Carbon Leakage in Maritime Transport:

Cost Analysis and Mitigation Strategies under FuelEU Maritime

TIL 5060: TIL Thesis

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by

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to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Monday July 14, 2025 at 9:00 AM.

Student number:	5943442	
Project duration:	February, 2025 – July, 2025	
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Preface

This thesis marks the end of my studies at TU Delft, where I pursued a Master's in Transport, Infrastructure, and Logistics. The first six months were especially challenging—particularly the courses in Quantitative Methods for Logistics and Statistical Analysis and Behaviour. The Dutch winter added to the difficulty, but along the way, I met many wonderful friends who supported me throughout this academic journey. I also had the privilege of learning from amazing and kind professors at TU Delft, who were always willing to help and patiently answer questions from a student from Indonesia. I am deeply grateful to everyone I have met during this time. Above all, I am thankful to God and to myself for making it to this point.

This work would not have been possible without the guidance and continuous feedback from my thesis committee. I am especially thankful to Jan Kiel from Panteia, who gave me the opportunity to work on this project, and to Gijs, whose insights and constant support—especially with data and stakeholder engagement results—were invaluable to this thesis.

I would also like to express my sincere gratitude to my supervisors, Jan Anne and Jeroen, who consistently provided thoughtful feedback and patiently answered all my questions. Without their support, this thesis would not have been completed on time.

Finally, I want to thank my parents for their unwavering support throughout my studies, all my friends, and everyone who has touched my life in meaningful ways. You will always have a place in my heart.

Anyway, don't be a stranger.

A.N. Maulana
Delft, July 2025

Summary

Introduction

Maritime transport plays a vital role in global trade by facilitating the movement of goods across continents. It accounts for approximately 80% of international cargo by volume, making it a cornerstone of economic development (World Bank Group, 2023). However, the sector also contributes significantly to environmental challenges, emitting around 2.9% of global carbon dioxide (CO_2) emissions (European Commission, 2021b).

In response to these challenges, the European Union (EU) has introduced the Fit for 55 legislative package to reduce its greenhouse gas (GHG) emissions by at least 55% by 2030. Two key policies targeting maritime emissions are the EU Emissions Trading System (EU ETS) and the FuelEU Maritime Regulation. These instruments aim to drive the maritime energy transition by introducing carbon pricing and requiring the use of cleaner fuels and Onshore Power Supply (OPS) at EU ports (European Commission, 2023a).

While these regulations are intended to reduce emissions, they may also lead to unintended consequences. Due to increased compliance costs, shipowners might choose to reroute services, avoid EU ports, or rely on non-EU transshipment hubs. These behaviors can undermine the environmental effectiveness of the regulations by shifting emissions outside EU jurisdiction, a phenomenon known as carbon leakage (Intergovernmental Panel on Climate Change, 2007).

Although there is growing academic interest in the costs and technologies associated with maritime decarbonisation, fewer studies have investigated the behavioral impacts of these new regulations, especially the FuelEU Maritime Regulation. As a result, there is limited understanding of how routing strategies might evolve and how such shifts may impact regulatory effectiveness and EU port competitiveness.

To address this gap, this thesis combines quantitative modeling and qualitative stakeholder insights to evaluate the risks of carbon leakage under the FuelEU Maritime Regulation. Using Panteia's Liner Shipping Model, it simulates routing decisions and regulatory outcomes under different policy scenarios. These findings are complemented by stakeholder perspectives to identify feasible mitigation strategies.

The main objective of this thesis is to assess the cost implications of FuelEU Maritime and identify effective policy responses. Specifically, it seeks to answer the question:

"To what extent does the FuelEU Maritime Regulation lead to carbon leakage risks in the maritime sector, and what strategies can mitigate these risks while maintaining EU competitiveness"?

Case Studies

This study focuses on two primary evasive mechanisms that shipping operators may adopt—evasive routing and transshipment shifts to non-EEA hubs—which could potentially result in carbon leakage under current EU maritime climate regulations. Three case studies were developed to illustrate and quantify these mechanisms. The first case study analyzes the MSC Britannia service, which includes a port call in the United Kingdom, a non-EEA country. This case explores how such routing decisions can reduce regulatory exposure under the FuelEU Maritime and EU ETS frameworks. The second case study examines the Maersk MECL service, which altered its route to exclude a stop at Algeciras, an EEA port. This change illustrates how avoiding EEA ports can significantly lower compliance costs. The third case study investigates whether the use of feeder vessels under 5000 GT, which fall below the regulatory threshold of FuelEU Maritime, can serve as an economically viable strategy to evade compliance. Together, these case studies provide insight into how operational decisions on routing and vessel deployment may undermine the intended environmental effectiveness of EU climate regulations.

Methods

To answer the main research question, this study incorporates both quantitative and qualitative methods. The quantitative approach uses the Panteia Liner Shipping Model to simulate liner shipping routes and assess how changes in routing affect compliance costs, fuel consumption, and emissions under the FuelEU Maritime and EU ETS frameworks. The qualitative approach involves stakeholder surveys and interviews to gather insights on perceived risks, practical challenges, and potential strategies for mitigating carbon leakage while maintaining the competitiveness of EU ports. Together, these methods provide a comprehensive understanding of both the economic and institutional dimensions of carbon leakage in maritime transport.

Quantitative Result

The model simulations show that conventional fuels like MGO and HFO already exceed FuelEU Maritime's GHG intensity limits, requiring blending or alternative fuels to comply. However, such strategies often incur higher costs. Evasive routing, as seen in the MSC Britannia case, can lower regulatory exposure by including a UK port, thereby reducing both FuelEU and ETS liabilities. Conversely, replacing UK calls with EEA ports increases compliance costs due to more regulated voyage legs.

Fuel and OPS strategies differ in effectiveness; while RFNBOs and LNG can help meet FuelEU targets, they are costly. OPS adoption, especially in ports with cleaner electricity, reduces ETS costs more efficiently. The Maersk MECL case shows that omitting an EEA port entirely avoids regulatory costs, though it may lead to longer travel times. Using feeder vessels under 5000 GT can shift emissions outside regulatory scope but is not economically viable.

Additional findings suggest that moderate slow steaming reduces both ETS and FuelEU penalties with minimal trade-offs, while very low speeds harm operational efficiency. Finally, OPS effectiveness depends on national electricity grid carbon intensity, reinforcing the value of strategic port selection.

Qualitative Result

Stakeholders confirm that carbon leakage and competitiveness risks are emerging as unintended consequences of the EU ETS and FuelEU Maritime regulations. These risks are mainly driven by evasive routing, transshipment shifts to non-EEA hubs, and potential modal shifts to road transport. High-risk areas identified include Southern European ports (e.g., Algeciras), North-Western Europe (e.g., Rotterdam, Hamburg), and Eastern Mediterranean regions, facing increasing competition from UK and North African ports. Transshipment relocation to hubs like Tanger Med and Nador West Med is seen as a likely response, particularly for EU-bound cargo.

Feedering using vessels below 5000 GT is generally viewed as economically unviable, limiting its practicality as an evasion strategy. In parallel, stakeholders flagged the risk of a modal shift to road transport in regions like the Baltics and Iberia, driven by high maritime compliance costs and delayed ETS implementation—potentially leading to higher overall emissions. While shifts in bunkering or STS transfers are not currently seen as major evasion routes, FuelEU Maritime is still expected to influence future port and bunkering infrastructure decisions. Over time, regulatory developments may promote the adoption of hub-and-spoke models, resulting in fewer direct EU port calls and greater reliance on transshipment hubs.

Competitiveness loss is attributed to asymmetric costs with non-EEA ports, slower permitting, and infrastructure uncertainty. Although not directly attributable to EU ETS or FuelEU Maritime, some market shifts are being detected, such as increased UK port activity and postponed investments at EEA ports. To address these issues, stakeholders emphasize the need for supportive mitigation policies such as ETS revenue recycling, port incentives, and stronger international alignment of climate regulations (for example with IMO Net-Zero Framework).

Discussion & Conclusion

The main objective of this thesis was to evaluate the extent to which the FuelEU Maritime Regulation leads to carbon leakage risks in the maritime sector, and to explore potential strategies that could mitigate these risks while preserving the competitiveness of EU ports. The findings demonstrate that evasive routing, port call omission, and transshipment relocation are key mechanisms through which ship operators may reduce regulatory exposure. These strategies are often driven by cost considerations, and their deployment can significantly lower FuelEU Maritime and EU ETS liabilities without actually reducing emissions.

The results from the Panteia Liner Shipping Model indicate that while the introduction of a transshipment clause has mitigated some risks of regulatory evasion via neighboring non-EEA ports, it remains insufficient in addressing carbon leakage stemming from Non-EEA to Non-EEA routing. Specifically, transshipment strategies involving ports such as Tanger Med or the UK allow operators to avoid significant portions of FuelEU Maritime and EU ETS obligations, particularly when final destinations lie outside the EEA. These routing adjustments lead to substantial regulatory cost savings for shipping companies, while placing EEA ports at a competitive disadvantage. Although cleaner fuels such as RFNBOs and the use of Onshore Power Supply (OPS) provide compliance advantages, their high costs limit widespread adoption in the absence of stronger incentives. Stakeholder engagement supports these findings, revealing that carbon leakage is not a hypothetical scenario but an emerging reality—especially in vulnerable regions such as Southern and Eastern Europe where the risk of rerouting is more pronounced.

This study contributes to the field of maritime policy and decarbonisation by offering a quantitative and qualitative analysis of the unintended consequences of EU regulations. It provides evidence-based insights into the trade-offs between environmental ambition and economic feasibility. The findings underline the importance of refining policy instruments to reduce loopholes, such as tightening transshipment rules and incentivising clean energy adoption, while ensuring that smaller operators are not disproportionately burdened. Recommendations for future action include improving regulatory alignment, introducing targeted incentives, and continuously monitoring behavioral shifts to adapt policies effectively.

Contents

List of Figures

List of Tables

Nomenclature

Abbreviations

Abbreviation	Definition
CBA	Cost-Benefit Analysis
CBAM	Carbon Border Adjustment Mechanism
EEA	European Economic Area
ETD	Energy Taxation Directive
ETS	Emission Trading System
EU	European Union
GHG	Greenhouse Gases
GT	Gross Tonnage
IMO	International Maritime Organization
MARPOL	International Convention for the Prevention of Pollution from Ships
MBM	Market-Based Measure
MEPC	Marine Environment Protection Committee
METS	Marine Emission Trading System
OPEX	Operational Expenditure
OPS	Onshore Power Supply
RFNBO	Renewable Fuels of Non-Biological Origin
TtW	Tank-to-Wake
WtW	Well-to-Wake
...	

1 Introduction

1.1 Background

Maritime transport is the backbone of international trade, responsible for transporting around 80% of global goods by volume (World Bank Group, 2023). While the sector is critical to global economic growth, it also poses a growing environmental challenge. Shipping contributes approximately 2.9% of global carbon dioxide (CO_2) emissions, and its share is expected to rise in the absence of effective climate action (European Commission, 2021b).

Recognizing this challenge, the European Union (EU) introduced the Fit for 55 legislative package, which sets out a comprehensive strategy to reduce the EU's net greenhouse gas (GHG) emissions by at least 55% by 2030 compared to 1990 levels (European Council, 2025). Within this framework, two key regulatory instruments specifically target emissions from the maritime sector:

- The EU Emissions Trading System (EU ETS), a carbon pricing mechanism, which from 2024 gradually includes CO_2 emissions from ships calling at EU ports, requiring shipowners to purchase emission allowances for a share of their voyages.
- The FuelEU Maritime Regulation, scheduled to take effect in 2025, which aims to reduce the GHG intensity of onboard energy use by setting progressive reduction targets and mandating the use of Onshore Power Supply (OPS) for large vessels while berthed at EU ports (European Commission, 2023a).

These regulations are designed to drive the maritime energy transition and decarbonize international shipping. However, their implementation introduces significant economic implications. Low-carbon fuels are generally more expensive than conventional marine fuels, and OPS retrofitting requires considerable capital investment. Additionally, ports must upgrade their infrastructure to support shore-side electricity supply. These factors may result in higher operating costs for shipowners, potentially affecting the competitiveness of routes connected to the EU.

As a response to these cost pressures, shipping operators may explore evasive strategies to limit their regulatory exposure. Such strategies can include rerouting via non-EU transshipment hubs, avoiding EU port calls, or selectively shifting cargo flows by skipping EEA ports altogether. While such maneuvers are legally permissible, they risk undermining the effectiveness of climate regulations by displacing emissions geographically rather than reducing them. This outcome—where emissions "leak" to less regulated jurisdictions—is known as carbon leakage (Intergovernmental Panel on Climate Change, 2007).

A growing body of literature has explored carbon leakage risks and the economic impacts of EU climate regulations on the maritime sector. Studies have examined the cost implications of instruments such as the EU ETS and the Energy Taxation Directive (ETD) (S. Wang, Zhen, et al., 2021; Christodoulou, Dalaklis, et al., 2021; Faber, Leestemaker, et al., 2022), as well as the broader decarbonization potential of the Fit for 55 package (Berg et al., 2022; Solakivi, Ojala, et al., 2022). However, relatively few studies focus specifically on the behavioral responses to the FuelEU Maritime Regulation—such as route changes, port avoidance, or transshipment relocation. For instance, Springer (2023) model the evolution of fuel demand under FuelEU but do not account for operational adjustments by shipping companies. Similarly, technical studies like CE Delft (2022) evaluate fuel options and emission reduction technologies, yet overlook emissions omitted due to rerouting or the cost burden of OPS infrastructure.

Recent policy monitoring efforts further underscore the importance of understanding these behavioral dynamics. The European Commission's first implementation report on the maritime EU ETS, based on data from the first three quarters of 2024, finds no substantial evidence of widespread evasive behavior. While some routing changes were observed, they were largely attributed to the Red Sea crisis—a disruption caused by regional tensions and attacks on commercial vessels, which led to rerouting, operational delays, and increased transit distances and costs for Asia–Europe trade (Bedoya-Maya et al., 2025). The report found no strong indications of transshipment relocation to non-EU ports, increased use of smaller vessels, or a modal shift to road transport. However, it emphasizes the need for continued monitoring—particularly as the FuelEU Maritime Regulation comes into force in 2025—due to data limitations, external disruptions, and the short implementation timeframe (European Commission, 2025b).

In parallel, academic research presents mixed findings on the presence and extent of carbon leakage. Lagouvardou and Psaraftis (2022) argue that weak carbon pricing mechanisms may incentivize evasive routing, while other studies report limited empirical evidence of such leakage to date (Vierth et al., 2024; Faber, Leestemaker, et al., 2022). These divergent conclusions suggest that the risk of carbon leakage is highly dependent on route characteristics, regulatory scope, and cost structures.

To address this knowledge gap, this thesis investigates whether the design of the FuelEU Maritime Regulation unintentionally encourages evasive behaviors that compromise its environmental effectiveness. Using Panteia's Liner Shipping Model, the research simulates different compliance and avoidance scenarios—such as the use of non-EU transshipment hubs like Tanger Med or Port Said—and quantifies the resulting differences in fuel consumption, emissions, and regulatory costs. Special focus is placed on emissions that fall outside the scope of the EU ETS and FuelEU Maritime due to routing decisions.

Finally, the study also explores potential mitigation strategies, including design improvements to the FuelEU regulation and enhanced incentives for OPS adoption. These findings will be complemented by insights from stakeholder interviews and are intended to inform practical policy recommendations.

1.2 Research Scoping

This study will focus specifically on container shipping routes as the primary area of analysis, excluding other vessel types such as bulk carriers, oil tankers, and cruise ships. The decision to limit the scope to container shipping is based on the need for research simplification, as container shipping plays a major role in global trade and is particularly sensitive to cost fluctuations under regulatory pressure. Additionally, the container sector is the most significant contributor to GHG emissions within the maritime industry (Faber, Hanayama, et al., 2020) (see Figure 1.1). This is due to the sector's high operational intensity and rapid growth: from 1980 to 2020, international trade carried by container ships surged from 0.1 billion to 1.85 billion tons. Although container vessels account for only about 16% of total maritime cargo volume, they represent over half of the value transported. At the same time, container ship capacity expanded substantially, with port traffic reaching 840,635 billion TEU in 2020 (B. Lu et al., 2023). These trends contribute to higher fuel consumption, longer voyages, and increased emissions. Moreover, transshipment operations are more prevalent in the container sector than in other shipping segments (Lagouvardou and Psaraftis, 2022). By concentrating on this segment, the study can deliver a more targeted and actionable assessment of carbon leakage risks.

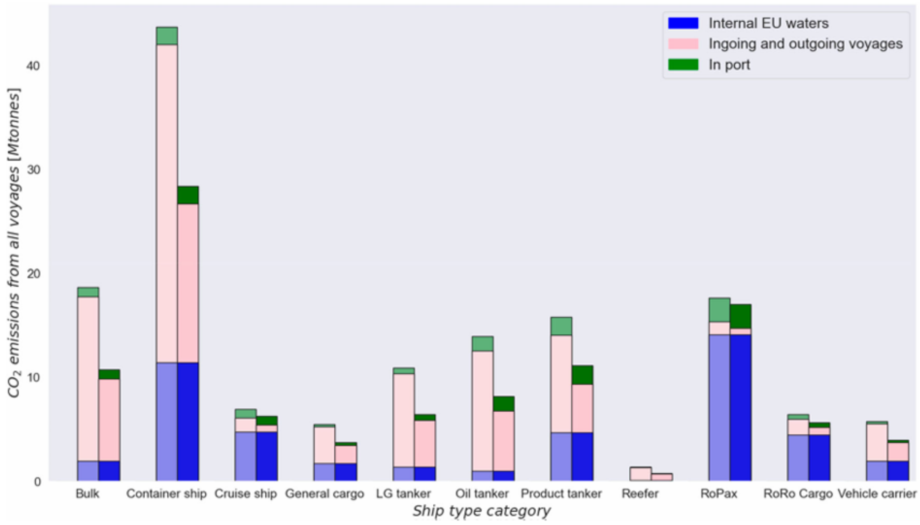


Figure 1.1: CO_2 emissions per shipping segment in 2019 for ships with GT >5000 (Flodén et al., 2024)

The study will primarily focus on ships with a gross tonnage (GT) of 5,000 or more, in alignment with the compliance thresholds set by the FuelEU Maritime Regulation and EU ETS. These thresholds define the regulatory scope, ensuring that the findings are directly applicable to vessels subject to current EU decarbonization policies.

However, feeder vessels, which may fall below the 5,000 GT threshold, are included in the analysis due to their operational relevance in transshipment strategies and their role in potential carbon leakage scenarios. While they are not directly regulated, their interactions with regulated mainliners make them a necessary part of the scenario analysis.

This inclusion broadens the analysis without diluting the study's focus, allowing for a more accurate representation of real-world routing and compliance behavior. The study will remain cost-based and sensitive to data availability, particularly regarding fuel prices, port fees, and emissions assumptions, which may present limitations for broader generalization.

It is important to note that this thesis is part of an ongoing research project commissioned by the European Commission and conducted at Panteia. As the project evolves, adjustments to the scope, case studies, or data inputs may be required. Ongoing collaboration with project stakeholders until December 2025 will help integrate emerging data, policy updates, and feedback, thereby ensuring the study's continued relevance and practical value.

1.3 State of the Art: Carbon Leakage and Cost Modeling in Maritime Transport

In addition to the IPCC definition, which describes carbon leakage as the geographic shift of emissions due to regulatory differences, European Commission (2021a) provides a complementary perspective. It defines carbon leakage as a situation in which businesses relocate their operations to countries with less stringent emission regulations to avoid the higher costs imposed by climate policies. Such relocation may result in an overall increase in global emissions, thereby undermining the intended environmental benefits of these regulations.

Although the maritime sector is not officially classified as being at high risk of carbon leakage, it remains particularly vulnerable due to its high operational flexibility and global nature. Shipping companies can alter their routes, refuel in non-regulated regions, or shift port activities to avoid carbon pricing mechanisms such as the EU Emissions Trading System (EU ETS) and the FuelEU Maritime Regulation. This potential for cost-driven rerouting—referred to as evasive routing—can undermine regulatory objectives by increasing total emissions or disadvantaging EU ports.

Recent findings from the European Commission's first implementation report on the maritime EU ETS provide context for this regulatory uncertainty. While acknowledging the sector's theoretical exposure to circumvention strategies, the report concludes that there is no substantial evidence of widespread evasive behavior since the regulation entered into force in January 2024 (European Commission, 2025a). The analysis of shipping traffic and port call data reveals no significant shifts in transshipment activity to non-EU ports, no increased deployment of smaller ships to avoid thresholds, and no modal shift toward road transport. This supports the view that, although the maritime sector is not formally labeled as high-risk, its operational characteristics still warrant close monitoring to detect potential future leakage risks.

In addition to emissions-related concerns, growing attention is being paid to the potential competitiveness impacts of EU decarbonization policies. Industry coalitions and non-profit alliances have voiced concerns that, while the EU is leading in green maritime regulation, uncertainty at the International Maritime Organization (IMO)—where mid-term measures remain in draft form and key debates persist over targeted exemptions and revenue distribution—creates a lack of clarity about the global regulatory trajectory (Fricaudet, 2025). This uncertainty is especially pressing as the EU ETS and FuelEU Maritime regulations raise compliance costs in the coming years (SASHA Coalition et al., 2025). These concerns underscore the importance of complementary policy support to preserve the EU's leadership in clean shipping while minimizing the risks of carbon leakage and economic displacement.

Existing Approaches to Analyze Carbon Leakage

Several approaches have been used to analyze carbon leakage across different sectors. Branger et al. (2016) conducted an econometric analysis of carbon leakage under the EU ETS, focusing on the cement and steel industries. Similarly, Aichele and Felbermayr (2015) applied a gravity model to measure the carbon dioxide content of trade, accounting for both domestic and imported intermediate inputs. Their study found that binding commitments under the Kyoto Protocol resulted in an 8% increase in embodied carbon imports from non-committed countries and a 3% rise in the emission intensity of imports, indicating that climate policies can inadvertently contribute to carbon leakage.

Empirical research on carbon leakage under the EU ETS has yielded mixed findings. Using survey data, Dechezleprêtre et al. (2022) found no significant evidence of economic relocation among multinational firms. However, administrative data analysis by Koch and Mama (2019) suggested that carbon leakage had occurred, particularly among German multinational firms. These contrasting results highlight the challenges in assessing carbon leakage, as different methodologies yield varying conclusions.

Most studies on carbon leakage rely on ex-ante analyses, which require extensive data and have been feasible due to the long-standing implementation of the EU ETS since 2005. However, given that the extension of the EU ETS to maritime transport took effect only in 2024 and the FuelEU Maritime regulation will be enforced starting in 2025, empirical research specifically addressing carbon leakage in the shipping sector remains limited. As a result, current studies primarily rely on cost modeling and scenario-based analyses to estimate potential carbon leakage risks in response to these policies, which are discussed in subsection 3.1.1.

