3		
Covariance Type:	nonrobust		

	coef	std err	t	P>|t|	[0.025	0.975]
const	nan	nan	nan	nan	nan	nan
treatment	nan	nan	nan	nan	nan	nan
post	nan	nan	nan	nan	nan	nan
treatment_post	nan	nan	nan	nan	nan	nan

Omnibus:	nan	Durbin-Watson:	nan
Prob(Omnibus):	nan	Jarque-Bera (JB):	nan
Skew:	nan	Prob(JB):	nan
Kurtosis:	nan	Cond. No.	8.48

Results for the DiD model for General Cargo Ship

OLS Regression Results

Dep. Variable:	emissions	R-squared:	0.427
Model:	OLS	Adj. R-squared:	0.426
Method:	Least Squares	F-statistic:	406.1
Date:	Mon, 22 Apr 2024	Prob (F-statistic):	3.78e-197
Time:	13:11:46	Log-Likelihood:	734.59
No. Observations:	1641	AIC:	-1461.
Df Residuals:	1637	BIC:	-1440.
Df Model:	3		
Covariance Type:	nonrobust		

	coef	std err	t	P>|t|	[0.025	0.975]
const	1.1826	0.006	206.364	0.000	1.171	1.194
treatment	-0.2688	0.008	-33.167	0.000	-0.285	-0.253
post	-0.0441	0.017	-2.550	0.011	-0.078	-0.010
treatment_post	0.0259	0.024	1.060	0.289	-0.022	0.074

Omnibus:	369.292	Durbin-Watson:	0.789
Prob(Omnibus):	0.000	Jarque-Bera (JB):	1441.910
Skew:	1.045	Prob(JB):	0.00
Kurtosis:	7.089	Cond. No.	8.48

Appendix 7: Granger causality test between prices and emissions

Appendix 7.1: Summary of the test pre-ETS

```
Granger Causality
number of lags (no zero) 1
ssr based F test:         F=0.5874  , p=0.4438  , df_denom=448, df_num=1
ssr based chi2 test:   chi2=0.5913  , p=0.4419  , df=1
likelihood ratio test: chi2=0.5909  , p=0.4421  , df=1
parameter F test:         F=0.5874  , p=0.4438  , df_denom=448, df_num=1

Granger Causality
number of lags (no zero) 2
ssr based F test:         F=1.0343  , p=0.3563  , df_denom=445, df_num=2
ssr based chi2 test:   chi2=2.0919  , p=0.3514  , df=2
likelihood ratio test: chi2=2.0870  , p=0.3522  , df=2
parameter F test:         F=1.0343  , p=0.3563  , df_denom=445, df_num=2

Granger Causality
number of lags (no zero) 3
ssr based F test:         F=1.0937  , p=0.3515  , df_denom=442, df_num=3
ssr based chi2 test:   chi2=3.3330  , p=0.3431  , df=3
likelihood ratio test: chi2=3.3207  , p=0.3448  , df=3
parameter F test:         F=1.0937  , p=0.3515  , df_denom=442, df_num=3

Granger Causality
number of lags (no zero) 4
ssr based F test:         F=1.5366  , p=0.1905  , df_denom=439, df_num=4
ssr based chi2 test:   chi2=6.2725  , p=0.1797  , df=4
likelihood ratio test: chi2=6.2290  , p=0.1827  , df=4
parameter F test:         F=1.5366  , p=0.1905  , df_denom=439, df_num=4
```