1.4 Research Questions

Based on the discussion in section 1.3, where gaps in existing approaches have been identified, this study aims to evaluate the cost-driven risks of carbon leakage under the FuelEU Maritime Regulation by addressing these model limitations through a cost-driven modeling approach. Specifically, the research will investigate the economic and environmental impacts of evasive routing behaviors in the maritime sector and analyze how compliance costs—arising from GHG intensity targets for maritime fuels and onshore power supply (OPS) requirements at EU ports—influence shipowners' operational decisions, including route selection, transshipment relocation, and port avoidance.

By integrating a cost-driven modeling approach, this study provides a structured framework to assess whether compliance costs are substantial enough to incentivize carbon leakage, and to identify potential policy measures to mitigate such risks. This approach will help bridge existing modeling gaps by incorporating a more dynamic and comprehensive evaluation of cost structures, regulatory compliance, and evasive behaviors.

Understanding these cost-driven risks is crucial to ensuring that the EU's decarbonization efforts under the Fit for 55 package do not lead to unintended consequences, such as traffic displacement and emissions shifting beyond EU jurisdiction. The main focus of this research is to quantify the impact of FuelEU compliance costs on carbon leakage risks and provide insights into potential mitigation strategies that can balance environmental objectives with European Economic Area (EEA) port competitiveness.

This study seeks to answer the following main research question:

To what extent does the FuelEU Maritime Regulation lead to carbon leakage risks in the maritime sector, and what strategies can mitigate these risks while maintaining EU competitiveness?

The main research questions can be answered by the following sub-questions:

1. **What are the key mechanisms contributing to carbon leakage in maritime transport under the FuelEU Maritime and EU ETS regulations?**

   This sub-question investigates the state-of-the-art carbon leakage mechanisms in maritime transport. It examines how past regulatory frameworks—such as the EU ETS—have influenced evasive routing, transshipment shifts, and port avoidance strategies. Understanding these established carbon leakage patterns provides a theoretical basis for analyzing how similar risks might emerge under the FuelEU Maritime Regulation.

2. **How can the cost impact of the FuelEU Maritime Regulation on shipowners be assessed?**

   This sub-question focuses on evaluating the financial implications of FuelEU compliance. It identifies key cost drivers, including fuel switching costs, onshore power supply (OPS) compliance costs, and port fees, and explores how these factors shape shipowners' routing decision. By assessing the economic burden of compliance, this question lays the groundwork for understanding the incentives that may lead to evasive behavior.

3. **How can the Panteia Liner Shipping Model be used to assess potential carbon leakage under the FuelEU Maritime Regulation?**

   This study applies the Panteia Liner Shipping Model to simulate how shipowners might respond to regulatory costs introduced by FuelEU Maritime and the EU ETS. The model enables detailed cost and emissions calculations across different routing and compliance scenarios. By incorporating factors such as GHG intensity thresholds, OPS requirements, and carbon pricing, it allows for assessing whether evasive strategies—like rerouting or transshipment shifts—offer financial advantages. This provides a structured basis to evaluate the risk of carbon leakage and its implications for both emissions reduction and EU port competitiveness..

4. **How can carbon leakage risks on key container shipping routes to and from the EU be mitigated?**

   This sub-question applies the methodology from sub-question 3 to a case study on Europe, identifying key risk factors on major trade corridors and evaluating mitigation strategies from stakeholders engagement.

Collectively, these sub-questions will provide a comprehensive understanding of carbon leakage risks under FuelEU Maritime and support the development of practical mitigation strategies. An overview of the research workflow is presented in Figure 1.2.

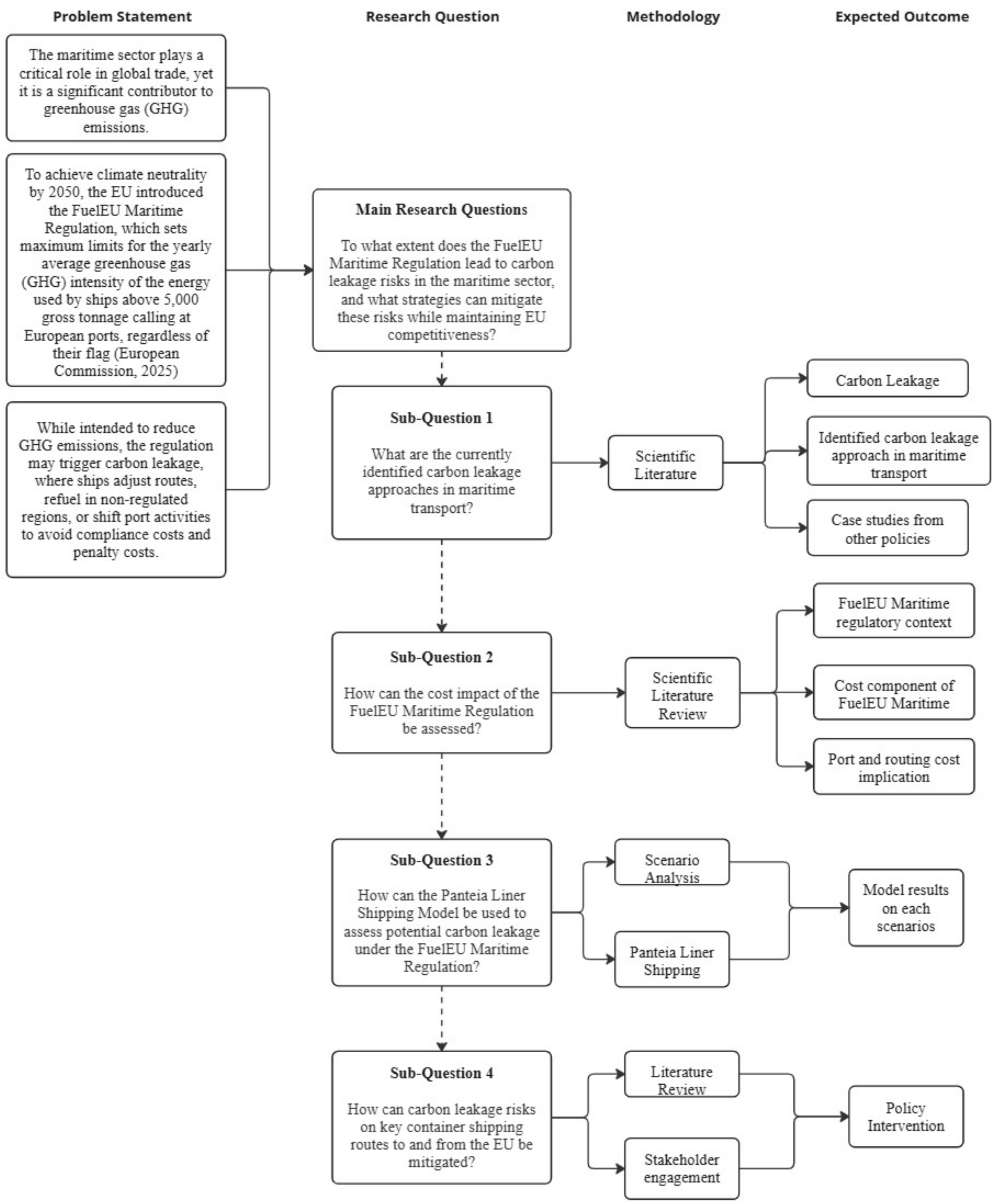


Figure 1.2: Thesis Research Flow

1.5 Structure of The Report

The structure of this report is as follows. Chapter 2 elaborates on the research methods applied in this study. Chapter 3 presents the findings from the literature review, addressing Sub-question 1 and Sub-question 2. Chapter 4 explains the Panteia liner shipping model, providing a detailed overview of its structure and application. Chapter 5 focuses on the scenario analysis using the Panteia liner shipping model, addressing Sub-question 3. Chapter 6 discusses the insights gathered from stakeholder engagement conducted by Panteia, addressing Sub-question 4. Chapter 7 presents the discussion and recommendations, followed by Chapter 8, which concludes the report by summarizing the key findings of the study.

1.6 Summary

Key Takeaways

- Maritime shipping is vital for global trade, carrying around 80% of goods by volume, but contributes significantly to global CO_2 emissions and faces increasing environmental regulation.
- The EU Fit for 55 package introduces the EU ETS and FuelEU Maritime Regulation to reduce maritime GHG emissions via carbon pricing and energy intensity targets.
- Compliance with these regulations imposes substantial operational and capital costs on shipowners, prompting concerns over cost-driven evasive behaviors such as rerouting, transshipment shifts, or OPS avoidance.
- These behaviors may result in carbon leakage, where emissions shift outside EU jurisdiction without being reduced globally, potentially undermining the regulations' environmental goals.
- Existing literature focuses more on technical and fuel-based assessments rather than route-level operational responses to FuelEU Maritime, revealing a gap in understanding behavioral adaptations.
- This thesis investigates how FuelEU Maritime's design may unintentionally incentivize avoidance strategies, using the Panteia Liner Shipping Model to simulate compliance vs. evasion impacts.
- The analysis focuses on container shipping (≥5,000 GT) due to its emission share, cost sensitivity, and regulatory exposure, offering a more actionable and targeted assessment.

2

Methodology

This chapter describes the methods that were performed to answer the research questions. Table 2.1 presents an overview of the sub-questions and methods used.

"To what extent does the FuelEU Maritime Regulation lead to carbon leakage risks in the maritime sector, and what strategies can mitigate these risks while maintaining EU competitiveness?"	
Sub-question	**Method**
1. What are the key mechanisms contributing to carbon leakage in maritime transport under the FuelEU Maritime and EU ETS regulations?	Literature review
2. How can the cost impact of the FuelEU Maritime Regulation on shipowners be assessed?	Literature review
3. How can the Panteia Liner Shipping Model be used to assess potential carbon leakage under the FuelEU Maritime Regulation?	Panteia Liner Shipping Model, Scenario Analysis
4. How can carbon leakage risks on key container shipping routes to and from the EU be mitigated?	Stakeholder Engagement

Table 2.1: Sub-questions and corresponding methods

2.1 Literature Review

To address the first two sub-questions, a comprehensive literature review was conducted to analyze state-of-the-art approaches to carbon leakage in maritime transport and assess the cost impact of the FuelEU Maritime Regulation. The primary sources of literature include academic databases such as Elsevier and Google Scholar. Search keywords included: carbon leakage, maritime transport, shipping evasion route, and FuelEU Maritime Regulation. Snowballing techniques were applied using key studies such as Lagouvardou and Psaraftis (2022) and Defour and Afonso (2020) to broaden the review's scope. Given the evolving nature of FuelEU Maritime, the review also incorporates recent policy reports and stakeholder perspectives found in official documents and reputable news sources.

The review begins by contextualizing carbon leakage in maritime transport within the evolving regulatory landscape, with a particular focus on the FuelEU Maritime Regulation. It explores key themes such as compliance costs (e.g., fuel switching and onshore power supply requirements), evasive routing behaviors, port competitiveness, and emissions displacement. Each theme is analyzed in relation to the operational and economic challenges faced by the shipping industry.

Articles were selected based on their relevance to carbon leakage in maritime transport and the FuelEU Maritime Regulation. A comprehensive analysis of these themes is provided in Chapter 3. Additionally, various policy mitigation measures from different regulatory frameworks were reviewed to support the discussion to answer sub-question 4.

2.2 Scenario Analysis

This study employs scenario analysis to evaluate a range of potential outcomes and assess carbon leakage risks under the FuelEU Maritime Regulation. Scenario analysis requires uncertain input variables in the model. In this study, both exogenous uncertainties (such as fuel prices and regulatory costs) and endogenous uncertainties (such as routing and port choice decisions) are explored. The key variables incorporated in the model are:

- Fuel Price Volatility: The cost of fuels (e.g., ammonia, LNG, methanol, MGO) fluctuates significantly (Y. Wang et al., 2018; Yao et al., 2012)
- Carbon Price Uncertainty: Carbon prices are volatile and increased substantially over time (Fuchs et al., 2024)
- Gradual GHG Intensity Limits: The FuelEU Maritime Regulation tightens GHG intensity limits over time, requiring fleet adjustments and increased compliance costs (European Commission, 2023a).
- Onshore Power Supply (OPS) Costs: The International Maritime Organization (IMO) recommends docked ships using shore power (SP) to power auxiliary engine instead of marine fuels to reduce carbon emissions during in-port time. The SP system has been successfully implemented in several ports, including Shanghai, Los Angeles, and Nagasaki, with all European ports expected to adopt this approach by 2025 (Z. Wang et al., 2024).
- Operational Adjustments: Shipowners may adapt by altering ship speed, since the sailing speed not only determines fuel consumption (ultimately, emissions) but also influences sailing time for each ship (Venturini et al., 2017; Zheng et al., 2022). Carbon leakage can also occur in the form of increased sailing speeds (Kotzampasakis, 2025). While slower sailing is encouraged on EU ETS-covered routes to reduce emissions and associated costs, shipping companies might increase speeds on routes not subject to regulation to recover lost time, potentially undermining overall emissions reduction efforts.

The scenario analysis also considers different case studies that explore how compliance costs could be avoided or reduced through transshipment relocation and evasive routing strategies:

1. **Transshipment Relocation**: This involves shifting transshipment activities to either EEA ports or Non-EEA ports:
    - EEA transshipment: Mainline vessels are substituted with feeder vessels, maintaining compliance within EU jurisdictions.
    - Non-EEA transshipment: Transshipment is relocated to non-EEA ports, requiring feeder vessels to transport cargo back to the EU. If these feeders are under 5000 GT, they are exempt from FuelEU Maritime and EU ETS, effectively reducing compliance costs.
2. **Evasive Port Calls**: This strategy involves adding an additional non-EEA port (e.g., Tanger Med) as an intermediate stop. If a ship stops at a non-EEA port before entering the EU, compliance costs apply only to the voyage segment between the non-EEA port and the EEA port destination, reducing the overall cost burden.

By exploring these scenarios, this study aims to quantify potential cost savings, assess the risks of carbon leakage arising from FuelEU Maritime compliance requirements, and address Sub-question 3.

2.3 Panteia Liner Shipping Model

To assess carbon leakage risks and regulatory cost impacts under the FuelEU Maritime Regulation, this study utilizes the Panteia Liner Shipping Model—a Python-based simulation tool designed to model real-world liner shipping operations and cost structures.

Originally developed for evaluating route-specific shipping economics, the model is well-suited for this study because it integrates detailed operational variables, such as fuel consumption, vessel speed, port handling costs, and sailing frequency. These parameters are essential for analyzing how routing adjustments (e.g., calling at non-EEA ports or omitting certain EEA transshipment hubs) influence both total costs and regulatory exposure.

Crucially, the model is enhanced to allow:

- Segmentation of voyage legs based on EEA coverage (EEA–EEA, EEA–non-EEA, non-EEA–non-EEA), enabling precise allocation of FuelEU and ETS obligations.
- Estimation of emissions using fuel consumption data, which can be extended to calculate Well-to-tank (WtT) and Tank-to-wake (TtW) emissions under FuelEU Maritime.
- Simulation of avoidance strategies, such as using non-EEA transshipment ports or smaller vessels exempt from regulation, to quantify their effect on cost and emissions.

Key outputs from the model include:

- Total voyage costs, including bunker fuel, crew, maintenance, and port handling.
- Annual operational expenditure (OPEX) and cost per TEU, allowing for route-level comparisons.
- Total fuel consumption per voyage and per year, serving as the basis for GHG emission calculations.
- Transit time and rotation estimates, relevant for service efficiency and competitiveness.

By enhancing the model to incorporate FuelEU Maritime and EU ETS mechanics, this study uses it as a decision-support tool to simulate realistic compliance scenarios, identify cost-effective routing choices, and explore how carbon leakage might occur under current policy design

2.4 Stakeholder Engagement

The stakeholder engagement, conducted by Panteia, focuses exclusively on key stakeholders within the EEA maritime sector. This includes regulatory and supervisory authorities, port operators, shipping companies, maritime workers, environmental organizations, and academic and research institutions.

The engagement process consists of preliminary scoping interviews, a survey questionnaire, two stakeholder workshops, and a number of targeted follow-up interviews. The stakeholder engagement process aims to gather insights on the operational impacts of the FuelEU Maritime and EU ETS regulations, as well as to identify practical measures to mitigate carbon leakage and support EU maritime competitiveness.

Due to the ongoing nature of the project and confidentiality agreements, the specific identities of stakeholders involved cannot be disclosed.

An overview of the stakeholder engagement timeline is provided in Figure 2.1.

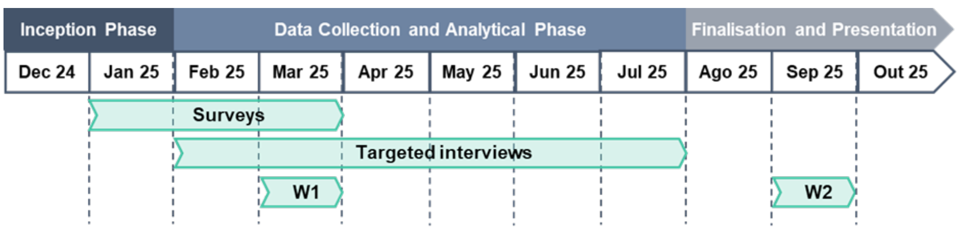


Figure 2.1: Stakeholder Engagement Timeline (TISPT et al., 2025)

Stakeholder engagement was included in this research as a complementary qualitative method. The interviews and surveys were conducted independently by Panteia as part of a parallel consultancy project. As such, the data obtained through these activities were used as secondary sources in this study.

The stakeholder responses were used to support three main objectives:

- To contextualize the results from the scenario-based modeling, particularly by reflecting on how shipowners and port stakeholders perceive and respond to the FuelEU Maritime and EU ETS regulations in practice.
- To inform the development of policy recommendations, by identifying concerns raised by stakeholders regarding feasibility, fairness, administrative complexity, and possible unintended consequences of each proposed measure.
- To validate or contrast the outcomes of the model simulations with real-world insights, helping to ensure that conclusions drawn from the quantitative analysis remain grounded in stakeholder realities.

Although the engagement activities were not carried out by the researcher, the data were carefully reviewed and integrated into the analysis chapters. Relevant quotes, summarized themes, and aggregate patterns were used to enrich the interpretation of the model findings and guide the formulation of more realistic and stakeholder-sensitive policy suggestions.

Targeted Interview

The targeted interviews aim to gather initial insights into the operational impacts of FuelEU Maritime and EU ETS, including potential shifts in port calls, bunkering, feedering, transshipment, and route selection. Additionally, the interviews explore policy responses to mitigate carbon leakage risks while ensuring that environmental objectives are met.

As of now, Panteia has hosted the initial stakeholder workshop, launched a large-scale questionnaire targeting diverse stakeholder groups, and conducted several targeted interviews. These consultations involve a broad range of European maritime actors, including representatives from maritime organizations, private shipping companies, ports, and terminal operators.

A visualization of the interview is provided in Figure 2.2.

		Page	1 / 1
To	EU	Reference	11xxx
From	Gijs Boekweit, Jan Kiel	Date	29 January 2025
Subject	Interview guide carbon leakage in maritime transport		

Introduction (10 minutes)

Introduction
Brief introduction of the participants

Recording the interview
For the purpose **making notes of the interview** we would like to record this interview. Do you agree?

Purpose of the interview
- Thank you for taking the time to speak with us.
- We are conducting this interview as part of a European Commission study on carbon leakage risks and competitiveness challenges in maritime transport, particularly in light of the FuelEU Maritime Regulation.
- Your insights will be important in helping to identify practical risks and solutions.
- All responses will be treated as confidential and will be used only in aggregated form for the study.
- You are welcome to decline any question or let us know if you would like to go off the record at any time.

Scope of the study
- The study is **focused on maritime transport** and the effects of **FuelEU Maritime, CBAM, and ETS** on competitiveness and carbon leakage.
- We are particularly interested in **operational impacts** (e.g., changes in port calls, bunkering, feedering, transshipment, and route selection).
- Additionally, we are examining **potential policy responses** to mitigate carbon leakage risks while ensuring environmental goals are met.

Structure of the Interview
- We will start with **general questions** and progressively move to more **detailed** aspects.
- The interview is structured into three key parts:
  1. **General perspectives** on regulatory impacts.
  2. **Specific risks and behavioural responses** (e.g., port evasion, rerouting).
  3. **Potential solutions and policy recommendations**.
- The conversation will last **approximately one hour**.
- At the end, we will **give you the opportunity to ask questions or share additional remarks**.

(a) Introduction of the Targeted Interview

Q1 - General regulatory impact *(Priority: High)*
How have regulatory developments (e.g. FuelEU Maritime, ETS, CBAM) influenced the decisions of your organisation in recent years?
- *Follow-up: Are there specific policies that have had a **notable impact** on your operations?*

Q2 - Definition of Carbon Leakage *(Priority: High)*
In your view, how would you define carbon leakage within the maritime industry?
- *Follow-up: Do you consider carbon leakage primarily an **economic concern, environmental concern, or both**?*

Q3 - Competitiveness risks *(Priority: High)*
Do you consider there is a risk of carbon leakage and loss of competitiveness loss for EU ports and operators as a result of regulatory developments?
- *Follow-up: Are there specific types of operators (e.g., deep-sea shipping, short-sea shipping, feeder services) that are more vulnerable than others?*

Part 2: Carbon leakage risks and behavioural responses (20 min)
This section focuses on geographic risks, specific behaviours, and market responses to regulatory changes.

Q4 - Geographic risks *(Priority: High)*
Where (geographically) do you see risks of carbon leakage or loss of competitiveness?
- *Follow-up: Are there specific **routes or ports** that could see increased or decreased activity due to these regulations?*

Q5 - Operational changes *(Priority: High)*
Do you foresee operational changes such as changes in bunkering locations, feeder services, port evasion, or rerouting due to regulatory developments?
- *Follow-up: Could you provide examples of specific **ports or trade lanes** where these changes may occur?*

(b) A Portion of the Questions from the Targeted Interview

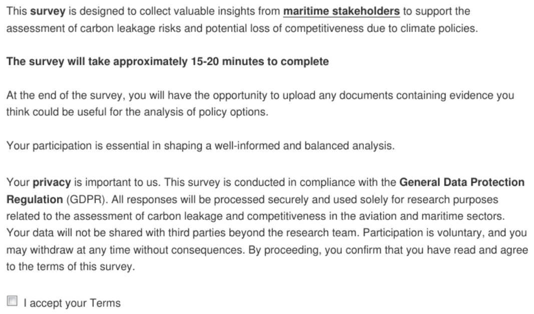
Figure 2.2: Visualization of a segment of the Targeted Interview conducted by Panteia

Survey Questionnaire

The survey questionnaire collects both quantitative data and qualitative information, ensuring standardization and consistency, which enables efficient data processing and analysis.

The survey is conducted to gather input to support the verification of case studies and, more importantly, to identify and evaluate potential policy measures aimed at reducing: (i) the risk of carbon leakage, and (ii) the loss of competitiveness in the maritime transport sector.

Since the evaluation of potential policy measures contributes to the development of mitigation strategies, it directly addresses Sub-question 4. The visualization of the survey questionnaire is provided in Figure 2.3.



This **survey** is designed to collect valuable insights from **maritime stakeholders** to support the assessment of carbon leakage risks and potential loss of competitiveness due to climate policies.

The survey will take approximately 15-20 minutes to complete

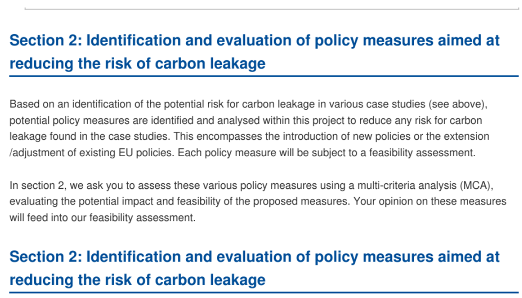
At the end of the survey, you will have the opportunity to upload any documents containing evidence you think could be useful for the analysis of policy options.

Your participation is essential in shaping a well-informed and balanced analysis.

Your **privacy** is important to us. This survey is conducted in compliance with the **General Data Protection Regulation** (GDPR). All responses will be processed securely and used solely for research purposes related to the assessment of carbon leakage and competitiveness in the aviation and maritime sectors. Your data will not be shared with third parties beyond the research team. Participation is voluntary, and you may withdraw at any time without consequences. By proceeding, you confirm that you have read and agree to the terms of this survey.

☐ I accept your Terms

(a) Introduction of the Survey Questionnaire



Section 2: Identification and evaluation of policy measures aimed at reducing the risk of carbon leakage

Based on an identification of the potential risk for carbon leakage in various case studies (see above), potential policy measures are identified and analysed within this project to reduce any risk for carbon leakage found in the case studies. This encompasses the introduction of new policies or the extension /adjustment of existing EU policies. Each policy measure will be subject to a feasibility assessment.

In section 2, we ask you to assess these various policy measures using a multi-criteria analysis (MCA), evaluating the potential impact and feasibility of the proposed measures. Your opinion on these measures will feed into our feasibility assessment.

Section 2: Identification and evaluation of policy measures aimed at reducing the risk of carbon leakage

(b) A Portion of the Questions from the Survey Questionnaire

Figure 2.3: Visualization of a segment of the Survey Questionnaire conducted by Panteia

2.5 Summary

Datasets and Methods

- The research addresses carbon leakage and competitiveness impacts of the FuelEU Maritime Regulation through four sub-questions using a combination of literature review, computational modeling, scenario analysis, and stakeholder engagement.
- A comprehensive literature review was conducted using sources from Elsevier and Google Scholar. Snowballing from key studies (e.g., Lagouvardou and Psaraftis (2022), Defour and Afonso (2020)) helped identify regulatory, economic, and operational drivers of carbon leakage and cost implications.
- A scenario analysis was designed to explore uncertainties in fuel prices, carbon prices, GHG intensity limits, OPS requirements, and ship operating speeds. Case-specific routing strategies (e.g., transshipment relocation, evasive port calls) were modeled to assess cost and emission outcomes.
- The Panteia Liner Shipping Model was adapted to simulate compliance behavior under FuelEU and EU ETS. Enhancements included carbon pricing, FuelEU penalties, Renewable Fuels of Non-Biological Origin (RFNBO) incentives, and alternative fuel integration. RFNBO itself is synthetic drop-in fuels mostly derived from electricity that can cover part of the EU's demand renewable fuels in the coming years (Buffi et al., 2022).
- Model outputs include: total route cost, fuel consumption, OPEX per vessel, TEU costs, and GHG emissions (TtW & WtT), enabling a quantitative assessment of leakage risk and mitigation impacts.
- Stakeholder engagement was performed by Panteia through targeted interviews and surveys targeting EU maritime stakeholders to identify perceived risks, policy gaps, and feasible mitigation options.

3 Literature Review

This chapter reviews existing literature to address two sub-questions: (1) What are the currently identified carbon leakage approaches in maritime transport? and (2) How can the cost impact of the FuelEU Maritime Regulation be assessed?

For Sub-Question 1, the review defines carbon leakage in maritime transport, explores its mechanisms, and examines assessment methodologies, including econometric models, cost-benefit analyses, and scenario-based modeling. It also draws insights from other regulatory impacts on carbon leakage, such as the EU ETS in maritime transport and the ongoing development of the IMO's Net-Zero Framework.

For Sub-Question 2, the review outlines the FuelEU Maritime Regulation, detailing compliance costs such as GHG intensity targets, on-shore power supply (OPS), and EU ETS carbon pricing. It further explores how these costs influence shipping routes, transshipment decisions, and EU port competitiveness.

3.1 Carbon Leakage in Maritime Sector

As the maritime sector faces increasing regulatory pressures under the EU's FuelEU Maritime Regulation, concerns over carbon leakage have intensified, primarily driven by cost-related incentives for shipowners to alter their operational patterns. Carbon leakage occurs when, due to climate policy-related costs, businesses relocate their operations to regions with less stringent emission constraints (European Commission, 2021a). Another definition highlights carbon leakage as the increase in CO_2 emissions in non-regulated regions compared to the reductions achieved by regions adopting ambitious climate policies, such as the EU (Felbermayr and Peterson, 2020).

In maritime transport, carbon leakage can manifest through evasive routing and transshipment strategies (Lagouvardou and Psaraftis, 2022). For example, a container ship traveling from Singapore to Europe may first call at a transshipment hub like Durban, South Africa, where the containers are unloaded and temporarily stored before being transferred to another vessel. This second vessel then carries the containers to their final destination, such as Rotterdam. Under EU ETS maritime regulations, only 50% of the emissions from the second leg (Durban to Rotterdam) are subject to carbon pricing, while emissions from the initial leg (Singapore to Durban) are excluded. When shipowners strategically employ such transshipment routes to bypass EU carbon pricing, the resulting emissions displacement is classified as carbon leakage (Peng et al., 2024). This dynamic poses a challenge to EU decarbonization efforts, as it undermines emission reduction targets and shifts emissions beyond the EU's regulatory scope.

A sector is considered at significant risk of carbon leakage when the combined effect of direct and indirect costs from regulatory compliance substantially increases production costs. Specifically, the European Commission defines this risk threshold as a production cost increase of at least 5% of the sector's gross value added, combined with a trade intensity with non-EU countries (imports and exports) exceeding 10% (European Commission, 2021a). In the maritime sector, these conditions are particularly relevant given its highly global nature, with extensive trade routes connecting Europe to non-EU regions. As compliance costs under the FuelEU Maritime Regulation and EU ETS increase, shipowners face heightened incentives to reroute or transship through less-regulated regions to maintain cost competitiveness.

Historical evidence further highlights the risks of carbon leakage under regulatory policies. A study by Grunewald and Martinez-Zarzoso (2016) on the Kyoto Protocol found that, although domestic emissions in committed countries were reduced by approximately 7%, their overall carbon footprints did not decrease. Instead, the share of emissions embedded in imports increased by about 14 percentage points, indicating a shift in production to less-regulated regions—a clear indication of carbon leakage (Felbermayr and Peterson, 2020). Similarly, Peng et al. (2024) concluded that under current environmental policies, shipping companies are highly likely to seek transshipment ports outside of EU ETS-designated areas, resulting in carbon leakage and reduced effectiveness of the EU's carbon pricing mechanism. Moreover, studies by Lagouvardou and Psaraftis (2022) found that the risk of evasion is particularly high when carbon permit prices are below €25/MT, creating cost-saving incentives for shipowners to avoid regulated EU ports. Another finding by Lagouvardou and Psaraftis (2022) is that the planned expansion of the Izmir terminals further encourages operators to shift their transshipment activities to this nearby non-EEA port. These findings emphasize the importance of targeted mitigation measures to address the vulnerabilities created by regulatory cost pressures in the maritime sector.

3.1.1. Cost Modeling Approaches for Carbon Leakage in Maritime Transport

A wide range of modeling approaches can be used to assess the economic implications of climate regulations in the maritime sector, including optimization models, econometric analyses, and scenario-based frameworks. Each of these methods offers distinct advantages, but also presents certain limitations when applied to newly introduced policies such as the FuelEU Maritime Regulation. While optimization-based models are effective in identifying cost-minimizing strategies, they often overlook the strategic decision-making behavior of shipowners, such as evasive routing or transshipment shifts. Econometric models, on the other hand, rely heavily on historical data, which is currently unavailable for FuelEU Maritime due to its recent implementation. Given these constraints, cost modeling emerges as a particularly suitable approach for assessing the regulation's impact. It enables scenario-based simulations that reflect real-world trade-offs and allows for the analysis of diverse compliance strategies under varying regulatory and market conditions.

Several studies have attempted to model the potential cost impacts of the EU ETS and FuelEU Maritime, using a variety of methodologies and assumptions:

- Lagouvardou and Psaraftis (2022) applied a cost-benefit analysis (CBA) to assess whether liner shipping companies would reconfigure their networks to evade the EU ETS extension to maritime transport. The study assumed that operators would replace EU ports with nearby non-EEA hubs with similar performance. The results indicated that when carbon prices fall below €25 per metric ton of CO_2, shifting to non-EEA hubs could become financially attractive, suggesting a potential incentive for evasive behavior under specific cost conditions.
- Vierth et al. (2024) estimated the cost impact of the EU ETS and the revision of the Energy Taxation Directive (ETD) on cargo ships calling at Swedish ports using a low-to-high scenario analysis, concluding that evasive behavior would likely remain minimal. Similarly, Faber, Leestemaker, et al. (2022) investigated potential evasive routing strategies through five case studies—including scenarios such as adding London Gateway as an intermediate port call between Algeciras and Rotterdam, and replacing Algeciras with Tangier. The study found limited evidence of large-scale evasive behavior, meaning that while rerouting could be beneficial for certain services, it is not universally advantageous. However, it is important to note that this study predates recent revisions to the EU ETS transshipment port clause, which may affect the current validity of its findings.
- The only known study that models the impact of FuelEU Maritime in conjunction with the EU ETS is by Springer (2023), which examines industry behavior toward fuel pricing and the slow transition toward alternative fuels. However, this study does not specifically assess evasive behavior or how FuelEU Maritime may contribute to carbon leakage.
- Other studies have used scenario-based modeling and optimization cost models to explore com-

pliance strategies under emissions trading schemes. For example, T. Wang et al. (2025) investigated emission reduction strategies under a Marine Emission Trading System (METS) using a model that incorporates fuel switching, fuel price sensitivity, and shore power utilization. However, this study does not account for FuelEU Maritime's energy intensity penalties, which significantly impact cost compliance.

- Trosvik and Brynolf (2024) developed a scenario modeling tool to assess the transition toward fossil-free fuels in the Swedish maritime sector, considering policy instruments such as the EU ETS and FuelEU Maritime regulation. However, the model does not factor in fuel consumption at berth, despite its significance in greenhouse gas (GHG) emissions at Swedish ports (Trosvik, 2023).

These studies highlight several limitations in existing cost models, particularly their inability to fully integrate FuelEU Maritime's energy intensity limits, evasive routing impacts, and emissions at berth. While optimization-based models minimize costs, they do not account for strategic decision-making by shipowners. Similarly, econometric models require historical data, which is currently unavailable for FuelEU Maritime.

3.2 Carbon Leakage Approach

Based on the analysis in section 3.1, two primary mechanisms driving carbon leakage in maritime transport are evasive routing and transshipment shifts to non-EEA hubs. These strategies allow shipowners to minimize regulatory costs associated with emissions trading and environmental compliance.

Another potential avenue for carbon leakage is modal shifts, where cargo is diverted to alternative transport modes, such as road or rail. However, this effect is relatively minor, as maritime transport remains highly cost-competitive, and the modal split in freight transport is generally inelastic (Vierth et al., 2024). Furthermore, with carbon pricing extending to road transport in 2027, the financial viability of shifting freight from ships to trucks is expected to decline, further limiting this pathway for carbon leakage (Kotzampasakis, 2025).

Carbon leakage can also occur through changes in ship sailing speeds. Park et al. (2024) found that while the EU ETS incentivizes speed reductions on regulated routes, shipping companies may compensate by increasing speeds on non-regulated routes to recover lost time. This phenomenon is not new, as Tavasszy et al. (2011) presented a scenario in which global shipping companies implemented significant reductions in operational speed (from 22-24 knots to 14-15 knots).

3.3 Impact of Evasive Routing and Transshipment Strategy

The study by Lagouvardou and Psaraftis (2022) emphasizes that relocating transshipment activities to non-EEA hubs results in revenue losses for the EU ETS and economic penalties for EEA transshipment hubs that directly compete with nearby non-EEA ports. Additionally, the imposition of the FuelEU Maritime Regulation, with its OPS requirements during berth, introduces further costs that could exacerbate the shift toward non-EEA transshipment hubs. This shift poses a significant threat to the economic activity and long-term development of EU ports, potentially undermining their strategic importance in regional and global maritime trade.

Another study by Faber, Leestemaker, et al. (2022) supports this finding by demonstrating that evasion of the EU ETS can be profitable under specific conditions. Their case studies show that shipowners can benefit from evasive routing by changing the order of port calls or adding an additional stop. The likelihood of avoidance having a net financial benefit increases under the following conditions:

- Higher prices for emission allowances create a stronger incentive to avoid EU ETS-related costs.
- Lower costs of evasion, such as port fees, operational expenses, charter costs, container handling charges, and opportunity costs, make avoidance strategies more feasible.
- Higher emissions on the last voyage to an EU port or the first voyage from an EU port result in higher savings when emissions-related costs are avoided.
- Lower transshipment costs at non-EU hubs make it financially attractive to reroute cargo through alternative ports.

These findings highlight how cost-driven decision-making plays a central role in determining the extent of evasive routing and transshipment shifts. Without effective policy interventions, shipowners are likely to continue exploiting these strategies, resulting in increased carbon leakage and diminished effectiveness of EU decarbonization measures.

3.3.1. Evasive Routing

Evasive routing is a potential consequence of increased regulatory costs and penalties under FuelEU Maritime and the EU ETS. As transport costs rise, shippers may reconsider their initial route choices and opt for lower-cost alternatives, similar to modal shifts observed in land-based transport (Halim et al., 2019). This could lead to a preference for transshipment hubs outside the EU, contributing to carbon leakage as emissions shift to non-EU jurisdictions. An example of evasive routing involves ships making a stopover at a nearby non-EEA port to reduce the portion of the voyage subject to EU regulatory coverage, thereby limiting compliance costs. For instance, a ship traveling from the USA to Spain could make a stopover—referred to as an evasive port call—in Morocco. Under this strategy, the ship would avoid paying CO_2 costs for the voyage from the USA to Morocco and would only incur costs for the leg from Morocco to Spain. As shown in Figure 3.1, this routing technique enables shipowners to bypass large portions of the regulated voyage. However, the ship must drop off at least one container or one passenger during its evasive port call to qualify as a valid stop (Defour and Afonso, 2020).

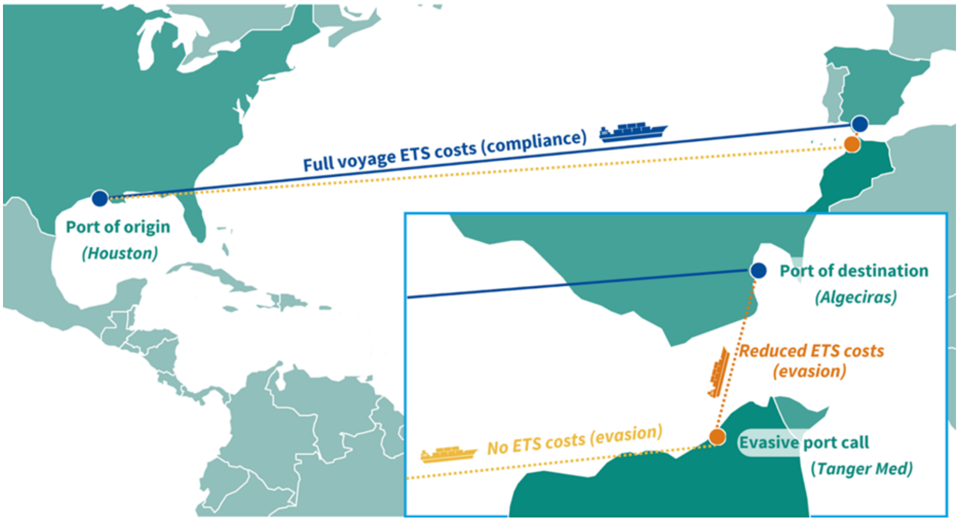


Figure 3.1: Illustration of Evasive Routing (Defour and Afonso, 2020)

To reduce the risk of port evasion, the EU ETS includes a provision that excludes certain transshipment ports in neighboring non-EU countries from being classified as "ports of call." As a result, stopping at these exempted ports does not break the voyage into separate segments, ensuring that EU ETS still applies to the entire journey between the non-EEA and EEA ports.

According to Article 3ga(2) of Directive 2003/87/EC, the designated neighboring container transshipment ports are East Port Said (Egypt) and Tanger Med (Morocco). Both ports are located within 300 nautical miles of an EU Member State's jurisdiction and have a transshipment share exceeding 65% of their total container traffic over the most recent twelve-month period for which relevant data is available. Based on these criteria, they are officially classified as neighboring transshipment ports under the EU ETS.

However, sources expect that the transshipment clause alone will not be sufficient to mitigate the increased risk of carbon leakage that may arise from major disruptions in shipping routes (Peng et al., 2024).

3.3.2. Transshipment Strategy

Transshipment involves transferring cargo between vessels at an intermediary port before reaching its final destination (Peng et al., 2024). Unlike standard port calls, this process requires unloading and reloading cargo onto a different vessel (European Commission, 2023b), known as a transshipment move (Lagouvardou and Psaraftis, 2022). On average, a container ship handles 3,000 transshipment moves per port call (IHS Markit, 2021).

To comply with FuelEU Maritime and EU ETS, shipowners face costs related to emissions compliance, including carbon pricing, OPS requirements, and fuel-related penalties. To reduce these costs, some operators transship at non-EU ports and use feeder vessels (<5000 GT) to complete the journey to EU ports, avoiding ETS costs. However, this strategy incurs transshipment tariffs and additional feeder service expenses, making the decision a trade-off between regulatory compliance and operational costs.

One transshipment strategy is swapping an EEA transshipment hub with a non-EEA hub located near an EU port, as analyzed by Lagouvardou and Psaraftis (2022). Their case study examines the replacement of Piraeus (Greece, EEA) with Izmir (Turkey, non-EEA) (see Figure 3.2). The results show that while this strategy reduces total emissions subject to the EU ETS and lowers the cost of surrendered EU Allowances (EUAs), it also increases overall service emissions, highlighting a significant risk of carbon leakage.

Figure 3.2: Illustration of the Pireaus to Izmir transshipment relocation scenario (Lagouvardou and Psaraftis, 2022)

3.4 FuelEU Maritime Regulation Context

As part of the EU's commitment to reducing emissions and promoting sustainability, the EU introduced the Fit for 55 Package, a comprehensive strategy aimed at achieving a 55% reduction in net greenhouse gas (GHG) emissions by 2030 (European Council, 2025). Within this package, several policies target different sectors, including the Emissions Trading System (ETS), Renewable Energy Directive (RED III), and Alternative Fuels Infrastructure Regulation (AFIR). However, due to the distinct operational and fuel-related challenges in the maritime sector, the EU introduced the FuelEU Maritime Regulation, designed specifically to reduce the GHG intensity of energy used onboard ships by up to 80% by 2050 (European Commission, 2023a). This regulation is the first of its kind aimed at directly increasing the demand for sustainable marine fuels (Springer, 2023), requiring shipping companies to progressively transition toward lower-carbon alternatives.

To better understand where FuelEU Maritime fits within emissions mitigation strategies, Psaraftis and Lagouvardou (2019) categorize emission reduction measures into three major classes:

1. **Technical Measures** – These focus on improving ship design and propulsion systems to enhance energy efficiency. Innovations such as optimized hull structures, alternative fuels, and more efficient engine technologies fall under this category.
2. **Operational Measures** – These involve optimizing ship operations to minimize emissions, such as adjusting sailing speeds (slow steaming), selecting more efficient routes, and implementing energy-saving strategies.

3. **Market-Based Measures (MBMs)** – These policies introduce financial incentives and penalties to regulate emissions. MBMs assign a cost to GHG emissions, creating economic incentives for shipowners to invest in low-carbon technologies and optimize fuel use.

Among these approaches, FuelEU Maritime aligns most closely with MBMs as it introduces a compliance framework with penalties for exceeding GHG intensity limits, incentives for alternative fuel adoption, and emission thresholds that impact operational costs. Similar to other MBMs, FuelEU Maritime internalizes the environmental costs of emissions, encouraging shipowners to adopt cleaner energy sources and operational adjustments to remain competitive in the industry.

3.4.1. Interaction of FuelEU Maritime with Other Policies (EU ETS, MRV)

The FuelEU Maritime Regulation operates in conjunction with the EU ETS and the EU Monitoring, Reporting, and Verification (MRV) system, creating a comprehensive framework aimed at reducing emissions from maritime transport. The EU MRV Regulation 2015/757 requires ships above 5,000 GT to monitor and report their annual fuel consumption, CO_2 emissions, and other parameters, providing essential data that supports both the FuelEU Maritime Regulation and the EU ETS (Nelissen et al., 2021). The 2020 MRV data serves as the baseline for setting GHG intensity targets under the FuelEU Maritime Regulation, making it an integral part of the overall policy landscape (Christodoulou and Cullinane, 2022).

The FuelEU Maritime Regulation, set to take effect in 2025, focuses on reducing the GHG intensity of marine fuels through a progressive, technology-neutral approach. It incentivizes shipowners to transition to low- and zero-carbon fuels while allowing flexibility in compliance strategies (European Council, 2025). Complementing this, the EU ETS extension to maritime transport, which began in 2024, introduces carbon pricing by requiring shipowners to purchase allowances for their CO_2 emissions. While the EU ETS directly penalizes emissions by requiring shipowners to purchase allowances for their CO_2 emissions, the FuelEU Maritime Regulation imposes penalties on ships that exceed the GHG intensity limits set for each compliance year. Beyond these financial penalties, FuelEU Maritime also drives structural change by incentivizing the adoption of cleaner fuels and offering flexibility in compliance strategies.

Although these policies are designed to work together, a key challenge lies in their recent implementation, leaving limited empirical data on their actual impacts. As the FuelEU Maritime Regulation and the EU ETS are still in their early phases, shipowners and policymakers face uncertainties related to compliance costs, fuel availability, and operational adjustments. While some case studies provide preliminary insights (Lagouvardou and Psaraftis, 2022; Springer, 2023; Defour and Afonso, 2020), there remains a significant research gap in understanding the long-term effectiveness of these overlapping regulations in reducing emissions without triggering unintended consequences, such as carbon leakage.

3.4.2. Impact on Transport Costs

The introduction of FuelEU Maritime and other GHG mitigation measures, such as carbon pricing, has direct implications for maritime transport costs. As highlighted by Rojon et al. (2021), these policies primarily influence two cost components:

1. **Voyage Costs/OPEX** – Increased short-term fuel expenditures due to compliance with GHG intensity limits and the transition to alternative fuels. As fuel prices remain a major determinant of voyage costs, compliance with FuelEU Maritime could lead to higher bunker costs.
2. **Capital Costs/CAPEX** – Long-term investments in ship retrofitting and technical modifications required to meet fuel efficiency standards and adopt new propulsion technologies.