Appendix 7.2: Summary of the test post-ETS

```
Granger Causality
number of lags (no zero) 1
ssr based F test:         F=0.0080  , p=0.9291  , df_denom=58, df_num=1
ssr based chi2 test:   chi2=0.0084  , p=0.9270  , df=1
likelihood ratio test: chi2=0.0084  , p=0.9270  , df=1
parameter F test:         F=0.0080  , p=0.9291  , df_denom=58, df_num=1

Granger Causality
number of lags (no zero) 2
ssr based F test:         F=0.6219  , p=0.5406  , df_denom=55, df_num=2
ssr based chi2 test:   chi2=1.3569  , p=0.5074  , df=2
likelihood ratio test: chi2=1.3418  , p=0.5113  , df=2
parameter F test:         F=0.6219  , p=0.5406  , df_denom=55, df_num=2

Granger Causality
number of lags (no zero) 3
ssr based F test:         F=0.6600  , p=0.5804  , df_denom=52, df_num=3
ssr based chi2 test:   chi2=2.2464  , p=0.5229  , df=3
likelihood ratio test: chi2=2.2047  , p=0.5310  , df=3
parameter F test:         F=0.6600  , p=0.5804  , df_denom=52, df_num=3

Granger Causality
number of lags (no zero) 4
ssr based F test:         F=1.4365  , p=0.2360  , df_denom=49, df_num=4
ssr based chi2 test:   chi2=6.8016  , p=0.1468  , df=4
likelihood ratio test: chi2=6.4314  , p=0.1692  , df=4
parameter F test:         F=1.4365  , p=0.2360  , df_denom=49, df_num=4
```

Appendix 8: Summary of the linear regressions of emission on prices per vessel type

Dry/Cargo/Passenger

Summary for Dry/Cargo/Passenger:

OLS Regression Results

Dep. Variable:	y100_co2_t_eq_processed	R-squared:	0.050
Model:	OLS	Adj. R-squared:	0.034
Method:	Least Squares	F-statistic:	3.211
Date:	Fri, 03 May 2024	Prob (F-statistic):	0.0781
Time:	10:56:40	Log-Likelihood:	-349.99
No. Observations:	63	AIC:	704.0
Df Residuals:	61	BIC:	708.3
Df Model:	1		
Covariance Type:	nonrobust		

	coef	std err	t	P>|t|	[0.025	0.975]
const	151.3940	87.148	1.737	0.087	-22.869	325.657
ETS_price	-2.6093	1.456	-1.792	0.078	-5.521	0.302

Omnibus:	7.404	Durbin-Watson:	2.377
Prob(Omnibus):	0.025	Jarque-Bera (JB):	8.583
Skew:	-0.470	Prob(JB):	0.0137
Kurtosis:	4.544	Cond. No.	651.

Summary for Tankers:

OLS Regression Results

Dep. Variable:	y100_co2_t_eq_processed	R-squared:	0.055
Model:	OLS	Adj. R-squared:	0.039
Method:	Least Squares	F-statistic:	3.522
Date:	Fri, 03 May 2024	Prob (F-statistic):	0.0653
Time:	10:56:40	Log-Likelihood:	-405.90
No. Observations:	63	AIC:	815.8
Df Residuals:	61	BIC:	820.1
Df Model:	1		
Covariance Type:	nonrobust		

	coef	std err	t	P>|t|	[0.025	0.975]
const	388.7326	211.659	1.837	0.071	-34.505	811.971
ETS_price	-6.6365	3.536	-1.877	0.065	-13.708	0.435

Omnibus:	20.413	Durbin-Watson:	2.080
Prob(Omnibus):	0.000	Jarque-Bera (JB):	32.879
Skew:	-1.142	Prob(JB):	7.25e-08
Kurtosis:	5.704	Cond. No.	651.

Summary for Miscellaneous:

OLS Regression Results

Dep. Variable:	y100_co2_t_eq	R-squared:	0.086
Model:	OLS	Adj. R-squared:	0.071
Method:	Least Squares	F-statistic:	5.662
Date:	Fri, 03 May 2024	Prob (F-statistic):	0.0205
Time:	10:56:40	Log-Likelihood:	-323.92
No. Observations:	62	AIC:	651.8
Df Residuals:	60	BIC:	656.1
Df Model:	1		
Covariance Type:	nonrobust		

	coef	std err	t	P>|t|	[0.025	0.975]
const	207.6162	63.123	3.289	0.002	81.352	333.880
ETS_price	-2.5061	1.053	-2.380	0.021	-4.613	-0.399

Omnibus:	28.205	Durbin-Watson:	2.066
Prob(Omnibus):	0.000	Jarque-Bera (JB):	47.520
Skew:	1.636	Prob(JB):	4.80e-11
Kurtosis:	5.772	Cond. No.	652.