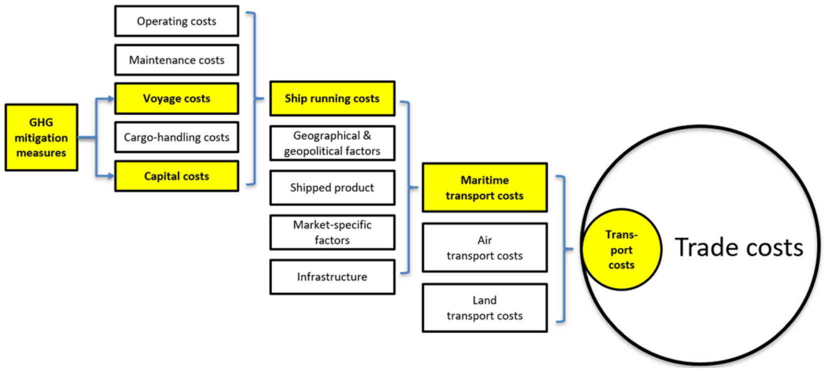


Figure 3.3: Maritime transport cost breakdown (Halim et al., 2019)

The breakdown of maritime transport costs in Figure 3.3 illustrates the impact of GHG mitigation measures such as FuelEU Maritime on overall cost structures. Rising compliance costs can affect routing decisions, influencing port calls, transshipment choices, and operational strategies as ship operators seek to minimize expenses. This financial burden may also increase the risk of carbon leakage, as companies explore alternative routes or strategies to evade regulatory costs. As a result, the competitive ability of a port to attract international cargo, whether as a gateway or a transshipment hub, can be influenced by changes in transport costs along the routes that use it (Halim et al., 2019). Ports subject to higher compliance costs may become less attractive to shippers, while those in non-regulated regions could gain a competitive advantage as cargo is rerouted to minimize costs.

3.5 FuelEU Maritime Mechanism

The FuelEU Maritime mechanism is established under Regulation (EU) 2023/1805, adopted by the European Parliament and the Council on 13 September 2023. To facilitate its implementation, the European Commission has published a Frequently Asked Questions (FAQ) document, summarized by ClassNK (2023), to clarify its requirements and compliance measures.

Set to take effect in 2025, the FuelEU Maritime Regulation aims to reduce emissions from maritime transport by regulating the carbon intensity of fuels used on ships operating within EU and EEA Member States. The regulation introduces a lifecycle-based approach that accounts for emissions from fuel production to consumption (Well-to-Wake), ensuring a gradual transition toward cleaner energy sources.

The mechanism consists of three key provisions:

1. **GHG Intensity Limits** – Ships must adhere to gradually tightening greenhouse gas (GHG) intensity limits for energy used on board. This ensures a progressive reduction in the carbon footprint of maritime fuels over time.
2. **Onshore Power Supply (OPS) Requirement** – Containerships and passenger ships are required to use shore-side electricity (OPS) or zero-emission technologies while docked at EU ports, reducing emissions from auxiliary engine use.
3. **Renewable Fuels Obligation** – The regulation promotes the use of Renewable Fuels of Non-Biological Origin (RFNBO) by establishing incentives and penalties, encouraging ship operators to transition toward alternative low-emission fuels.

By enforcing emission limits, mandating cleaner port operations, and incentivizing the use of renewable fuels, the FuelEU Maritime Regulation aims to drive fuel decarbonization and support the transition toward a more sustainable shipping sector. The regulation also provides a detailed methodology for calculating both Well-to-Tank (WtT) and Tank-to-Wake (TtW) emissions. Accordingly, these calculations are incorporated into the model to ensure alignment with the policy framework.

3.5.1. GHG Intensity Limit Overview

FuelEU Maritime imposes annual limits on the greenhouse gas (GHG) intensity of energy used by ships over 5,000 GT calling at European ports, regardless of their flag. The regulation mandates a gradual reduction in fuel-related emissions, starting with a 2% cut in 2025 and aiming for an 80% decrease by 2050. These limits apply to CO_2, methane, and nitrous oxide emissions, assessed on a full lifecycle Well-to-Wake (WtW) basis.

The GHG intensity threshold will be gradually reduced every five years based on a reference value derived from the average energy used onboard ships in 2020. This reference value, calculated at 91.16 gCO_{2eq}/MJ, is sourced from the EU MRV data of that year. Table 3.1 provides the reduction rates and corresponding GHG intensity limit values for each year.

Year	Reduction rate (%)	GHG Limit (gCO_{2eq}/MJ)
2020 (reference value)	0	91.16
2025∼2029	2	89.34
2030∼2034	6	85.69
2035∼2039	14.5	77.94
2040∼2044	31	62.90
2045∼2049	62	34.64
2050∼	80	18.23

Table 3.1: GHG intensity reduction targets for FuelEU Maritime (European Commission, 2023a)

The GHG intensity is determined by converting emissions of CO_2, CH_4, and N_2O into their CO_2-equivalent values. It is expressed in terms of "CO_2-equivalent emissions per unit of energy" with the unit [gCO_{2eq}/MJ]. If the greenhouse gas (GHG) intensity of the fuel used on board a vessel surpasses the designated limit for a given year under the GHG intensity provision, the shipowner is required to pay a penalty. Based on Regulation (EU) 2023/1805, the GHG intensity of the energy used on board by a ship is calculated using Equation 4.8, Equation 4.7, and Equation 4.11.

The FuelEU Maritime regulation defines the energy consumption within its geographical scope for the purpose of GHG intensity calculations is provided in Table 3.2, and the illustration is provided in Figure 3.4.

Voyage Type	Energy Used
Voyages between EU/EEA and non-EU/EEA ports (Route 1)	50%
Voyages within EU/EEA ports (Route 2)	100%
Berthing in EU/EEA ports	100%

Table 3.2: Energy usage under FuelEU Maritime (European Commission, 2023a)

a

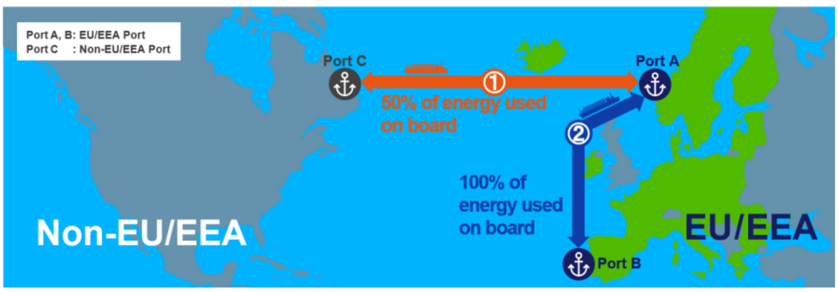


Figure 3.4: Illustration of energy usage under the geographical scope of FuelEU Maritime (ClassNK, 2023)

If the greenhouse gas (GHG) intensity of the fuel used onboard a ship exceeds the designated limit for a given year, a penalty will be imposed under the GHG intensity provision. The penalty amount is determined based on factors such as the type of fuel used and the total fuel consumption. The penalty is calculated using formula in Equation 4.13.

3.5.2. Onshore Power Supply (OPS) Requirement Overview

Beginning January 1, 2030, containerships and passenger vessels must utilize on-shore power supply (OPS) for their electricity consumption while docked at specified EU/EEA ports.

These ports are categorized as Trans-European Transport Network (TEN-T) maritime ports under the EU Alternative Fuels Infrastructure Regulation (AFIR) (Regulation (EU) 2023/1804) and are listed in Annex II of the Trans-European Transport Network, replacing the previous classification outlined in Regulation (EU) 1315/2013.

Furthermore, from January 1, 2035, ships moored at quaysides outside these designated TEN-T ports will also be required to connect to OPS if the infrastructure is available. Additionally, between 2030 and 2034, EU/EEA Member States may extend this requirement to other ports under their jurisdiction, provided they notify the European Commission at least one year in advance.

The requirement to use on-shore power supply (OPS) does not apply to ships under the following conditions:

- When moored at the quay for less than two hours.
- If they rely entirely on zero-emission technologies, such as fuel cells, batteries, wind, or solar power, to meet their electrical needs while docked.
- In cases of unscheduled port calls due to safety concerns or life-saving emergencies at sea.
- If OPS is unavailable at the port.
- When connecting to OPS poses an exceptional risk to the stability of the electrical grid.
- If the port's shore installation is incompatible with the ship's onboard OPS equipment.
- During emergency situations requiring temporary onboard energy generation due to immediate threats to life, the vessel, or the environment, or due to force majeure.
- When performing essential maintenance or functional tests while connected to OPS, provided these tests are requested by a competent authority or an authorized organization conducting inspections or surveys.

Since the 2030 OPS requirement mandates that all TEN-T ports provide on-shore power supply (OPS) infrastructure, it is reasonable to assume compliance across all EEA ports in the model analysis. While the regulation specifically applies to designated TEN-T maritime ports, the provision allowing EU/EEA Member States to extend OPS requirements to additional ports between 2030 and 2034 suggests a broader trend toward widespread implementation. Moreover, given the long-term policy direction emphasizing port electrification and emissions reduction, it is likely that most major ports within the EEA will align with the regulatory framework to ensure consistency in operations and compliance. Therefore, for modeling purposes, assuming full compliance across EEA ports provides a simplified yet realistic approach to evaluating the impact of OPS integration in the maritime sector. However, in practice, smaller ports may lag in OPS deployment and may require financial or policy support to meet investment needs.

The Well-to-Tank (WtT) emission factor for OPS is directly influenced by the carbon intensity of a country's electricity grid. Countries such as France and Sweden have notably low CO_2-equivalent emissions from electricity production, while others like Poland and Australia exhibit significantly higher emission intensities. These variations can affect a shipowner's decision on whether to utilize OPS at specific ports, depending on the local grid's cleanliness. Figure 3.5 provides a detailed comparison of WtT emission factors for electricity generation across selected countries.

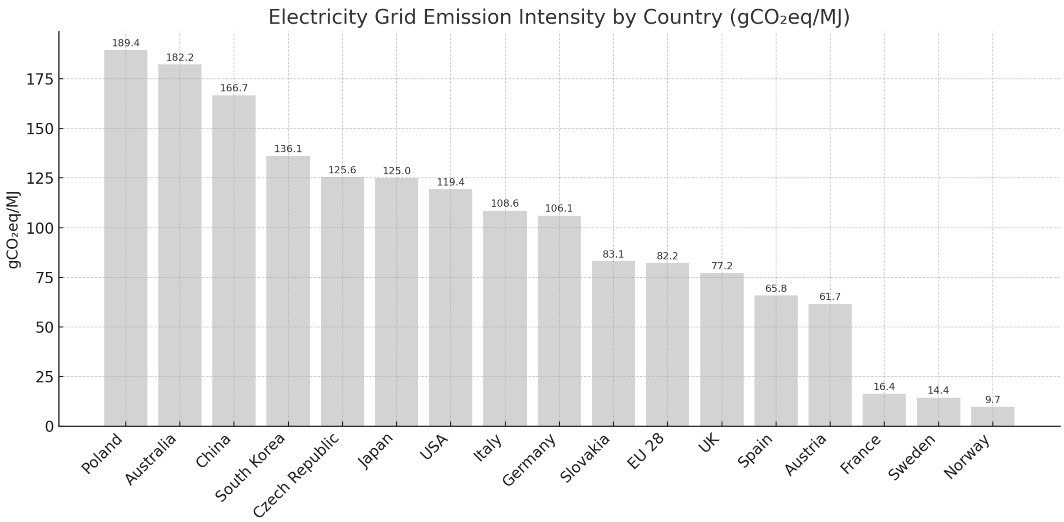


Figure 3.5: CO_2-equivalent emission intensity of electricity production in selected countries, adapted from Hirz and Nguyen (2022)

3.5.3. RFNBO Overview

Starting January 1, 2034, ships will be required to use Renewable Fuels of Non-Biological Origin (RFNBO) for at least 2% of their total annual energy consumption. However, this mandate applies only if RFNBO usage across the fleet covered by FuelEU Maritime remains below 1% in 2031. The primary method for producing RFNBOs involves using electrolysis powered by renewable electricity to generate hydrogen. This hydrogen can then be combined with nitrogen to form ammonia, or with carbon to create various synthetic hydrocarbon fuels (Transport & Environment, 2023a).

This 2% subtarget will not apply if monitoring data before January 1, 2033, confirms that RFNBO usage has already exceeded 2%. Additionally, Solakivi, Paimander, et al. (2022) project that RFNBO fuels will not become cost-competitive until after 2050. Given this outlook, it is expected that from 2034 onward, most ships will strive to meet only the minimum required RFNBO threshold rather than exceeding it voluntarily. Consequently, the enforcement of this provision is assumed to be unnecessary. Therefore, in the analysis, the penalty for non-compliance with the RFNBO subtarget is assumed to be zero.

Furthermore, from January 1, 2025, to December 31, 2033, a compensation factor of 2 applies only if the ship uses RFNBO when calculating the GHG intensity of the energy used onboard. This factor, represented by the notation *RWD*, is incorporated into the equations presented in Equation 4.7 and Equation 4.8. RFNBOs, as defined under Regulation (EU) 2023/1805, include renewable e-diesel, e-methanol, e-LNG, e-hydrogen (e-H_2), e-ammonia (e-NH_3), e-LPG, and e-DME (CH_3OCH_3). By incorporating this compensation mechanism, the regulation aims to accelerate the market uptake of RFNBOs and support the broader decarbonization goals of the maritime sector.

According to European Commission (2023a), for voyages between EEA and non-EEA ports, renewable fuels of non-biological origin (RFNBOs) may contribute to the GHG intensity calculation for up to 50% of the energy used during the voyage. This constraint is explicitly accounted for in the calculation methodology.

3.6 Policy Development: IMO Net-zero Framework

The Marine Environment Protection Committee, during its 83rd session (MEPC 83) from 7–11 April 2025, approved the IMO Net-Zero Framework—the first global initiative to combine mandatory emissions limits and GHG pricing across an entire industry sector (International Maritime Organization, 2025).

These measures, scheduled for formal adoption in October 2025 and entry into force in 2027, will be mandatory for large ocean-going vessels over 5,000 gross tonnage, which account for approximately 85% of CO_2 emissions from international shipping (International Maritime Organization, 2025).

Under the draft regulations, ships will be required to comply with:

- Global Fuel Standard: Ships must progressively reduce their annual greenhouse gas fuel intensity (GFI)—defined as GHG emissions per unit of energy used—calculated on a well-to-wake basis.
- Global Economic Measure: Ships exceeding GFI thresholds must acquire remedial units to offset their emission deficits. Conversely, ships using zero or near-zero (ZNZ) GHG technologies will be eligible for financial rewards through the IMO Net-Zero Fund.

While the IMO Net-Zero Framework shares many similarities with the FuelEU Maritime Regulation—such as the use of GHG intensity thresholds and a surplus/deficit mechanism—it differs in several key aspects. For instance, FuelEU Maritime does not offer direct financial rewards for the use of RFNBOs (Renewable Fuels of Non-Biological Origin), whereas the IMO framework incentivizes ZNZ technologies through a reward scheme. Additionally, the IMO framework does not mandate Onshore Power Supply (OPS), although OPS may qualify as a ZNZ technology under the regulation. The summary comparison of IMO Net-Zero Framework and FuelEU maritime is provided in Table 3.3.

Category	**FuelEU Maritime**	**IMO Net-Zero Framework**
Scope	>5000 GT	>5000 GT
Fossil fuel baseline	91.16 gCO_2/MJ	93.3 gCO_2/MJ
GHG reduction targets (gCO_2/MJ)	• 2028: 89.34 • 2030: **85.69** • 2035: **77.94** • 2040: **62.90** • 2045: **34.64** • 2050: **18.23**	• 2028: 89.57 • 2030: **85.84** • 2035: **65.31** • 2040: **32.66** • 2045: **tbd** • 2050: **tbd**
Flexibility mechanism	Positive Compliance balance can be: • Banked • Sold • Pooled with vessels • Cancelled	Surplus unit can be: • Banked for 2 years • Traded with non-compliant ships • Pooled with vessels • Cancelled
Fuels (Biofuels + RFNBO)	• Crop-based biofuels are not classified as RFNBO	• No restrictions on crop-based biofuels • For the biofuels, the threshold are ≤19 gCO_2/MJ until 2034, & ≤14 gCO_2/MJ from 2035
Special incentives	• Multiplier of 2 for RFNBOs till 2033 • 2% RFNBO sub-target by 2034 • Mandatory OPS connection (2030)	• ZNZ fuels rewarded via Net Zero Fund • No specific OPS mandates
Penalties	Calculation-based	\$380/tonne CO_2e until 2030

Table 3.3: Comparison between FuelEU Maritime and IMO Net-Zero Framework, adapted from (Dijkstra, 2025)
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From Table 3.3, it is evident that both the FuelEU Maritime and the IMO Net-Zero Framework share the same overarching objective: reducing GHG emissions and promoting the adoption of renewable fuels and clean technologies in the shipping sector. However, their scopes differ significantly. FuelEU Maritime applies specifically to voyages involving EU and EEA ports, while the IMO framework has a global scope. This overlap in regulatory frameworks may create uncertainty for shipowners and stakeholders. A key concern is whether FuelEU Maritime will eventually be replaced by the IMO framework, or whether ships calling at EEA ports will be required to comply with both regulations, potentially resulting in overlapping obligations and double penalties. The detailed implementation of the IMO Net-Zero Framework is scheduled for approval in spring 2026 during MEPC 84, so these concerns are expected to be clarified by then.

3.7 Summary

Literature Review

This chapter provides answers to **sub-question 1**, ”What are the key mechanisms contributing to carbon leakage in maritime transport under the FuelEU Maritime and EU ETS regulations?”:

- **Evasive Routing**: Ships may reroute to include nearby non-EEA ports (e.g., Morocco, Egypt, Turkey) to reduce the portion of the voyage subject to EU ETS or FuelEU compliance, thereby lowering regulatory costs.
- **Transshipment Shifts**: Cargo is transferred at non-EEA hubs instead of EU ports, often using smaller feeder vessels to complete the journey. This reduces the share of emissions regulated under EU policies.
- **Port Call Optimization**: By rearranging or adding specific port calls (e.g., using a short stopover at a non-EEA port), ships can bypass full compliance while still accessing EU destinations.
- **Use of Neighboring Non-EU Transshipment Ports**: Ports like Tanger Med and East Port Said, though exempted from breaking voyage segments, still pose a leakage risk due to high transshipment volumes near the EU border.
- **Speed Adjustments**: Operators may reduce speed on EEA legs (to cut emissions and costs) but increase speed on non-EEA legs, offsetting the environmental gains of regulated segments.
- **Modal Shifts (Limited)**: Although relatively minor, some cargo might shift from maritime to road/rail to avoid maritime compliance costs. However, this is unlikely to be widespread due to maritime cost competitiveness and future carbon pricing in road transport.
- **Strategic Port Selection Based on OPS Grid Emission Factors**: Shipowners may choose ports in countries with cleaner electricity grids (e.g., Norway, Sweden) to minimize OPS-related emissions and comply with GHG intensity thresholds.
- **Policy Threshold Sensitivity**: The likelihood of leakage increases when EUA prices are low (e.g., below €25/ton CO_2), making avoidance financially attractive.

This chapter also addresses **sub-question 2**: “How can the cost impact of the FuelEU Maritime Regulation on shipowners be assessed?”.

- **Use of Cost Components:** FuelEU Maritime introduces both **OPEX impacts** (e.g., higher fuel costs from cleaner alternatives, OPS electricity costs) and **CAPEX impacts** (e.g., retrofitting for fuel-switching or OPS capability). These components are included in model-based cost breakdowns.
- **Emission-Linked Penalties:** FuelEU penalties are calculated based on the GHG intensity gap between the actual fuel mix and regulatory thresholds. The use of RFNBOs introduces further cost variability due to both their high price and multiplier effect in GHG accounting.
- **Port-Level OPS Factors:** Onshore power costs are influenced by country-level electricity emission intensities (WtT). Assessment includes grid-based WtT factors, which affect compliance costs differently depending on port selection.
- **Cost-Benefit Modeling from Literature:** Studies such as Lagouvardou and Psaraftis (2022) and T. Wang et al. (2025) provide cost modeling frameworks (e.g., CBA, scenario analysis) that quantify financial trade-offs under various compliance and evasion strategies.
- **Penalty Formulas and Policy Parameters:** The cost assessment leverages official FuelEU formulas (e.g., GHG intensity penalties and OPS thresholds), enabling calculation of precise cost burdens in response to different ship behaviors or route changes.
- **Interplay of Fuel Mix and Policy Design:** The methodology incorporates regulatory design—such as RFNBO targets, energy usage scope, and OPS exemptions—into the cost model, capturing how specific FuelEU Maritime features affect shipowner finances.

The findings from this chapter highlight the key mechanisms behind carbon leakage—such as evasive routing, transshipment shifts, and port selection—driven by the cost structure of FuelEU Maritime and EU ETS regulations. Assessing these behaviors requires a model that captures route-level cost trade-offs, emission penalties, and operational decisions.

To address these needs, Chapter 4 introduces the Panteia Liner Shipping Model. Its ability to simulate detailed shipping routes, fuel choices, and policy compliance makes it well-suited to evaluate the cost impacts of FuelEU Maritime and the potential for carbon leakage across alternative routing strategies.

4

Panteia Liner Shipping Model

4.1 Overview

The Panteia Liner Shipping Model is a Python-based computational model designed to simulate the cost structure and operational performance of liner shipping services. It calculates the total voyage costs by integrating parameters such as vessel speed, port fees, fuel consumption, and transit times. The model is structured to estimate:

- **Total voyage costs** based on fuel use, operational expenses, and port charges.
- **Fuel consumption** per route, ship, and operational cycle.
- **Operational costs**, including maintenance, insurance, and crew wages.
- **Transit times per voyage**, including sailing and port stay durations.
- **Cost per TEU transported**, enabling a comparison across different shipping services.

The model is used to analyze the economic feasibility of various shipping routes, evaluate different fleet configurations, and optimize voyage strategies. A detailed explanation of how the model works is provided in Appendix B.

As part of this study, the Panteia Liner Shipping Model has been modified to incorporate the effects of the EU ETS and FuelEU Maritime regulations. The enhanced model:

- **Calculate total route costs**, including FuelEU Maritime compliance penalties, EU ETS carbon pricing, and additional operational costs associated with regulatory compliance.
- **Integrate alternative fuel scenarios** (e.g., LNG, methanol, ammonia, biofuels) by incorporating Well-to-Wake (WTW) emissions factors and fuel price variations to evaluate their economic viability under different regulatory conditions.
- **Model feeder vessel operations**, allowing for the assessment of transshipment strategies in non-EU ports and evaluating the economic and regulatory implications of using feeder vessels below 5000 GT to avoid EU ETS and FuelEU Maritime penalties.
- **Assess the impact of carbon leakage** and evasive routing strategies by modeling fuel consumption, emissions, and cost differentials between compliant (direct EU port calls) and non-compliant (transshipment via non-EU hubs) routes.
- **Estimate total greenhouse gas (GHG) emissions**, incorporating Tank-to-Wake (TTW) and Well-to-Wake (WTW) emissions calculations to determine compliance with FuelEU Maritime's annual GHG intensity limits and potential penalties.
- **Compare fleet operational costs and emissions for different speed**, evaluating the impact of different ship's speed.

These modifications enable a more comprehensive and dynamic analysis of how environmental policies affect shipping costs, fleet decision-making, fuel choices, and the risk of regulatory avoidance. The enhanced model also supports the scenario analysis described in section 2.2, allowing for a detailed assessment of the economic trade-offs between regulatory compliance and evasive routing strategies in the maritime sector. A summary of the data requirements is provided in Appendix A.

Given these features, the Panteia Liner Shipping Model is particularly well-suited for this research. It enables detailed estimation of costs, fuel consumption, and emissions under various routing and compliance scenarios. Its flexibility to simulate different fuel types, vessel configurations, and regulatory mechanisms makes it a valuable tool for evaluating the economic implications of the FuelEU Maritime Regulation and the EU ETS. By integrating both cost and emissions parameters, the model helps to identify when and why shipowners might adopt evasive strategies, and what such decisions mean for carbon leakage and the competitiveness of EU ports.

Overall, the model directly supports the main objective of this thesis: to evaluate the cost-driven risks of carbon leakage and explore effective mitigation strategies.

4.2 FuelEU Maritime Components

To integrate the FuelEU Maritime Regulation into the Panteia Liner Shipping Model, modifications are introduced in a step-by-step approach. The flowchart is provided in Appendix F.

Step 1: Classification of Voyage Legs and Ports

The first step involves categorizing ports and voyage legs based on their location within or outside the European Economic Area (EEA). This classification is essential for determining the proportion of the voyage subject to FuelEU Maritime regulations and follows the categorization framework previously discussed in subsection 3.5.1. A port is classified as an **EEA port** if its International Maritime Organization (IMO) code belongs to an EEA country. The model checks port codes against a predefined list of EEA countries to automate this classification.

Step 2: Fuel Consumption Per Voyage Leg

After classifying voyage legs into EEA and Non-EEA segments, the model calculates fuel consumption for each leg separately. This modification ensures that FuelEU Maritime compliance costs are applied only to the relevant portions of the voyage.

The updated fuel consumption calculation is implemented in `LinerCost.py`. Instead of estimating total fuel use based on voyage duration, the model now determines fuel consumption per leg using the voyage distance, engine power output, and fuel efficiency. The fuel consumption per leg is calculated in metric tonnes (mt). The formula used is:

$$\begin{aligned}\text{Fuel Consumption per Leg} = &\ (\text{Power Output (kW)} \times \text{Fuel Burn Rate (g/kWh)}) \\ &\times \left(\frac{\text{Distance (km)}}{\text{Ship Speed (knots)} \times 1.852}\right) \times (\text{Load Factor})^{2/3} \div 10^6\end{aligned} \tag{4.1}$$

where:

- Power Output is the total installed engine power of the ship, the detailed calculation is provided in Equation B.1.
- Fuel Burn Rate is the grams of fuel consumed per horsepower per hour, derived from the fuel's lower calorific value as:
  $$\text{Fuel Burn Rate (g/kWh)} = \frac{3.6\text{(MJ)}}{\text{LCV(MJ/g)}} \tag{4.2}$$
  where 3.6 MJ his how much energy is in 1 kWh, and LCV is the Lower Calorific Value of the fuel in MJ/g.
- Ship Speed is the vessel's operating speed in knots.
- Distance represents the length of each voyage leg in kilometers, converted to nautical miles.

- Load Factor reflects the vessel's degree of utilization and its impact on fuel consumption. Since displacement increases approximately with the load and fuel consumption is related to displacement to the power of $\frac{2}{3}$ (under constant speed), the load factor is raised to the power of $\frac{2}{3}$ to capture this non-linear relationship (Network for Transport Measures (NTM), 2024).

The calculated fuel consumption per leg is stored in the model and used for further cost and emissions calculations. This per-leg approach is necessary for integrating FuelEU Maritime compliance, as only voyage segments involving EEA ports are subject to regulatory penalties (see Table 3.2). With fuel consumption now assigned to each leg, the next step involves integrating FuelEU Maritime compliance costs.

Step 3: OPS Consumption and Fuel Use at Berth

A key aspect of FuelEU Maritime compliance is the requirement for ships to use Onshore Power Supply (OPS) when berthed at ports within the European Economic Area (EEA), as discussed in subsection 3.5.2. If a vessel berths in an EEA port, it is assumed to use electricity from the port rather than burning fuel, whereas in Non-EEA ports, ships continue consuming fuel at berth.

To incorporate this requirement into the model, an adjustment is made in `LinerCost.py`. The function calculates fuel consumption at berth for each port call, and determines whether OPS consumption applies based on the next port's EEA status. Since OPS is more efficient than using the ship's auxiliary engine (Springer, 2023), the OPS energy consumption is assumed to be 50% of the equivalent fuel-based energy. As a result, the calculated OPS energy replaces the fuel consumption during EEA berthing for GHG intensity calculations.

The model adopts a simplified GT-based approach to estimate fuel use at berth (Geilenkirchen et al., 2022), following the equation:

$$\text{Fuel Consumption at Berth (kg)} = \text{GT} \times \text{Time at Berth (hours)} \times \text{Berth Fuel Rate} \tag{4.3}$$

where:

- GT is the gross tonnage of the vessel.
- Time at Berth (hours) is defined per port call, typically 21 hours for container ships (Hulskotte and Denier van der Gon, 2010).
- Berth Fuel Rate(kg/GT·hour) is a constant, typically 0.005 kg/GT·hour for container ships (Hulskotte and Denier van der Gon, 2010).

The model determines OPS usage by checking if the next port in the schedule is in the EEA:

$$\sum_{\text{legs}} \text{OPS}_{\text{Energy, leg}} = \begin{cases} \text{Fuel Consumption at Berth} \times \text{Fuel LCV} \times 0.5, & \text{if next port is in the EEA} \\ 0, & \text{otherwise} \end{cases} \tag{4.4}$$

where:

- Fuel LCV converts fuel consumption from tonnes to MJ to match electricity consumption.
- OPS replaces fuel usage at berth only if the vessel is at an EEA port.
- Battery electric technology, such as OPS in this case, is 50% more efficient relative to internal combustion engine technology (Raucci et al., 2019).

This ensures that ships comply with FuelEU Maritime rules by switching to electricity when at berth in EEA ports, while Non-EEA berthing continues to rely on fuel.

To account for the economic impact of using OPS, the model also calculates the total annual OPS cost per ship. This includes both the energy cost of electricity consumed while at berth and a fixed connection fee charged per port call. The OPS cost is only applied at ports within the EEA where the OPS requirement is enforced and from 2030 onward.

The total OPS cost per ship per year is calculated using Equation 4.5.

$$\text{Annual OPS Cost} = \left(\sum_{\text{legs}} \text{OPS}_{\text{Energy, leg}} \times \frac{\text{Electricity Price}}{3.6 \text{ MJ/kWh}} + \text{Connection Fee} \times N_{\text{OPS Ports}} \right) \quad (4.5)$$

Where:

- OPS $\text{Energy}_{\text{leg}}$ is the energy in MJ that the vessel would consume at berth.
- Electricity Price (USD/kWh) is the average cost of shore power, e.g., $0.159/kWh.
- 3.6 is the conversion factor from kWh to MJ.
- Connection Fee is a fixed port service charge for using OPS infrastructure, e.g., $114 per call (Faber, Berg, et al., 2022).
- $N_{\text{OPS Ports}}$ is the number of EEA ports in the rotation where OPS is used.

This approach reflects both the variable energy cost of using OPS and the fixed infrastructure or service costs per connection. By multiplying the per-rotation cost by the number of annual rotations, the model estimates the total yearly OPS expenditure for a single vessel. This value can be scaled up by the number of ships operating the service to compute the total OPS cost at the fleet level.

Step 4: Compliance Factor for FuelEU Maritime

To determine the portion of a voyage subject to FuelEU Maritime regulations, a compliance factor is applied based on the voyage classification. The compliance factor is assigned as follows:

$$\text{Compliance Factor} = \begin{cases} 1.0, & \text{if the voyage is between two EEA ports (EEA} \rightarrow \text{EEA)} \\ 0.5, & \text{if the voyage is between an EEA and a non-EEA port (EEA} \leftrightarrow \text{Non-EEA)} \\ 0.0, & \text{if the voyage is between two non-EEA ports (Non-EEA} \rightarrow \text{Non-EEA)} \end{cases} \quad (4.6)$$

The compliance factor is essential for adjusting the WTT and TTW emissions calculation, ensuring that only the appropriate voyage segments are penalized under FuelEU Maritime regulations.

Step 5: Well-to-Tank (WTT) Energy Intensity Calculation

The WtT energy intensity has been updated to incorporate both fuel consumption and OPS (Onshore Power Supply) consumption, in line with the FuelEU Maritime Regulation's Well-to-Wake (WtW) accounting approach. As such, the inclusion of Well-to-Tank (WtT) emissions is necessary, as discussed in section 3.5. The revised formula follows the FuelEU Maritime framework:

$$WtT = \frac{\sum_i^{n \text{ fuel}} M_i \times CO_{2eq\,\text{WtT},i} \times LCV_i + \sum_k^c E_k \times CO_{2eq\,\text{electricity},k}}{\sum_i^{n \text{ fuel}} M_i \times LCV_i \times RWD_i + \sum_k^c E_k} \quad (4.7)$$

where:

- WtT is the Well-to-tank energy intensity **[gCO$_{2eq}$/MJ]]**.
- M_i is the total fuel mass **[gFuel]** for each voyage leg. To determine the portion of the fuel mass, the detailed calculation is provided in Appendix C.
- $CO_{2eq\,\text{WTT},i}$ is the Well-to-Tank emission factor for the fuel type **[gCO$_{2eq}$/MJ]**.
- LCV_i is the fuel's Lower Calorific Value **[MJ/gFuel]**.
- RWD_i is the Renewable Energy Directive weighting factor for renewable fuels (unitless). If the fuel is of non-biological origin, a reward factor of 2 may be applied from 1 January 2025 to 31 December 2033. Otherwise, $RWD_i = 1$.
- E_k is the electricity consumption (OPS) at berth **[MJ]**.
- $CO_{2eq\,\text{electricity},k}$ is the emission factor for electricity generation, which varies by country **[gCO$_{2eq}$/MJ]**. The specific values are illustrated in Figure 3.5.

This formula accounts for both the fuel used during voyages and the electricity used at berth, ensuring that all emissions sources are included in the FuelEU Maritime compliance framework.

Step 6: Tank-to-Wake (TtW) Energy Intensity Calculation

The next component of FuelEU Maritime compliance involves calculating Tank-to-Wake (TTW) energy intensity. TtW energy intensity is computed using the following FuelEU regulation framework, as outlined in section 3.5, which includes slip emissions and combines them with combustion emissions.

The total TtW energy intensity are calculated as:

$$TtW = \frac{\sum_i^{n \text{ fuel}} \sum_j^{m \text{ engine}} M_{i,j} \times \left[\left(1 - \frac{1}{100} C_{\text{slip},j}\right) \times \left(CO_{2eq,\text{ TtW},i,j}\right) + \left(\frac{1}{100} C_{\text{slip},j} \times CO_{2eq,\text{ TtW, slip},i,j}\right)\right]}{\sum_i^{n \text{ fuel}} M_i \times LCV_i \times RWD_i + \sum_k^c E_k} \quad (4.8)$$

Where:

- TtW: Tank-to-wake energy intensity **gCO_{2eq}/MJ**
- $M_{i,j}$: Mass of fuel used by engine j for fuel type i. To determine the portion of the fuel mass, the detailed calculation is provided in Appendix C.
- $C_{\text{slip},j}$: Slip rate of engine j in percentage.
- $CO_{2eq,\text{TTW},i,j}$: CO2eq emissions from complete combustion of fuel i in engine j.
- $CO_{2eq,\text{TTWslip},i,j}$: CO_2eq emissions from unburned (slipped) fuel.

The CO_2 equivalent emissions per gram of fuel are calculated using the following formulas:

$$CO_{2eq,\text{TTW},i,j} = (C_{fCO_2,j} \cdot GWP_{CO_2} + C_{fCH_4,j} \cdot GWP_{CH_4} + C_{fN_2O,j} \cdot GWP_{N_2O}) \quad (4.9)$$

$$CO_{2eq,\text{TTWslip},i,j} = (C_{sfCO_2,j} \cdot GWP_{CO_2} + C_{sfCH_4,j} \cdot GWP_{CH_4} + C_{sfN_2O,j} \cdot GWP_{N_2O}) \quad (4.10)$$

Global Warming Potential (GWP) values are based on the Renewable Energy Directive II (RED II, 2018) and are defined as:

- $GWP_{CO_2} = 1$
- $GWP_{CH_4} = 28$
- $GWP_{N_2O} = 265$

Emission Factors:

- $C_{fCO_2,j}, C_{fCH_4,j}, C_{fN_2O,j}$: CO_2, CH_4, and N_2O emissions from combustion, in gGHG/gFuel.
- $C_{sfCO_2,j}, C_{sfCH_4,j}, C_{sfN_2O,j}$: CO_2, CH_4, and N_2O emissions from slip (unburned fuel), in gCO_{2eq}/gFuel .

Note that slip emissions typically apply only to CH_4, and in most cases, $CsfCO_2, j$ and $C_{sfN_2O,j}$ are assumed to be 0 in accordance with REGULATION (EU) 2023/1805 of the European Parliament and of the Council. Slip emissions are mainly relevant for LNG or LNG-like fuels.

This step ensures direct emissions from combustion and potential unburned fuel are properly reflected in the vessel's carbon footprint.

Step 7: GHG Intensity per Voyage Leg

After computing the WTT and TTW emissions per leg, the model proceeds to calculate the GHG intensity, expressed as grams of CO_2eq per megajoule (gCO_2eq/MJ). This value reflects the carbon efficiency of the vessel's energy use, in line with FuelEU Maritime performance standards.

$$GHGIE_{actual,i}\left[\frac{gCO_2eq}{MJ}\right] = WtT + TtW \tag{4.11}$$

The GHG intensity per leg is calculated only for voyage segments with a non-zero compliance factor (i.e., excluding "Non-EEA → Non-EEA" legs) to ensure the average reflects only the regulated portion of the voyage.

Step 8: Compliance Balance and Penalty Calculation

Once the average GHG intensity (GHGIEactual) is computed, it is compared against the FuelEU Maritime target intensity for the respective year (denoted as GHGIEtarget). If the actual intensity exceeds the target, a penalty is imposed for the amount of greenhouse gas emissions above the regulatory threshold.

The model calculates the compliance balance using the FuelEU Maritime formula:

$$\text{Compliance Balance}[gCO_2eq] = (\text{GHGIEtarget} - \text{GHGIE}_{\text{actual}}) \times \left[\sum_i M_i \cdot LCV_i + \sum_k E_k\right] \tag{4.12}$$

Where:

- M_i: Adjusted fuel mass of compliant legs (in grams).
- LCV_i: Lower calorific value of fuel (MJ/g).
- E_k: OPS electricity consumption (MJ).

The fuel energy term accounts only for compliant legs by multiplying adjusted fuel mass with the LCV, while electricity consumption is summed from all OPS-using ports. This ensures the compliance balance reflects the actual regulated energy use of the vessel.

- If $\text{GHGIE}_{\text{actual}} \leq \text{GHGIE}_{\text{target}}$, the vessel is in compliance. The resulting compliance balance is positive, and no penalty is applied. In some cases, surplus compliance can be banked or traded.
- If $\text{GHGIE}_{\text{actual}} > \text{GHGIE}_{\text{target}}$, the vessel exceeds the allowable emission intensity. The compliance balance is negative, and a penalty is incurred based on the energy deficit.

To convert this compliance balance into a monetary penalty (FuelEU Penalty), the following formula is applied:

$$\text{FuelEU Penalty[EUR]} = \left|\frac{\text{Compliance Balance}}{\text{GHGIEactual} \times 41{,}000}\right| \times 2{,}400 \tag{4.13}$$

Where:

- $41{,}000$ MJ represents the energy content of one metric tonne of VLSFO (Very Low Sulphur Fuel Oil).
- €2,400 is the fixed penalty rate.Hhowever, since the regulation is new and still evolving, this value may be subject to change in future policy revisions

.

This penalty is implemented in the model within `LinerCost.py`, where:

- The compliant fuel energy is calculated from the adjusted fuel mass of compliant legs.
- OPS electricity consumption is summed across all relevant ports.

This final step completes the integration of FuelEU Maritime regulatory compliance into the cost structure of liner shipping, allowing the model not only to estimate operational costs and emissions but also to quantify potential economic consequences of regulatory non-compliance. This capability is useful for shipowners and policy analysts evaluating alternative fuels, technologies, or routing strategies.

4.3 EU ETS to Maritime Components

The integration of the European Union Emissions Trading System (EU ETS) into the Panteia Liner Shipping Model is essential for capturing additional regulatory costs associated with carbon emissions. Unlike the FuelEU Maritime Regulation, which accounts for full life-cycle emissions (including methane and nitrous oxide), the EU ETS focuses solely on direct CO_2 emissions from fuel combustion (Tank-to-Wake). This distinction is reflected in the model's implementation.

Step 1: Scope of Application and Coverage

The EU ETS applies to maritime voyages involving European ports, with varying coverage:

- 100% of emissions for intra-EEA voyages (EEA $\rightarrow$ EEA).
- 50% of emissions for incoming and outgoing voyages (EEA $\leftrightarrow$ Non-EEA).
- 0% of emissions for extra-EEA voyages (Non-EEA $\rightarrow$ Non-EEA).

The model uses the same compliance factor classification described in the FuelEU Maritime integration (Step 4) to determine the portion of TTW CO_2 emissions subject to EU ETS obligations.

Step 2: CO_2 Emission Calculation for EU ETS

For each voyage leg, the TTW CO_2 emissions are calculated separately from the FuelEU TTW calculation, as only CO_2 is relevant for EU ETS. The emission factor is based on the fuel type used. For example, VLSFO has a TTW CO_2 emission intensity of 79.43 gCO_2/MJ.

The total ETS-covered CO2 emissions are computed using the following formula:

$$\text{ETS CO}_2 \text{ (tonnes)} = \frac{(\sum_i M_{i,\text{compliant}}) \times LCV \times EF_{CO_2}}{10^6} \tag{4.14}$$

Where:

- $M_{i,\text{compliant}}$ = Adjusted fuel mass (g) for each voyage leg, already filtered by the compliance factor.
- LCV = Lower Calorific Value of the fuel (MJ/g).
- EF_{CO_2} = TTW CO_2 emission factor for the fuel (gCO_2/MJ), e.g., 79.43 for VLSFO.

This method ensures the ETS CO_2 emissions reflect only compliant voyage segments and exclude methane or nitrous oxide emissions.

Step 3: Cost Calculation for EU ETS

Once the total ETS-regulated CO_2 emissions are calculated, the monetary cost is derived using the current carbon price in the EU ETS market. The formula is:

$$\text{ETS Cost (EUR)} = \text{ETS CO}_2 \text{ (tonnes)} \times \text{Carbon Price (EUR/tonne)} \tag{4.15}$$

In the model, the carbon price is set to a default value of 61 EUR/tonne CO_2 (subject to change in sensitivity analyses). The resulting ETS cost is then added to the total annual running cost per ship, enabling users to assess how compliance with the EU ETS affects the financial viability of different fuel or routing strategies.

This implementation complements the FuelEU Maritime integration, offering a more complete view of regulatory costs and helping stakeholders understand the dual compliance burden imposed by both GHG intensity limits and CO_2 pricing mechanisms.

4.4 Summary

Literature Review

This chapter provides answers to **sub-question 3**, ”How can the Panteia Liner Shipping Model be used to assess potential carbon leakage under the FuelEU Maritime Regulation”:

- **Simulates real-world shipping operations:** The model computes total voyage costs, fuel consumption, transit time, and CO_2 emissions for different liner services, enabling detailed comparison across routes and scenarios.
- **Integrates FuelEU Maritime and EU ETS compliance:** The model calculates both Well-to-Tank (WTT) and Tank-to-Wake (TTW) emissions and applies GHG intensity thresholds to determine potential penalties or surpluses under FuelEU Maritime.
- **Captures voyage segmentation and regulatory scope:** It classifies each voyage leg as EEA–EEA, EEA–non-EEA, or non-EEA–non-EEA, assigning compliance factors (1.0, 0.5, or 0.0 respectively) to isolate emissions subject to EU regulations.
- **Models Onshore Power Supply (OPS) usage at berth:** For ships docking at EEA ports, the model accounts for electricity use and port-specific emission factors, helping assess how OPS adoption affects GHG intensity and compliance costs.
- **Accounts for alternative fuels and energy sources:** Users can test fuel scenarios (e.g., LNG, RFNBO, methanol) with varying emissions and prices, revealing which fuel strategies meet compliance goals most efficiently.
- **Includes routing and evasion strategies:** By simulating scenarios where services bypass EEA ports or transfer cargo via non-EEA transshipment hubs or sub-5000 GT feeder vessels, the model quantifies how evasion reduces regulatory exposure.
- **Estimates penalties and economic incentives:** The model applies FuelEU Maritime penalty formulas and EU ETS carbon pricing, helping evaluate when the cost of compliance drives operators to reroute or adopt cleaner technologies.
- **Supports sensitivity and scenario analysis:** Analysts can vary sailing speeds, port selection, fuel prices, and carbon prices to understand how external factors influence carbon leakage risk and regulatory compliance.

5 Scenario Analysis

5.1 Fuel-Based GHG Intensity Comparison

Before the evasion scenarios are analyzed, it is important to establish a baseline understanding of fuel-based greenhouse gas performance. This provides context for why certain fuels may trigger higher compliance costs under FuelEU Maritime, thereby influencing routing decisions.

To support shipowners in making informed decisions under the FuelEU Maritime Regulation, Figure 5.1 presents the total greenhouse gas (GHG) intensity of various marine fuels, expressed in grams of CO_2-equivalent per megajoule (gCO_{2eq}/MJ). The values shown reflect the sum of Well-to-Tank (WtT) and Tank-to-Wake (TtW) emissions, based on the calculation using Equation 4.7 and Equation 4.8, without accounting for regulatory incentives.