Summary for Bulk Carriers:

OLS Regression Results

Dep. Variable:	y100_co2_t_eq_processed	R-squared:	0.015
Model:	OLS	Adj. R-squared:	-0.001
Method:	Least Squares	F-statistic:	0.9370
Date:	Fri, 03 May 2024	Prob (F-statistic):	0.337
Time:	10:56:40	Log-Likelihood:	-384.46
No. Observations:	63	AIC:	772.9
Df Residuals:	61	BIC:	777.2
Df Model:	1		
Covariance Type:	nonrobust		

	coef	std err	t	P>|t|	[0.025	0.975]
const	147.4675	150.608	0.979	0.331	-153.692	448.627
ETS_price	-2.4357	2.516	-0.968	0.337	-7.467	2.596

Omnibus:	18.643	Durbin-Watson:	2.137
Prob(Omnibus):	0.000	Jarque-Bera (JB):	32.013
Skew:	-0.995	Prob(JB):	1.12e-07
Kurtosis:	5.870	Cond. No.	651.

Summary for Offshore:

OLS Regression Results

Dep. Variable:	y100_co2_t_eq_processed	R-squared:	0.001
Model:	OLS	Adj. R-squared:	-0.015
Method:	Least Squares	F-statistic:	0.08104
Date:	Fri, 03 May 2024	Prob (F-statistic):	0.777
Time:	10:56:40	Log-Likelihood:	-424.31
No. Observations:	62	AIC:	852.6
Df Residuals:	60	BIC:	856.9
Df Model:	1		
Covariance Type:	nonrobust		

	coef	std err	t	P>|t|	[0.025	0.975]
const	88.9004	317.077	0.280	0.780	-545.348	723.149
ETS_price	-1.5096	5.303	-0.285	0.777	-12.117	9.098

Omnibus:	28.355	Durbin-Watson:	2.044
Prob(Omnibus):	0.000	Jarque-Bera (JB):	100.175
Skew:	1.168	Prob(JB):	1.77e-22
Kurtosis:	8.772	Cond. No.	647.

Summary for Fishing:

OLS Regression Results

Dep. Variable:	y100_co2_t_eq	R-squared:	0.174
Model:	OLS	Adj. R-squared:	0.143
Method:	Least Squares	F-statistic:	5.673
Date:	Fri, 03 May 2024	Prob (F-statistic):	0.0245
Time:	10:56:40	Log-Likelihood:	-198.69
No. Observations:	29	AIC:	401.4
Df Residuals:	27	BIC:	404.1
Df Model:	1		
Covariance Type:	nonrobust		

	coef	std err	t	P>|t|	[0.025	0.975]
const	1638.4806	590.866	2.773	0.010	426.124	2850.837
ETS_price	-23.7256	9.961	-2.382	0.025	-44.164	-3.287

Omnibus:	5.511	Durbin-Watson:	2.324
Prob(Omnibus):	0.064	Jarque-Bera (JB):	1.909
Skew:	0.166	Prob(JB):	0.385
Kurtosis:	1.788	Cond. No.	797.

Appendix 9: Summary of the linear regressions of emission on carbon leakage

OLS Regression Results

Dep. Variable:	y100_co2_t_eq	R-squared:	0.001
Model:	OLS	Adj. R-squared:	0.001
Method:	Least Squares	F-statistic:	201.3
Date:	Fri, 24 May 2024	Prob (F-statistic):	1.14e-45
Time:	17:04:34	Log-Likelihood:	-1.5361e+06
No. Observations:	187319	AIC:	3.072e+06
Df Residuals:	187317	BIC:	3.072e+06
Df Model:	1		
Covariance Type:	nonrobust		

	coef	std err	t	P>|t|	[0.025	0.975]
const	414.9052	2.878	144.142	0.000	409.263	420.547
group	-57.7770	4.072	-14.189	0.000	-65.758	-49.796

Omnibus:	192939.565	Durbin-Watson:	1.801
Prob(Omnibus):	0.000	Jarque-Bera (JB):	13845563.473
Skew:	5.155	Prob(JB):	0.00
Kurtosis:	43.837	Cond. No.	2.62