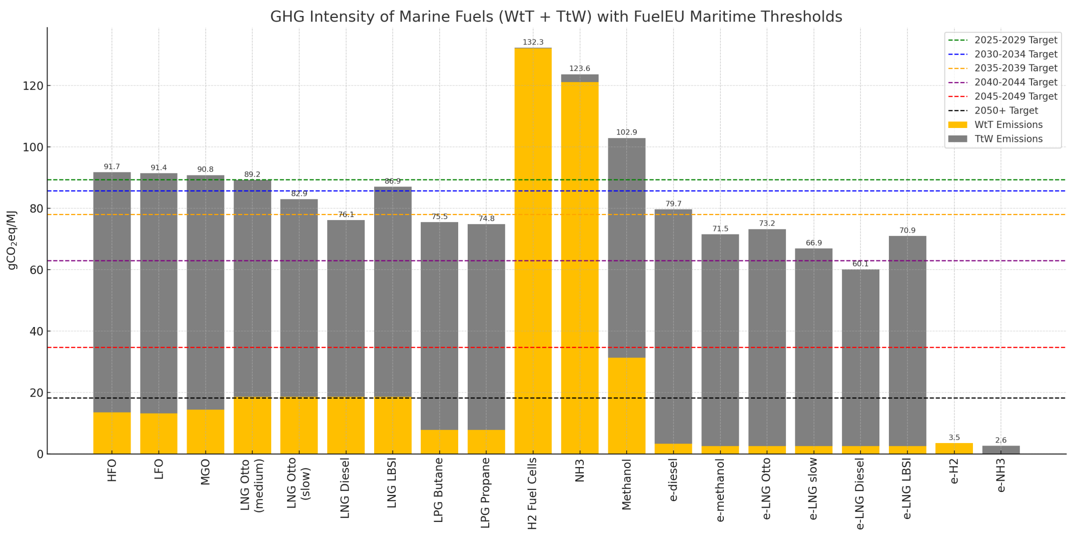


Figure 5.1: GHG intensities of marine fuels compared to FuelEU Maritime GHG limits

Figure 5.1 serves as a useful starting point for preliminary screening of fuel options. It allows shipowners to quickly assess whether the use of a single fuel type would comply with upcoming FuelEU Maritime targets. For instance, in 2025, conventional fuels like HFO and MGO already exceed the target threshold and would therefore not be compliant unless blended with lower-emission fuels (e.g., e-methanol or biofuels) or entirely replaced with alternative fuels such as e-LNG or e-ammonia.

It is important to note that the chart assumes full fuel usage of a single type and does not reflect operational adjustments such as route-based fuel switching or OPS usage at berth. Additionally, the reward factor (RWD) for Renewable Fuels of Non-Biological Origin (RFNBOs), which halves the GHG intensity during the 2025–2033 period, is not applied in this figure. Since this incentive is time-limited, RFNBOs may appear more compliant in the short term than they will be in later phases of the regulation. Furthermore, the comparison uses current Well-to-Tank (WtT) emission intensities and does not reflect the likely decarbonization of fuel production pathways over time. As a result, comparing today's fuel intensities against future thresholds (e.g., 2040 and 2050) may overstate the compliance gap, as cleaner electricity grids and technological advancements are expected to reduce emissions associated with alternative fuels in the long term.

5.2 Evasive Port Call Scenario

One of the case studies proposed by the European Commission for assessment by Panteia is the evasive port call scenario. This scenario involves modifying the port rotation by adding an intermediate non-EEA port, such as a port in the United Kingdom or the Mediterranean, before arriving at an EEA port. The main objective of this adjustment is to reduce regulatory compliance costs, since the voyage segment between two non-EEA ports is exempt from FuelEU Maritime and EU ETS obligations. However, such routing changes raise concerns about carbon leakage and a potential loss of competitiveness for EEA ports, as mainline calls may be redirected to avoid regulatory exposure.

5.2.1. Case Study 1: Far East Asia - (UK) - Northwest (NW) Europe

This case study examines the MSC Britannia service, a deep-sea container route connecting Far East Asia with Northwest Europe—one of the busiest trade corridors in global liner shipping. This particular service is of interest due to its strategic inclusion of a port call in the United Kingdom, a non-EEA country. As FuelEU Maritime and EU ETS regulations apply only to voyages involving EEA ports, the presence of a non-EEA intermediate stop introduces the potential for carbon leakage.

By inserting a UK port call before entering the EEA, operators can reduce their exposure to regulatory compliance costs, as the segment from a non-EEA origin to a non-EEA destination is exempt from FuelEU Maritime obligations. This makes the MSC Britannia service a relevant example for analyzing evasive routing behavior. In addition to Liverpool, the service connects with key Northern European ports such as Rotterdam, Antwerp, and Hamburg, providing access to Scandinavian and Baltic regions (MSC Mediterranean Shipping Company, 2024). The route passes through the Cape of Good Hope due to ongoing geopolitical tensions. The complete port rotation is listed in Table 5.1, and a visual representation of the route is provided in Figure 5.2.

Voyage Leg	Voyage Type
Shanghai → Ningbo	Non-EEA → Non-EEA
Ningbo → Yantian	Non-EEA → Non-EEA
Yantian → Vung Tau	Non-EEA → Non-EEA
Vung Tau → Liverpool	Non-EEA → Non-EEA
Liverpool → Rotterdam	Non-EEA → EEA
Rotterdam → Antwerp	EEA → EEA
Antwerp → Hamburg	EEA → EEA
Hamburg → London Gateway	EEA → Non-EEA
London Gateway → Singapore	Non-EEA → Non-EEA
Singapore → Shanghai	Non-EEA → Non-EEA

Table 5.1: Voyage legs and voyage Classification for MSC Britannia service

Figure 5.2: MSC Britannia service route (MSC Mediterranean Shipping Company, 2024)

To evaluate the impact of different fuel strategies under the FuelEU Maritime regulation, six scenarios are assessed for the 2025–2029 period, during which the GHG intensity threshold remains constant.

- Scenario 1 uses **only Marine Gas Oil (MGO)** and serves as the fossil-fuel baseline.
- Scenario 2 **blends 2% Renewable Fuels of Non-Biological Origin (RFNBO), specifically e-H_2**, with MGO to meet the minimum RFNBO requirement.
- Scenario 3 **adds Onshore Power Supply (OPS)** at EEA ports to the Scenario 2 fuel mix.
- Scenario 4 assumes the use of only **Liquefied Natural Gas (LNG)**.
- Scenario 5 **combines LNG with a 2% share of e-H_2** to meet RFNBO blending rules.
- Scenario 6 **adds OPS usage to the Scenario 5** combination.

LNG is included in these scenarios because it is currently the most widely used alternative fuel, accounting for approximately 0.1% of global maritime fuel consumption (Solakivi, Paimander, et al., 2022). The results are presented in Table 5.2.

Scenario	OPS Cost	Fuel (ton)	Fuel Cost	WtT (gCO_{2eq}/MJ)	TtW (gCO_{2eq}/MJ)	Average GHG (gCO_{2eq}/MJ)	FuelEU Penalty (2025-2029)	CO_2 Compliance (ton)	Total CO_2 (ton)	ETS Cost
1	$–	6502.95	$ (4,978,005)	57.6	304.93	90.632	$ (12,965)	1086.3	21158.9	$ (66,805)
2	$–	6487.58	$ (4,988,803)	56.1	295.78	87.967	$ 13,961	1035.5	21097.3	$ (63,681)
3	$52,696	6433.78	$ (4,945,173)	81.0	264.70	86.427	$ 28,538	891.2	20923.5	$ (54,811)
4	$–	5678.69	$ (4,832,653)	74.0	230.63	76.129	$ 161,242	826.3	15714.4	$ (50,820)
5	$–	5667.95	$ (4,846,275)	72.0	223.71	73.927	$ 192,021	792.1	15741.4	$ (53,095)
6	$60,147.70	5614.15	$ (4,797,719)	97.8	197.64	73.855	$ 181,480	669.0	15593.1	$ (44,846)

Table 5.2: Case Study 1: MSC Britannia scenario comparison of costs and emissions

Scenario 1 exceeds the FuelEU Maritime GHG limit of 89.340 gCO_{2eq}/MJ, with an average intensity of 90.632 gCO_{2eq}/MJ. As a result, the ship is non-compliant and incurs a FuelEU penalty of $12,965. It also generates the highest EU ETS cost of $66,805, with total CO_2 emissions reaching 21,158.9 tonnes. This reflects a conventional, high-emission operation with significant regulatory cost burdens.

Scenario 2 achieves FuelEU compliance, indicated by a positive FuelEU value of $13,961, due to the addition of 2% RFNBO which reduces the GHG intensity to 87.967 gCO_{2eq}/MJ. Although this avoids FuelEU penalties, the fuel cost increases and ETS costs remain relatively high at $63,681, suggesting limited financial benefit despite regulatory compliance.

Scenario 3 adds OPS to the Scenario 2 setup, at an additional cost of $52,696. This lowers the GHG intensity slightly further to 86.427 gCO_{2eq}/MJ, maintaining compliance (FuelEU value: $28,538). More notably, ETS costs are reduced by nearly $9,000 to $54,811, and total CO_2 emissions decrease to 20,923.5 tonnes. This demonstrates that OPS is more effective in cutting ETS-related costs than in improving FuelEU GHG intensity—especially when grid electricity remains moderately carbon-intensive.

Scenario 4 switches entirely to LNG, lowering the GHG intensity to 76.129 gCO_{2eq}/MJ and achieving strong compliance (FuelEU value: $161,242). Total CO_2 emissions fall to 15,714.4 tonnes, and ETS costs drop to $50,820. However, this configuration does not include RFNBO or OPS, which may raise concerns about infrastructure readiness or upstream emission profiles.

Scenario 5 builds on Scenario 4 by blending in 2% RFNBO, further reducing the average GHG intensity to 73.927 gCO_{2eq}/MJ. This leads to a higher FuelEU credit of $192,021 and slightly lowers ETS costs to $53,095. However, the marginal improvement suggests diminishing returns from minimal RFNBO blending when LNG is already in use.

Scenario 6 adds OPS to the LNG + RFNBO setup. While OPS costs rise to $60,147.70, the GHG intensity remains nearly unchanged at 73.855 gCO_{2eq}/MJ, due to the relatively high emission factor of OPS electricity. Nonetheless, this scenario yields the lowest total CO_2 emissions (15,593.1 tonnes) and the lowest ETS cost ($44,846), confirming that OPS is more effective at reducing ETS liabilities than improving FuelEU GHG scores.

Non-Evasive Route

To assess the impact of calling at a UK port under the FuelEU Maritime Regulation, the MSC Britannia service—which currently includes UK ports—is compared with an alternative scenario in which the service calls only at EEA ports. In this scenario, Le Havre (France) replaces Liverpool, and Gothenburg (Sweden) replaces London Gateway. These substitutions are chosen to ensure minimal changes to the original service, maintaining the same number of voyage legs (10), comparable sailing days, and selecting geographically proximate EEA ports. This allows for an isolated evaluation of the regulatory and cost implications of including non-EEA ports such as the UK. The full rotation is shown in Table 5.3 and the visualization of the route is shown in Figure 5.3.

Voyage Leg	**Voyage Type**
Shanghai → Ningbo	Non-EEA → Non-EEA
Ningbo → Yantian	Non-EEA → Non-EEA
Yantian → Vung Tau	Non-EEA → Non-EEA
Vung Tau → Le Havre	Non-EEA → EEA
Le Havre → Rotterdam	Non-EEA → EEA
Rotterdam → Antwerp	EEA → EEA
Antwerp → Hamburg	EEA → EEA
Hamburg → Gothenburg	EEA → EEA
Gothenburg → Singapore	EEA → Non-EEA
Singapore → Shanghai	Non-EEA → Non-EEA

Table 5.3: Voyage legs and voyage Classification for Far East Asia - Northwest Europe route

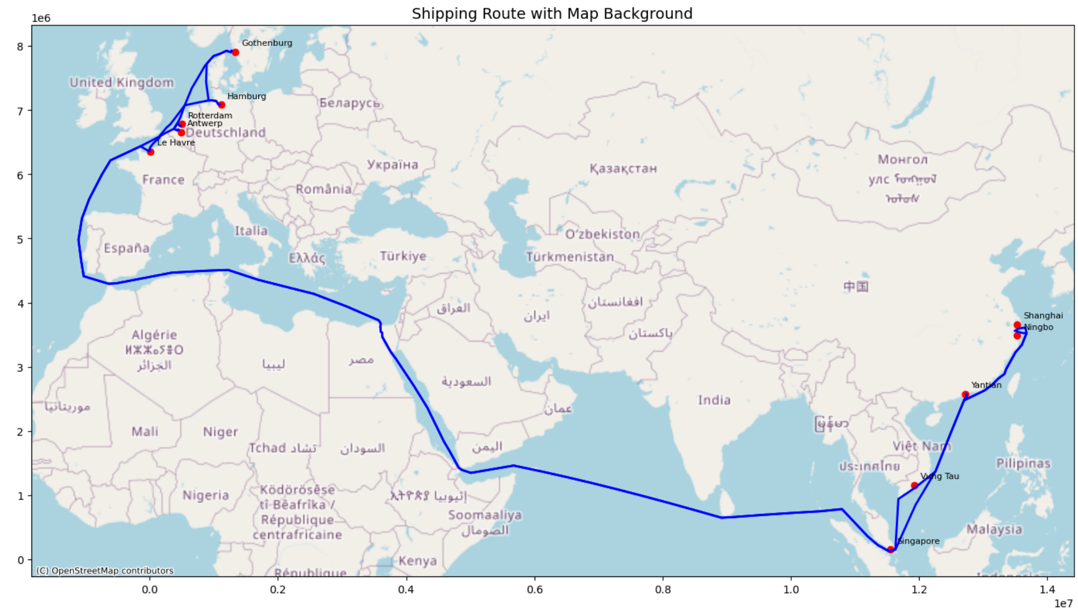


Figure 5.3: Far East Asia - Northwest Europe shipping route

For this route, the same set of scenarios as presented in Table 5.2 is applied. The results for the Far East Asia–Northwest Europe route are summarized in Table 5.4. To illustrate a clear comparison, Scenario 1—which results in non-compliance and a FuelEU penalty—is visualized in Figure 5.4.

Scenario	OPS Cost	Fuel (ton)	Fuel Cost	WtT (gCO_{2eq}/MJ)	TtW (gCO_{2eq}/MJ)	Average GHG (gCO_{2eq}/MJ)	FuelEU Penalty (2025-2029)	CO_2 Compliance (ton)	Total CO_2 (ton)	ETS Cost
1	$–	5763.760	$ (4,412,158)	86.4	457.4	90.632	$ -96,454	8081.49	18753.78	$ (497,011)
2	$–	5607.502	$ (4,493,664)	84.4	445.2	88.263	$ 350,356	7619.62	18141.59	$ (468,606)
3	$87,826.70	5517.835	$ (4,420,966)	115.8	405.8	86.9379	$ 423,477	7359.53	17851.94	$ (452,611)
4	$–	5035.851	$ (4,285,509)	111.0	345.9	76.1292	$ 1,177,646	6035.27	13994.93	$ (404,574)
5	$–	4926.686	$ (4,392,910)	108.3	336.7	74.1747	$ 1,369,755	5724.42	13602.09	$ (383,736)
6	$100,246	4837.01	$ (4,311,983)	140.9	303.6	74.0871	$ 1,356,378	5502.52	13354.96	$ (368,861)

Table 5.4: Case Study 1: Far East Asia - Northwest Europe scenario comparison of costs and emissions (no UK port calls)

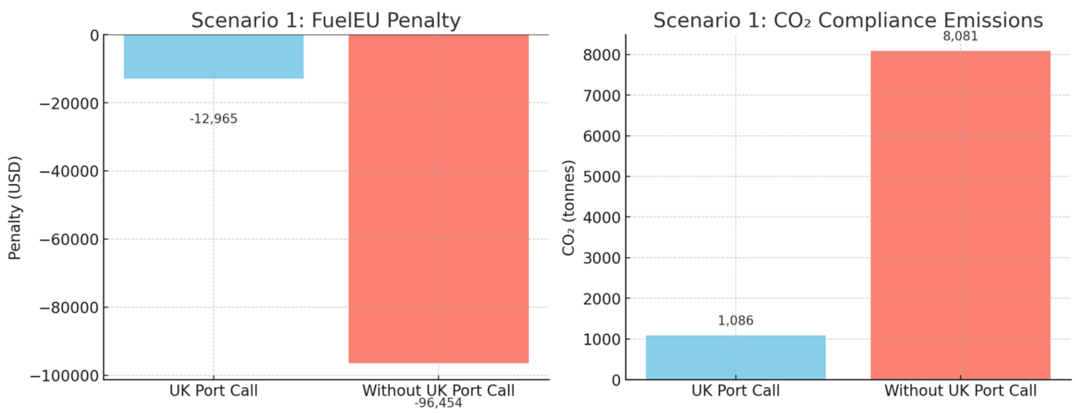


Figure 5.4: FuelEU Maritime penalty comparison in Scenario 1 for routes with and without UK port calls.

From Table 5.4, it is evident that the total Well-to-Tank (WtT) and Tank-to-Wake (TtW) energy intensity for the Far East Asia–Northwest Europe route are notably higher than those observed in the MSC Britannia scenario. This outcome is expected, as the direct EEA routing includes a greater number of voyage segments that fall under the scope of both the FuelEU Maritime and EU ETS regulations. Importantly, the reported WtT and TtW values reflect only the portions of the voyage covered by FuelEU Maritime. As such, routes with a larger share of EEA-compliant legs inherently yield higher regulated emissions, even if total emissions over the entire journey remain comparable. As illustrated in Figure 5.4, compliance CO_2 emissions are nearly 7.5 times higher in the EEA-only route, significantly increasing both FuelEU and ETS cost exposure.

In Scenario 1 (MGO only), the CO_2 compliance volume reaches 8,081.49 tonnes, compared to just 1,086.3 tonnes in the MSC Britannia case. Likewise, the associated TtW emissions intensity increases to 457.4 gCO_{2eq}/MJ, whereas it was only 304.93 gCO_{2eq}/MJ in the UK-port scenario. This results in a significantly higher EU ETS cost of $497,011 in Scenario 1—over seven times the $66,805 reported for the evasive routing case. These differences illustrate how the share of regulated voyage segments directly influences cost exposure under both regulatory frameworks.

Scenario 3, which incorporates OPS use at EEA ports, also shows a notable increase in shore power costs—rising to $87,826.70 compared to $52,696 in the MSC Britannia route. This increase reflects the larger number of OPS-compliant port calls in the direct EEA scenario (e.g., Le Havre, Rotterdam, and Gothenburg), and underscores how routing decisions affect not only emissions profiles but also auxiliary compliance costs.

Additionally, the FuelEU penalty in Scenario 1 reaches a deficit of $96,454, compared to a smaller non-compliance penalty of $12,965 in the Britannia case. This contrast reflects the broader compliance burden associated with full EEA routes, where a higher volume of energy is subject to FuelEU Maritime thresholds. However, when cleaner fuels are used—such as in Scenarios 4, 5, and 6 (LNG-based)—the FuelEU credits increase substantially. For instance, Scenario 5 yields a FuelEU credit of $1,369,755, which can be banked for future compliance periods, providing long-term strategic value.

Nonetheless, even with cleaner fuels and FuelEU compliance, the EU ETS cost remains significantly higher on the non-evasive route. In Scenario 5, the ETS cost is $383,736, compared to just $53,095 in the Britannia scenario. This reinforces the finding that EU ETS cost exposure is strongly shaped by routing decisions, due to the differences in regulatory coverage between EEA and non-EEA voyage segments.

5.2.2. Conclusion: Case Study 1

Case Study 1 clearly illustrates that carbon leakage can occur as a result of evasive port calls, particularly when vessels choose to call at a UK port instead of an EEA port.

While the total CO_2 emissions between the UK and EEA routes are comparable, the emissions subject to FuelEU Maritime and EU ETS compliance (i.e., compliance CO_2) are significantly lower on the UK route. This indicates that when vessels operate outside the jurisdiction of EU climate regulations, a substantial share of their emissions—while possibly monitored—falls outside the scope of regulatory enforcement or associated costs. The resulting gap between actual emissions and those addressed by compliance measures provides a strong indication of regulatory loopholes that can lead to carbon leakage, thereby undermining the EU's decarbonization objectives.

In addition to environmental concerns, this evasion strategy is economically appealing. Both ETS costs and FuelEU Maritime penalties are substantially lower when vessels operate on the UK route, thereby reducing the overall compliance burden for shipowners. This cost advantage could lead to lower freight rates and further incentivize operators to reroute services through non-EEA ports. Moreover, the UK currently imposes no emission-related penalties on shipping; its UK-MRV scheme is limited to emissions monitoring. Without appropriate countermeasures, EEA ports risk losing competitiveness to non-EEA hubs due to this regulatory loophole.

Among all scenarios analyzed, Scenario 1 presents the highest risk of carbon leakage. The use of marine gas oil (MGO), a fossil-based fuel, results in a GHG intensity of 90.632 gCO_{2eq}/MJ—already exceeding the strictest FuelEU Maritime threshold set for 2025–2029. This non-compliant configuration triggers both FuelEU penalties and high ETS costs, thereby increasing the incentive to avoid regulation through evasive routing. Critically, MGO and conventional fuels remain the dominant fuel in the container shipping sector as of 2023, accounting for 60.3% of current fuel consumption (X. Wang et al., 2023). The widespread reliance on MGO significantly amplifies the risk of regulatory evasion across the global fleet, particularly if rerouting to non-EEA ports is perceived as a cost-saving opportunity.

Furthermore, the analysis reveals that OPS is more effective at reducing ETS liabilities than at improving FuelEU GHG scores. This is primarily due to the Well-to-Tank (WtT) emission factor used in the model, which is based on the EU average of 73.74 gCO_{2eq}/MJ. As a result, the GHG intensity improvements from OPS are modest under current grid conditions. However, if the electricity grid used for OPS becomes significantly cleaner in the future, the contribution of OPS to reducing overall GHG emissions—and achieving FuelEU compliance—could become much more substantial. This underscores the importance of aligning shore power infrastructure development with broader energy system decarbonization efforts.

5.2.3. Case Study 2: Asia - (Algeciras) - North America

This case study examines a carbon leakage scenario in which a liner service between Asia and North America avoids regulatory exposure to the EU ETS and FuelEU Maritime by removing a port call within the European Economic Area (EEA). Specifically, Maersk's MECL service has adjusted its westbound rotation by eliminating the call at Algeciras (Spain), thereby placing the voyage outside the scope of both regulatory frameworks. This development has raised concerns from the Port Authority of Algeciras regarding the potential loss of competitiveness for EU ports (Atalayar, 2024).

Industry reports suggest that the route change by Maersk may be financially motivated, as omitting the Algeciras port call enables shipping companies to reduce or avoid the additional costs associated with the EU's emissions regulations. The EU Emissions Trading System (ETS), which came into effect on December 1, 2024, is estimated to increase voyage costs by approximately €150,000 per ship (FP Editor, 2025). By calling exclusively at non-EEA ports, the service strategically minimizes regulatory expenses. Consultations conducted by Panteia with a shipowner further indicate that this route modification also results in a time saving of approximately six days, and Maersk officials stated the decision was based on "commercial decisions" aimed at improving transit times (Faouzi, 2025).

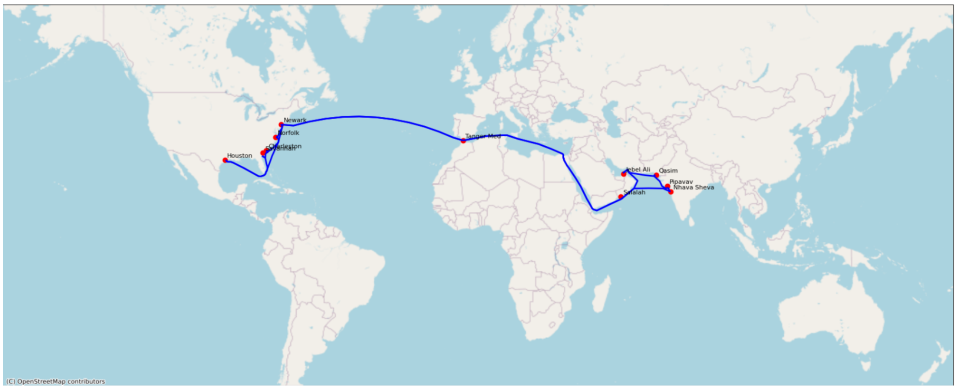
This case study compares the previous route, which included a port call at Algeciras, with the updated route that omits it, in order to assess the cost and emissions implications of this evasive adjustment. The complete port rotations for each route are provided in Table 5.5 and Table 5.6, while the route visualizations are presented in Figure 5.5.

Voyage Leg	**Voyage Type**
Jebel Ali → Qasim	Non-EEA → Non-EEA
Qasim → Pipavav	Non-EEA → Non-EEA
Pipavav → Nhava Sheva	Non-EEA → Non-EEA
Nhava Sheva → Salalah	Non-EEA → Non-EEA
Salalah → Tanger Med	Non-EEA → Non-EEA
Tanger Med → Newark	Non-EEA → Non-EEA
Newark → Charleston	Non-EEA → Non-EEA
Charleston → Savannah	Non-EEA → Non-EEA
Savannah → Houston	Non-EEA → Non-EEA
Houston → Norfolk	Non-EEA → Non-EEA
Norfolk → Newark	Non-EEA → Non-EEA
Newark → Salalah	Non-EEA → Non-EEA
Salalah → Jebel Ali	Non-EEA → Non-EEA

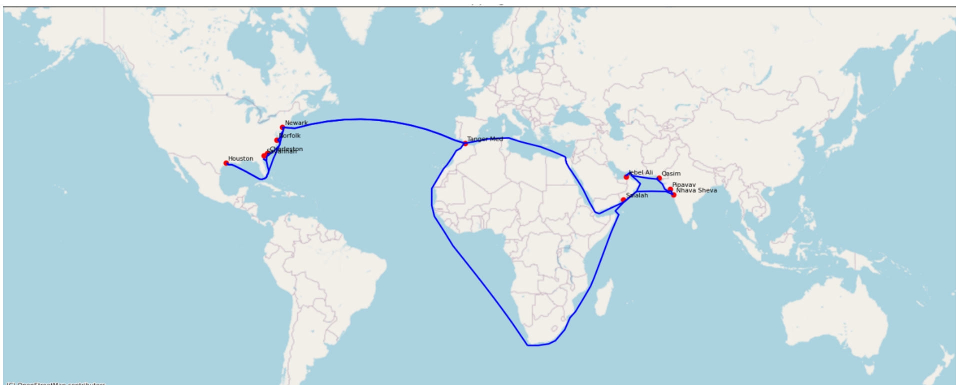
Table 5.5: Voyage legs and voyage classification for Asia – North America route

Voyage Leg	Voyage Type
Jebel Ali → Qasim	Non-EEA → Non-EEA
Qasim → Pipavav	Non-EEA → Non-EEA
Pipavav → Nhava Sheva	Non-EEA → Non-EEA
Nhava Sheva → Salalah	Non-EEA → Non-EEA
Salalah → Tanger Med	Non-EEA → Non-EEA
Tanger Med → Newark	Non-EEA → Non-EEA
Newark → Charleston	Non-EEA → Non-EEA
Charleston → Savannah	Non-EEA → Non-EEA
Savannah → Houston	Non-EEA → Non-EEA
Houston → Norfolk	Non-EEA → Non-EEA
Norfolk → Newark	Non-EEA → Non-EEA
Newark → Algeciras	Non-EEA → EEA
Algeciras → Salalah	EEA → Non-EEA
Salalah → Jebel Ali	Non-EEA → Non-EEA

Table 5.6: Voyage legs and voyage classification for Asia – North America route via Algeciras



(a) Asia - Northwest America shipping route (Maersk, 2025)



(b) Asia - Northwest America shipping route via Algeciras

Figure 5.5: MAERSK MECL Service Route

For this case study, since both the origin and destination of the route lie outside the scope of EU regulations, and the only change involves removing the EEA port of Algeciras, it is not necessary to compare multiple compliance scenarios as in Case Study 1. Instead, a single compliance scenario is applied to both the previous and updated routes, which involves the use of LNG blended with 2% RFNBO e-H_2, along with OPS use at the EEA port. The resulting differences in costs and emissions are then analyzed. The results are summarized in Table 5.7.

Metric	No Stop at Algeciras	Calling at Algeciras
Total Sailing Days	54.03	65.89
Total Fuel Consumption (ton)	2814.78	3468.67
Total Fuel Cost ($)	$2,395,380	$3,032,844
Cost Per TEU ($/TEU)	1031.13	1221.49
FuelEU Penalty ($)	$–	$552,713
Total CO_2 Compliance Emission (ton)	0	2122.16
Total CO_2 (ton)	7822.45	9603.48
EU ETS Compliance ($)	$0	$142,259
Omitted CO_2	100%	78%

Table 5.7: Case Study 2: Comparison of cost and emissions with and without Algeciras port call

From Table 5.7, it is evident that the updated route—which omits the Algeciras port call—results in significantly shorter total sailing days (54.03 days) compared to the route that includes Algeciras (65.89 days). This 11-day reduction aligns with industry reports and Panteia's consultation with the stakeholder, which noted a time saving of approximately 6–7 days per leg, confirming that the change affects both the westbound and eastbound legs of the service.

The regulatory cost implications are significant. The route calling at Algeciras triggers both EU ETS and FuelEU Maritime obligations. Under the FuelEU Maritime regulation, the vessel generates a surplus of $552,713 in 2025, indicating over-compliance with the GHG intensity limits. This surplus can be banked and used to offset future deficits but offers limited immediate financial benefit. Meanwhile, the route also incurs an EU ETS compliance cost of $142,259, which must be paid and cannot be deferred or traded. As the FuelEU thresholds become increasingly stringent, a vessel that currently produces a surplus may face penalties in the future. In contrast, the alternative route that avoids Algeciras—and thus bypasses all EEA ports—completely avoids both FuelEU and EU ETS compliance obligations. This makes it a more attractive option for shipowners seeking to minimize current and future regulatory risks.

From an economic standpoint, the difference in fuel cost between the two routes is $637,464, with the Cape route being more expensive. When this is combined with the avoided regulatory costs, the evasion route (via Suez, skipping Algeciras) proves to be more financially attractive.

Lastly, the analysis highlights that 100% of CO_2 emissions are omitted from EU regulatory oversight when Algeciras is avoided, compared to 79% coverage omission when Algeciras is included. Though a 22% gap may appear small, it becomes significant when scaled across recurring voyages and the global fleet. Without appropriate safeguards, such evasive strategies risk undermining the effectiveness of EU climate regulations and reducing the competitiveness of EU transshipment hubs such as Algeciras.

5.2.4. Conclusion: Case Study 2

The findings from Case Study 2 show that skipping Algeciras can be economically advantageous, primarily due to lower compliance costs under FuelEU Maritime and the EU ETS. This supports the concerns raised by the Port Authority of Algeciras about potential competitiveness risks for EU transshipment hubs.

Although FuelEU Maritime and the EU ETS include a transshipment clause to prevent regulatory evasion, the analysis reveals that routes operating entirely between non-EEA ports can still significantly impact the competitiveness of EU ports. In the case studied, Algeciras faces a clear risk of losing transshipment traffic to non-EU alternatives.

This highlights a regulatory blind spot: while the current framework focuses on voyages calling at EEA ports, it does not fully account for competitive distortions caused by non-EEA to non-EEA routes. Additional policy measures may be needed to address this issue and protect the strategic role of EU ports.

5.3 Transshipment Strategy: Feeder Scenario

Another proposed case study explores the transshipment strategy through a feeder scenario. In this approach, a smaller feeder vessel—under 5000 gross tonnage (GT)—is used to transport containers to the final port of destination. The rationale behind this strategy is to avoid the scope of FuelEU Maritime and EU ETS regulations, which do not apply to ships below the 5000 GT threshold.

5.3.1. Case Study 3: Asia - North Europe

This case study investigates a route proposed by the European Commission, focusing on shipping from Asia to Europe. The MSC Swan Sentosa service is selected due to its extensive port coverage across major European hubs. Given that a substantial portion of its voyage legs falls within the scope of the FuelEU Maritime regulation—owing to the high number of EEA port calls—this route presents a relevant opportunity to explore potential compliance strategies. Notably, the introduction of MSC's feeder service in Le Havre (since 2013) (MarineLink, 2013) enables a meaningful comparison between routes that do and do not utilize feeder transport from this port. The objective is to assess whether the use of a feeder from Le Havre can reduce overall shipping costs—including, but not limited to, FuelEU Maritime and EU ETS-related compliance costs, even if it results in partial regulatory evasion or carbon leakage.

The full rotation is shown in Table 5.8 and the visualization of the route is shown in Figure 5.6.

Voyage Leg	**Voyage Type**
Yokohama → Ningbo	Non-EEA → Non-EEA
Ningbo → Shanghai	Non-EEA → Non-EEA
Shanghai → Xiamen	Non-EEA → Non-EEA
Xiamen → Yantian	Non-EEA → Non-EEA
Yantian → Singapore	Non-EEA → Non-EEA
Singapore → Sines	Non-EEA → EEA
Sines → Le Havre	EEA → EEA
Le Havre → Rotterdam	EEA → EEA
Rotterdam → Gothenburg	EEA → EEA
Gothenburg → Aarhus	EEA → EEA
Aarhus → Hamburg	EEA → EEA
Hamburg → Antwerp	EEA → EEA

Table 5.8: Voyage legs and voyage classification for the East Asia to Northern Europe service

Figure 5.6: MSC Swan Sentosa route visualization

For this case study, a single compliance scenario is applied to both service configurations — with and without the use of feeder vessels. The compliance setup includes the use of LNG blended with 2% RFNBO (e-H_2) and the application of OPS at EEA ports. However, for the feeder vessels, only HFO is used, as they are not required to comply with the FuelEU Maritime regulation. To ensure a fair comparison between scenarios, the operational data for the feeder service has been scaled to match the capacity of the mainline vessel.

The mainline vessel in this case study has a capacity of 6,478 TEU, while the selected feeder vessel—M.V. Vantage—has a capacity of 354 TEU. To transport an equivalent volume, approximately 20.64 feeder vessels would be required (6,478 ÷ 354 ≈ 20.64). Therefore, the total cost and emissions for the feeder scenario are scaled by this factor to ensure a fair comparison with the mainline option. The M.V. Vantage, developed specifically for the North European feeder market, is selected for this scenario due to its regional suitability and availability (Conoship International, 2019). Its gross tonnage of 3,871 GT also places it below the threshold imposed by the FuelEU Maritime regulation, making it a compliant and practical choice.

The detailed results of the model are presented in Table 5.9.

Metric	Mainline Vessel Only	Mainline + Feeder (Mainline)	Mainline + Feeder (Feeder)	Mainline + Feeder (Total)
Total Sailing Days	69.05	60.74	6.57	67.31
Total Fuel Consumption (ton)	3022.4	2816.7	1292.98	4109.68
Total Fuel Cost ($)	$2,900,861	$2,700,190	$601,237	$3,301,427
OPS Cost ($)	$11,613	$3,318	$0	$3,318
Cost Per TEU ($/TEU)	1109.4	1593.7	575.7	–
FuelEU Penalty (2025–2029)	$1,068,628	$1,114,439	$0	$1,114,439
FuelEU Penalty (2040–2044)	$(-584,308)	$-428,950	$0	$-428,950
Total CO_2 Compliance Emission (ton)	3836.15	3302.49	0	3302.49
Total CO_2 (ton)	8252.719	7692.431	4089.77	11782.20
EU ETS Compliance ($)	$235,923.30	$203,103.34	$0	$203,103.34
Omitted CO_2	54%	57%	0%	–

Table 5.9: Case Study 3: Comparison of cost and emissions with and without using a feeder service

From Table 5.9, it can be observed that the total CO_2 emissions of the Mainline Vessel + Feeder setup are significantly higher, reaching 11,782.20 tons, compared to 8,252.72 tons for the Mainline Vessel Only scenario. This raises environmental concerns, as such an increase in emissions could undermine the goals of the EU Fit for 55 package.

A key reason for this discrepancy is that the feeder vessel operates below the 5,000 GT threshold, making it exempt from both FuelEU Maritime and EU ETS regulations. As a result, the 4,089.77 tonnes of CO_2 emitted by the feeder are not subject to compliance costs. This exclusion lowers the overall regulatory burden for the route and highlights a loophole where a substantial volume of emissions remains outside the scope of EU climate policy, potentially weakening its environmental and financial effectiveness.

This regulatory exemption also translates into a revenue loss for the EU. Because the feeder vessel is not covered by FuelEU or ETS, the EU misses out on potential compliance-related income. The feeder leg alone avoids an estimated EU ETS cost of $488,815.80, and while there is no separate FuelEU penalty for the feeder leg, the total penalty in the combined scenario is slightly higher than the mainline-only case, not lower.

From a cost standpoint, the feeder strategy is not economically favorable. The combined fuel and OPS costs for the Mainline + Feeder setup total $3,301,427, which is approximately $400,566 more than the $2,900,861 incurred under the mainline-only scenario. Additionally, the combined FuelEU and ETS compliance cost in the feeder setup amounts to $1,317,542, compared to $1,304,551 in the mainline-only case—a net increase of nearly $13,000.

5.3.2. Conclusion: Case Study 3

The findings from Case Study 3 indicate that while using a feeder vessel may reduce apparent compliance obligations due to current regulatory exemptions, it does not offer a clear financial benefit and results in significantly higher overall CO_2 emissions. Therefore, the carbon leakage risk associated with using a feeder is relatively low, as the strategy does not create strong incentives for evasion under current cost conditions.

Unless the operational costs of feeder services can be substantially reduced, or the regulatory scope is expanded to include smaller vessels, this approach is unlikely to be economically or environmentally sustainable in the long term.

5.4 Sensitivity Analysis

5.4.1. Sensitivity Analysis

Sensitivity analysis is conducted to evaluate how changes in key operational and regulatory parameters influence the outcomes of the model. While the main case studies rely on fixed assumptions, real-world liner shipping operations face varying conditions—particularly in sailing speed and the carbon intensity of electricity used for Onshore Power Supply (OPS) during berthing. To isolate their effects, this analysis varies one parameter at a time while holding all others constant.

Two key factors are assessed in this section. First, the impact of sailing speed on regulatory compliance and operational costs is explored. Specifically, we assess how slower speeds influence total fuel consumption, CO_2 emissions, and resulting FuelEU Maritime penalties and EU ETS costs. Second, the effect of different national electricity grid emission intensities on OPS effectiveness is evaluated. By applying OPS across EU countries with varying grid cleanliness, we test whether the benefits of OPS in lowering GHG intensity—and thus improving FuelEU compliance—differ significantly between EU countries.

To ensure consistency and comparability, the MSC Britannia route is used as the baseline in all sensitivity tests. These targeted assessments help clarify the role of key variables in shaping both environmental performance and compliance strategies under the FuelEU Maritime and EU ETS frameworks.

5.4.2. Sailing Speed

Sailing speed is a critical operational variable influencing both the fuel consumption and the service frequency requirements in liner shipping. Although reducing sailing speeds lowers fuel consumption and associated emissions, it also results in longer voyage durations, which may necessitate deploying additional vessels to maintain the desired service frequency. The main ship speed classes according to Rodrigue (2024) are:

- **Normal cruising speed** (20–25 knots): The conventional design speed of container vessels, balancing hydrodynamic efficiency and engine performance. Most container ships are optimized for operations around 24 knots under this regime.

- **Slow steaming** (18–20 knots): A practice of operating engines below their maximum capacity to reduce fuel consumption, commonly adopted after 2010 to mitigate high fuel prices and environmental pressures.
- **Extra slow steaming** (15–18 knots): Also referred to as economical or super slow steaming, this involves a significant speed reduction to achieve the lowest possible fuel consumption while still maintaining service viability, particularly over shorter or regional routes.
- **Minimal commercial speed** (12–15 knots): The technically feasible lower bound of sailing speeds, yielding little additional fuel savings but compromising service schedules severely. As such, it is rarely adopted for commercial liner services.

In the context of this study, sensitivity tests on sailing speed will provide insights into the trade-offs between operational costs, emissions compliance under FuelEU Maritime and EU ETS, and maintaining service reliability. The detailed results are shown in Table 5.10, Figure 5.7, and Figure 5.8.

Metric	**12 knots**	**15 knots**	**18 knots**	**21 knots**
Sailing Days	87.39	71.66	61.18	53.69
Ship Needed	12.95	10.71	9.22	8.15
Total Fuel Consumption (ton)	3776.22	5799.46	8272.32	11194.79
Total Fuel Cost ($)	$2,240,179	$3,440,438	$4,907,420	$6,641,127
Cost Per TEU ($/TEU)	730.29	701.21	706.65	735.81
Cost Per KM (per ship)	0.0348	0.0334	0.0337	0.0351
FuelEU Penalty ($)	$52,631	$74,761	$101,810	$133,776
CO_2 Compliance Emission (ton)	660.54	938.29	1277.76	1678.95
Total CO_2 (ton)	11705.47	17977.11	25642.44	34701.47
EU ETS Cost ($)	$40,623	$57,704	$78,582	$103,255
Omitted CO_2	94%	95%	95%	95%

Table 5.10: Sensitivity analysis of speed variation on costs and emissions for the MSC Britannia route

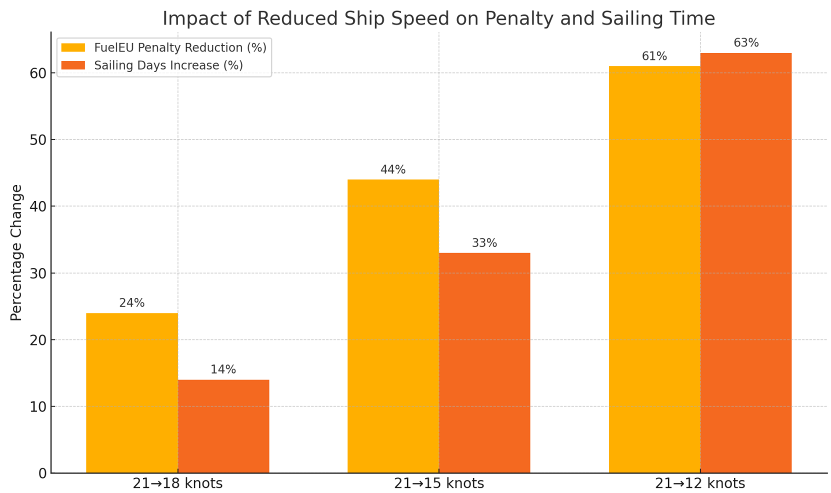


Figure 5.7: Impact of sailing speed on FuelEU Penalty and sailing time

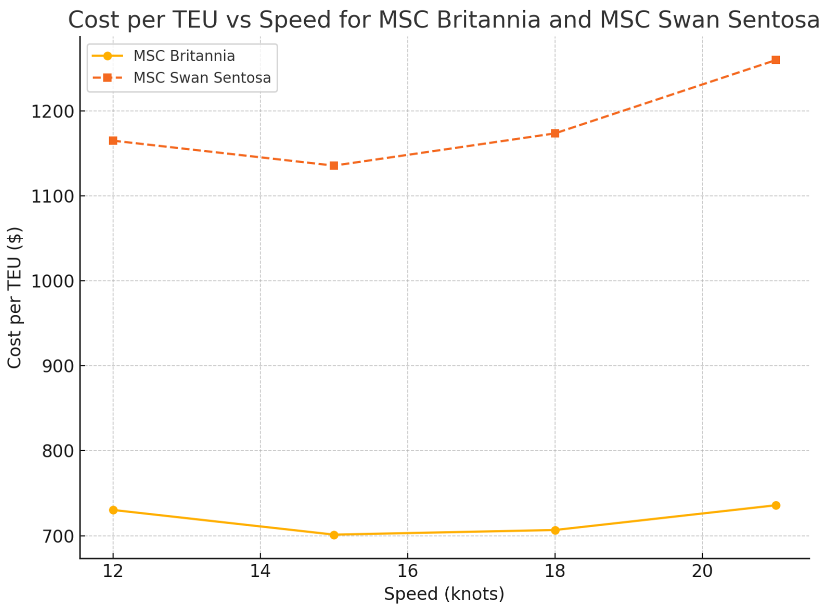


Figure 5.8: Impact of sailing speed on cost per TEU

Figure 5.7 presents the trade-off between FuelEU penalty reductions and the increase in sailing time when ship speeds are reduced from 21 knots to lower operational levels. As shown, reducing the sailing speed from 21 to 18 knots results in a 24% reduction in FuelEU penalty, with only a 14% increase in sailing days. This indicates that moderate slow steaming can be a highly effective strategy, offering regulatory cost savings with relatively limited impact on service time.

Further speed reductions continue to lower the FuelEU penalty, but with diminishing marginal benefits. A speed reduction from 21 to 15 knots achieves a 44% penalty reduction, though it comes at the cost of a 33% increase in sailing time. When speed is further reduced to 12 knots, the penalty reduction reaches 61%, yet the sailing days increase nearly matches it at 63%. This suggests that extreme slow steaming may lead to service delays that offset the cost savings, particularly on routes where frequency and delivery time are critical.

These results emphasize that while slower speeds are an effective tool to meet environmental regulations such as FuelEU Maritime, they must be carefully balanced against the operational and commercial requirements of the service. The range between 15 and 18 knots appears to provide the most favorable trade-off between cost savings and sailing time, serving as a practical compromise for many container operators.

In addition to the environmental cost indicators, the cost-efficiency of different sailing speeds can be observed in Figure 5.8. Interestingly, the cost per TEU does not decrease linearly with lower speeds. While a reduction from 21 to 15 knots shows a decrease in cost per TEU, further reduction to 12 knots leads to a rebound in per-unit cost. This suggests that although slower speeds may save fuel and reduce penalties, the diminishing economies of scale and increased ship requirements due to longer voyage times can offset these savings.

5.4.3. OPS Emission Intensity

The FuelEU Maritime regulation encourages the use of Onshore Power Supply (OPS) during berthing to reduce a vessel's overall GHG intensity. The effectiveness of OPS, however, depends not only on the main fuel used for propulsion but also on the carbon intensity of the electricity grid supplying the OPS. Since electricity emission factors vary significantly across countries, the impact of OPS on regulatory compliance can differ by port, as illustrated in Figure 3.5.

This sensitivity analysis explores how variations in OPS emission intensity across countries affect compliance. For each selected fuel type, the total GHG intensity is recalculated using different electricity grid emission factors and compared to the FuelEU Maritime thresholds. To ensure consistency, the analysis uses a single representative route consisting entirely of EEA ports—where OPS use is mandated—so that the effect of grid carbon intensity can be isolated from other variables. The result is provided in Figure 5.9.