OLS Regression Results

Dep. Variable:	y100_co2_t_eq	R-squared:	0.001
Model:	OLS	Adj. R-squared:	0.001
Method:	Least Squares	F-statistic:	1970.
Date:	Fri, 24 May 2024	Prob (F-statistic):	0.00
Time:	17:08:12	Log-Likelihood:	-1.3676e+07
No. Observations:	1666014	AIC:	2.735e+07
Df Residuals:	1666012	BIC:	2.735e+07
Df Model:	1		
Covariance Type:	nonrobust		

	coef	std err	t	P>|t|	[0.025	0.975]
const	419.4065	0.975	430.342	0.000	417.496	421.317
group	-61.1483	1.378	-44.389	0.000	-63.848	-58.448

Omnibus:	1713168.477	Durbin-Watson:	1.612
Prob(Omnibus):	0.000	Jarque-Bera (JB):	122673679.149
Skew:	5.143	Prob(JB):	0.00
Kurtosis:	43.760	Cond. No.	2.62

Appendix 10: Summary of the linear regressions of emission on carbon leakage for Q1 2022, Q1 2023, Q1 2024

OLS Regression Results for 2022:

OLS Regression Results

Dep. Variable:	y100_co2_t_eq	R-squared:	-0.000
Model:	OLS	Adj. R-squared:	-0.000
Method:	Least Squares	F-statistic:	nan
Date:	Mon, 27 May 2024	Prob (F-statistic):	nan
Time:	09:34:07	Log-Likelihood:	-7.6296e+05
No. Observations:	94495	AIC:	1.526e+06
Df Residuals:	94494	BIC:	1.526e+06
Df Model:	0		
Covariance Type:	nonrobust		

	coef	std err	t	P>|t|	[0.025	0.975]
const	353.0195	2.527	139.702	0.000	348.067	357.972

Omnibus:	90341.868	Durbin-Watson:	1.569
Prob(Omnibus):	0.000	Jarque-Bera (JB):	4233214.400
Skew:	4.712	Prob(JB):	0.00
Kurtosis:	34.406	Cond. No.	1.00

OLS Regression Results for 2024:

OLS Regression Results

Dep. Variable:	y100_co2_t_eq	R-squared:	-0.000
Model:	OLS	Adj. R-squared:	-0.000
Method:	Least Squares	F-statistic:	nan
Date:	Mon, 27 May 2024	Prob (F-statistic):	nan
Time:	09:34:07	Log-Likelihood:	-7.5804e+05
No. Observations:	93721	AIC:	1.516e+06
Df Residuals:	93720	BIC:	1.516e+06
Df Model:	0		
Covariance Type:	nonrobust		

	coef	std err	t	P>|t|	[0.025	0.975]
const	357.0949	2.573	138.760	0.000	352.051	362.139

Omnibus:	90292.879	Durbin-Watson:	1.499
Prob(Omnibus):	0.000	Jarque-Bera (JB):	4413469.234
Skew:	4.754	Prob(JB):	0.00
Kurtosis:	35.246	Cond. No.	1.00

OLS Regression Results for 2023:

OLS Regression Results

Dep. Variable:	y100_co2_t_eq	R-squared:	-0.000
Model:	OLS	Adj. R-squared:	-0.000
Method:	Least Squares	F-statistic:	nan
Date:	Mon, 27 May 2024	Prob (F-statistic):	nan
Time:	09:34:07	Log-Likelihood:	-7.6296e+05
No. Observations:	94495	AIC:	1.526e+06
Df Residuals:	94494	BIC:	1.526e+06
Df Model:	0		
Covariance Type:	nonrobust		

	coef	std err	t	P>|t|	[0.025	0.975]
const	353.0195	2.527	139.702	0.000	348.067	357.972

Omnibus:	90341.868	Durbin-Watson:	1.569
Prob(Omnibus):	0.000	Jarque-Bera (JB):	4233214.400
Skew:	4.712	Prob(JB):	0.00
Kurtosis:	34.406	Cond. No.	1.00

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