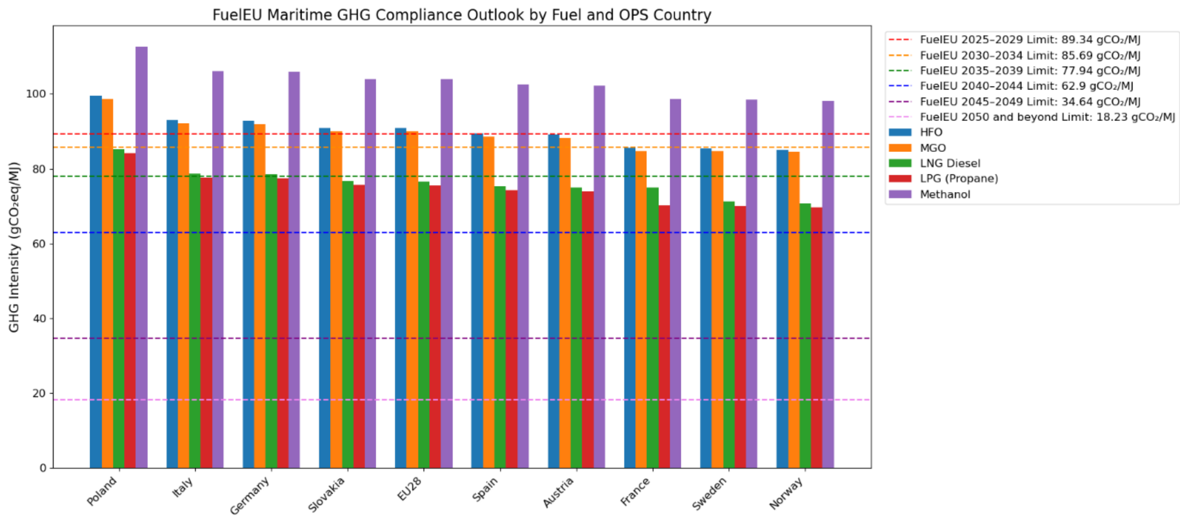


Figure 5.9: Impact of OPS electricity mix on GHG intensity by fuel type and country

From Figure 5.9, it is evident that OPS grid emission intensity plays a significant role in a vessel's overall GHG performance. Although OPS is used only during berthing, its impact on reducing overall GHG intensity is limited compared to changes in main propulsion fuels. However, under the increasingly stringent FuelEU Maritime regulation, even these marginal reductions can be meaningful for compliance.

The results show that countries with cleaner electricity grids, such as Norway, Sweden, and France, enable fuels like LNG and LPG to remain compliant up to the 2035–2039 period, whereas the same fuels may exceed the GHG threshold in countries with higher grid emission factors, like Poland or Italy. This indicates a valuable compliance strategy: shipowners may prefer ports in low-emission countries to reduce their total GHG intensity and avoid penalties.

Moreover, if electricity prices decrease in the future, it may become economically attractive for shipowners to fully shift to electricity during port stays, or even adopt hybrid or battery-electric solutions where feasible, further improving their compliance position.

5.5 Summary

Key Takeaways

- **Fuel-Based Compliance Challenges**: Scenario analysis confirms that conventional fuels like MGO and HFO exceed FuelEU Maritime GHG intensity thresholds, especially in the 2025–2029 period. Without switching to cleaner alternatives or blending with RFNBOs, these fuels trigger penalties and raise ETS costs. Given that MGO accounts for over 60% of container ship fuel use, this significantly increases the risk of regulatory evasion if cost-saving alternatives such as non-EEA routing remain viable.
- **Case Study 1 – UK Port Call Evasion Increases Carbon Leakage Risk**: Replacing an EEA port with a UK port reduces FuelEU and ETS compliance obligations without significantly changing total CO_2 emissions. This regulatory gap results in lower reported emissions, lower costs, and a strong incentive for evasive routing—demonstrating a clear case of carbon leakage. The UK's limited regulatory enforcement further exacerbates this loophole, undermining EU climate goals and reducing competitiveness of EEA ports.
- **Case Study 2 – Transshipment Avoidance via Port Omission**: Skipping a single EEA transshipment port (e.g., Algeciras) removes the route from FuelEU and ETS regulatory coverage, allowing full avoidance of compliance costs. Although the FuelEU Maritime regulation includes a transshipment clause to mitigate evasion, this case highlights that non-EEA to non-EEA routes still pose a carbon leakage risk. The significant cost advantage raises concerns—such as those expressed by the Port Authority of Algeciras—about the potential loss of transshipment traffic to non-EU hubs, revealing regulatory blind spots that can undermine EU port competitiveness.
- **Case Study 3 – Feeder Strategy Creates Apparent Loophole, but Low Evasion Risk**: Using feeder vessels under 5,000 GT shifts emissions outside the regulatory scope, reducing reported compliance emissions by up to 40%. However, this results in higher overall CO_2 and lacks strong financial benefit, indicating low practical risk of carbon leakage unless regulatory exemptions persist or feeder costs drop significantly.
- **OPS Effectiveness Depends on Electricity Grid**: OPS reduces ETS costs more effectively than it improves FuelEU GHG intensity, as its emissions are primarily from the Well-to-Tank (WtT) component. Its overall effectiveness depends heavily on the carbon intensity of the national electricity grid. Using OPS in countries with cleaner electricity (e.g., Norway, France) can significantly enhance compliance outcomes. This suggests that port selection may influence emissions performance and could affect competitiveness among EEA ports, as shipowners may favor ports with cleaner grid electricity.
- **Fuel and OPS Strategies Show Mixed Cost-Effectiveness**: Alternative fuels (e.g., LNG, RFNBOs) help achieve FuelEU compliance but come with significant cost trade-offs. OPS offers a cost-effective way to reduce ETS costs but has limited effect on GHG intensity under current grid conditions.
- **Sensitivity Analysis – Sailing Speed Influences Compliance Cost and Time Trade-offs**: Moderate slow steaming (e.g., 18 knots) significantly reduces FuelEU and ETS penalties with minimal increases in voyage time, making it a viable compliance strategy within EEA jurisdiction. However, further speed reductions yield diminishing economic returns and potential schedule disruptions. A carbon leakage risk may arise if vessels selectively slow down only within EEA-regulated waters to reduce compliance exposure, while accelerating outside those jurisdictions—thereby shifting emissions geographically without reducing total output.

6 Stakeholder Engagement

This chapter presents the results from stakeholder engagement conducted by Panteia, which are used to support the analysis in chapter 5 and to assess potential policies or strategies for mitigating carbon leakage, if present.

6.1 Targeted Interview

This section presents findings from stakeholder interviews conducted by Panteia as part of an initial scoping exercise. The interviews aimed to gather expert perspectives on the potential implications of recent regulatory developments, which are the FuelEU Maritime and the EU ETS, on the competitiveness of EU ports and the associated risks of carbon leakage. The full set of interview questions and corresponding responses can be found in Appendix D.

Each stakeholder was asked a series of standardized questions regarding the impact and effectiveness of maritime climate policies.

- Stakeholder 1 has been actively involved with FuelEU Maritime and the EU ETS since their inception but is not actively engaged with CBAM, as it currently does not cover shipping.
- Stakeholder 2, representing port interests, indicated that this topic is especially relevant for the Port of Algeciras. They have observed rerouting in the Mediterranean and shifts in northern Europe toward the UK. Stakeholder 2 expressed general support for the EU ETS.
- Stakeholder 3 noted that since 2020, FuelEU Maritime and the EU ETS have had a clear impact on their members' operations. Their focus has been on ensuring that port infrastructure is utilized, to avoid stranded investments. They also highlighted the risk of changing port call sequences or transshipment routes to reduce regulatory costs. Regarding CBAM, Stakeholder 3 does not currently foresee a significant risk of carbon leakage.
- Stakeholder 4 emphasized that FuelEU and the EU ETS have been of high strategic importance. They reported active involvement in shaping the regulatory frameworks to ensure their effectiveness in supporting shipping decarbonization. Stakeholder 4 also noted that their members are committed to achieving decarbonization goals.

A summary of these interviews is provided in Table 6.1.

Question	Main Themes	Common Views	Notable Exceptions
Q1: Influence of Regulations	Regulatory awareness	FuelEU and ETS influenced decisions; CBAM seen as less relevant	Stakeholder 3 highlighted port infra concerns; Stakeholder 1/4 highly engaged
Q2: Definition of Carbon Leakage	Operational and policy interpretations	Defined via route changes, modal shift, or lost port business	Stakeholder 4 cited UNFCCC/IPCC definition
Q3: Risk of Leakage or Competitiveness Loss	Risk perception	Most agreed there is a risk, esp. in Med.	Stakeholder 4 did not comment; Stakeholder 1 cited no evidence yet
Q4: Geographic Risk Areas	Regional hotspots	Med. and Northern Europe frequently mentioned	Stakeholder 2 also noted Middle East and Africa
Q5: Operational Changes Expected	Adaptation behavior	Port evasion, transshipment, bunkering shifts foreseen	Stakeholder 4 noted risk if fuels aren't supplied at hubs
Q6: Relevance of Proposed Scenarios	Scenario validation	Most stakeholders agreed with scenarios	Stakeholder 3 proposed EU-transit-only scenarios
Q7: Third-Country Policy Impacts	Policy alignment	IMO-level/global policies preferred	Stakeholder 3 suggested fuel levy; Stakeholder 4 emphasized global pricing
Q8: Mitigation Strategies	Policy proposals	Incentives, fuel supplier mandates, expanded port lists	Stakeholder 2 warned on Global Gateway support to competitors
Q9: Alt. Fuel Cost-Effectiveness	Compliance challenges	Fuels costly (4× conventional); supply gaps remain	Stakeholder 4 noted investments in renewable-ready ships

Table 6.1: Summary of preliminary stakeholder interviews on maritime climate policy

Discussion & Key Takeaways

- Most stakeholders confirm carbon leakage and competitiveness risks—especially due to rerouting, transshipment shifts, and modal backshifts.
- High-risk areas identified: Mediterranean (e.g., Spain, Italy), Northern Europe (e.g., Rotterdam, Antwerp), and even the UK and Middle East.
- Stakeholders anticipate changes in bunkering, feedering, and port call patterns. According to Stakeholder 3, regulatory developments may encourage the adoption of the hub-and-spoke model, resulting in fewer direct EU port calls and a stronger reliance on transshipment hubs. The hub-and-spoke system is a widely used approach for optimizing maritime transport networks by consolidating cargo at central hub ports before distributing it to smaller spoke ports. This model improves operational efficiency, reduces transportation costs, and enables economies of scale through strategic network design (Humang et al., 2025). Major shipping lines such as Hapag-Lloyd and Maersk have begun implementing this model through their joint initiative, the Gemini Cooperation, which will commence in February 2025 (Hapag-Lloyd, 2024).
- Stakeholders note that alternative fuels are approximately four times more expensive than conventional fuels and are not widely available, particularly at traditional bunkering hubs. This concern is supported by the findings of Solakivi, Paimander, et al. (2022), which indicate that even when accounting for the EU ETS, the projected prices of alternative fuels will remain significantly higher than those of fossil fuels for the foreseeable future.
- Stakeholders propose several mitigation strategies, including expanding the list of exempted ports, implementing fuel supplier mandates, and using EU ETS revenues to subsidize the use of clean fuels. Stakeholder 1, in particular, advocates for a voluntary mandate on fuel suppliers

to ensure sufficient production of alternative fuels, noting that no binding obligation currently exists. A comparable policy can be found in the United Kingdom, where the Sustainable Aviation Fuels (SAF) scheme mandates fuel suppliers to progressively increase the share of SAF in the aviation sector. This policy aims to reduce GHG emissions by legally requiring the supply of SAF over time (UK Department for Transport, 2024).

- Stakeholder 3 highlights the risk of stranded port investments if vessels begin to avoid regulated ports. For instance, a study by Jeong et al. (2023) on the implications of the Paris Agreement under carbon pricing found that shipowners could face approximately US$26.5 million in stranded asset risk. This risk could be slightly reduced to US$25.2 million if ships slow down to meet carbon intensity requirements.

6.2 Survey Questionnaire

The maritime survey received a total of 53 responses. Respondents were asked to rate how likely they considered the presented changes to be reactions to the introduction and enforcement of the aforementioned legislation. This question was answered separately for each case study and scenario. The detailed results are provided in Appendix E.

6.2.1. Additional Questions on Scenarios

The survey included additional questions regarding the proposed scenarios. The detailed results are provided in Appendix E.

Q1: Apart from the eight presented scenarios, are there other scenarios you think will be relevant? Stakeholders mentioned risks of displacing EU logistics hubs (especially transshipment ports) to non-EU territories, weakening EU control over supply chains and circular economy opportunities. One stakeholder suggested all scenarios converge into a broader risk of losing control over global logistics. A decline in demand for ammonia and methanol bunkering in the EU was also noted.

Q2: Do you consider any additional maritime routes particularly vulnerable to carbon leakage and competitiveness loss? Routes involving Canary Islands, Algeciras, Valencia, Barcelona, and ports in the North-West and Mediterranean were highlighted. High-risk routes include Far East–Europe, US–Europe, South Africa–Europe, and the Hamburg–Le Havre to Baltic transition.

Q3: Which routes/rotations could see the greatest impact on costs, competitiveness, or fuel choice? Key routes include Baltic transshipment services, intra-Mediterranean services, US/Asia–Europe services via major hubs, and SECA zone routes. Examples include Far East–East Med–Adriatic, and US–Far East routes previously calling EEA ports but now rerouted.

Q4: For which vessel types might there be a risk of carbon leakage or competitiveness loss? Risks were cited for Ro-Ro/Ro-Pax vessels (due to modal shift), older ships (20–25 years), short-sea vessels, tramp ships, and vessels below 5000 GT. Offshore vessels are also impacted due to regulatory definitions disadvantaging EU operators.

Q5: Have you noticed market shifts or preferences toward non-EEA routes or ports? Yes. Increased port calls to the UK were observed, with examples like Maersk's MECL route avoiding Algeciras and MSC's Britannia service. Transshipment is shifting to North African ports (e.g., Nador, Abu Qir). Expansion of London Gateway and plans in Jeddah and Egypt reinforce this trend.

Q6: Which EEA ports are most vulnerable to carbon leakage or loss of competitiveness? Southern European hubs (Algeciras, Valencia, Sines, Barcelona), North-Western ports, and Eastern Mediterranean hubs (e.g., Malta Freeport, Gioia Tauro) were named, especially amid Red Sea disruptions.

Q7: To what extent are passengers or consumers expected to be impacted? Consumers are already affected via ETS surcharges on freight. Risks include higher inland logistics costs, loss of direct connectivity, and potential inflation. Some foresee rising awareness and demand for low-emission transport.

Q8: How would you define loss of competitiveness in the EEA maritime sector? Loss of competitiveness refers to declining ability of EEA operators to attract cargo and investment due to higher operating and compliance costs versus non-EEA competitors. This could lead to traffic diversion and weakened EU strategic position.

Q9: Do you foresee an impact on competitiveness from EU decarbonisation policies? Yes. Examples include rerouting, cost-driven modal shifts, and investment loss. Ferry service quality could decline. A 5000 GRT ship may incur €12,000 extra for a 3-day EU voyage. Cost gaps risk shifting traffic to cheaper non-EEA ports.

Q10: Are there non-EU policy or operational factors that may impact competitiveness? Yes. Key factors include unequal public funding, slower port automation, labour costs, Red Sea disruptions, and port strikes. Non-EU ports offer cheaper fuel, faster development, and political stability. Many stakeholders noted increasing investments in non-EEA terminals.

Q11: What are the main drivers of shifts away from EEA port calls? Cost pressures are dominant: compliance, labour, energy, infrastructure, and legislative uncertainty. Other drivers include congestion, inadequate hinterland links, proximity of competing ports, and strategic repositioning by shipping lines.

Discussion & Key Takeaways

The responses to the additional survey questions offer valuable insights into how stakeholders perceive the risk of carbon leakage and competitiveness loss under current EU maritime climate regulations. Several recurring themes emerged.

First, it became clear that carbon leakage is already a tangible concern, not just a theoretical risk. Stakeholders pointed to recent trends—such as increased use of UK ports and a growing shift in transshipment activity to North African hubs—as early indicators that some ship operators are actively adjusting their routing strategies to avoid EU regulations. These developments align closely with the findings from Case Study 1 and 2, where rerouting or port omission led to significant reductions in compliance costs.

Several stakeholders emphasized that Southern and transshipment-dependent ports in the EEA—such as Algeciras, Valencia, and Malta—are particularly vulnerable. Their proximity to non-EU alternatives and dependence on hub-and-spoke logistics models make them susceptible to cargo diversion. This highlights that carbon leakage is not only about emissions relocation, but also about the risk of losing control over key logistics functions and associated economic activity.

Certain vessel types were also seen as more exposed to leakage-related pressures, especially Ro-Ro/Pax vessels, short-sea shipping, and sub-5000 GT ships that are currently exempt from FuelEU Maritime and EU ETS. These exemptions may unintentionally encourage operators to reconfigure fleets or services in ways that reduce their regulatory exposure, further contributing to leakage risk.

Importantly, cost remains the main factor driving avoidance behavior. Stakeholders frequently mentioned that compliance costs, especially from ETS surcharges, are prompting shipowners to reconsider EEA port calls.

In addition to cost, other non-policy factors were mentioned, including labour expenses, slower port automation, and geopolitical disruptions. These amplify the attractiveness of non-EU ports, where operational costs are often lower. Together, these structural disadvantages may accelerate competitiveness loss for EEA ports if not addressed in parallel with climate policies.

Overall, the survey responses reinforce the idea that carbon leakage is a multi-dimensional issue. It affects not only emissions accounting, but also long-term port competitiveness, vessel deployment strategies, and overall supply chain resilience. These findings suggest that mitigating carbon leakage will require a broader approach—one that considers both regulatory design and the underlying market conditions shaping operational decisions. Addressing this challenge may also require global policy coordination, as currently being pursued through the IMO's Net-Zero Framework.

6.2.2. Mitigating Measures: Survey Results of Feasibility Analysis

Stakeholders were asked to elaborate on the feasibility of each proposed mitigation measure. These measures include: (1) the extension of the Carbon Border Adjustment Mechanism (CBAM) to the maritime sector; (2) the introduction of an EU levy on all vessels departing from the EEA based on their final destination; (3) changes to the criteria for establishing the list of neighboring transshipment ports under FuelEU Maritime and/or ETS Maritime; (4) amendments to the FuelEU Maritime regulation; and (5) the introduction of a levy on containers, with proceeds allocated to a dedicated shipping fund. The summary of the stakeholder perspectives across the five policy measures is provided in Table 6.2. The discussion and feasibility of these measures are examined in chapter 7.

Measure 1: Extension of CBAM to Maritime

- Stakeholders noted the difficulty of applying CBAM to shipping, given the complexity of tracking emissions across international voyages.
- Concerns were raised about how the carbon content of shipping would be defined and verified.
- Many believed CBAM would overlap with existing measures like EU ETS and IMO regulations, creating administrative burden and risk of double counting.
- CBAM was seen as ineffective in addressing transshipment relocation, especially for Non-EU / EU / Non-EU routes.
- Some warned it could incentivize evasive port calls just outside the EEA, harming nearby EU ports.
- Trade risks were flagged, including potential retaliation from non-EU countries and WTO challenges.
- Economic impacts were expected, such as higher costs for consumers and disadvantages for exporters.
- The main consensus among several stakeholders was that a single global instrument under the IMO would be more workable and less prone to loopholes. Alignment of EU legislation with IMO measures was strongly recommended, not only for this measure but for all other below measures as well.

Measure 2: Introduction of an EU levy on All Vessels Departing from the EEA based on The Final Destination

- Stakeholders argued that the levy would further harm the competitiveness of EU ports and exporters by adding to the financial burden already imposed by the EU ETS.
- Determining a vessel's final destination was considered ambiguous, particularly for container ships operating on complex rotation schedules.
- The levy was criticised for resulting in double charging, as it would apply on top of existing ETS obligations.
- Many believed the measure would not prevent carbon leakage, since vessels could still reroute through non-EEA ports to avoid both the levy and EU obligations.
- Several responses stressed the need for positive incentives to promote competitiveness, rather than additional regulatory charges.
- One stakeholder noted that higher freight costs caused by the levy could disproportionately affect developing regions, such as Africa, and contribute to inflation.

Measure 3: Changes to the criteria for the establishment of the list of neighboring transshipment ports for FuelEU Maritime and/or ETS Maritime

- Stakeholders suggested adjusting the criteria used to designate "neighboring transshipment ports" under EU climate regulations.
- Proposed changes included lowering the transshipment share threshold from 65% to 50%, incorporating ports handling other unitised cargo (not just containers), and considering ports like Tanger or Nador for 100% emissions coverage instead of the current 50%.
- There was support for shifting the focus from transshipment share alone to include proximity to the EEA, with a call for continuous monitoring and annual updates to the list.
- However, many respondents noted that even revised criteria would not address the broader issue of EU port competitiveness.

- For example, a ship calling at Port Said (a non-EEA port on the list) before arriving in Rotterdam is charged for only 50% of emissions, whereas calling at Valencia (an EEA port) results in 100% coverage for the second leg.
- This creates a cost incentive to stop at non-EEA ports like Port Said, especially if the final destination lies outside the EEA, where the EU ETS may not apply at all.

Measure 4: Amendments to the FuelEU Maritime regulation

- Several stakeholders proposed extending the scope of the regulation to cover 100% of international voyages and to include smaller vessels above 400 GT, arguing this would reduce carbon leakage and broaden decarbonisation incentives.
- The upcoming expansion of the EU MRV system in 2025, which will begin collecting data on smaller vessels, was cited as a practical enabler for such an extension.
- A change from 50% to 100% emissions coverage for calls at neighboring non-EEA ports was again suggested to close existing loopholes.
- However, expanding the regulation's scope was also seen as potentially counterproductive, with risks of increased rerouting to non-EEA ports and economic or diplomatic fallout.
- Concerns were raised that smaller shipping companies may struggle to comply, especially due to their inability to average emissions across a large fleet, as larger operators can.
- The limited availability and high cost of alternative fuels were highlighted as significant barriers to broader compliance and effective decarbonisation.

Measure 5: Introduction of a Levy on Containers with a Dedicated Shipping Fund

- The proposal was viewed by some stakeholders as more transparent and less discriminatory toward EU ports, particularly those located near non-EU transshipment hubs. It was also seen as a way to address relay evasion.
- However, concerns were raised that containers themselves do not emit carbon; emissions depend on variables such as vessel efficiency, fuel type, and routing. Accurately tracking these factors would add significant complexity.
- There was uncertainty about the practical implementation of the levy, including who would be responsible for payment and collection, and how to account for the differing value of goods transported in each container.
- Stakeholders noted that the measure would not solve the core issue of EU transshipment hubs losing cargo flows between non-EU ports.
- Concerns were also raised that the levy could disproportionately affect Less-than-Container-Load (LCL) shipments, as multiple small exporters sharing one container might bear higher relative costs compared to single shippers using Full Container Load (FCL) services.
- Additional concerns included the potential for exporters to be disadvantaged and the risk of double payment when combined with the EU ETS.

Measure	Effectiveness in Reducing Leakage	Impact on Competitiveness / Trade	Feasibility and Administrative Concerns
CBAM Extension to Maritime	Limited – does not address transshipment avoidance; mainly overlaps with ETS and IMO measures	Negative – may incentivize evasive port calls; could trigger trade retaliation and WTO disputes	High complexity; hard to verify shipping emissions; risk of double regulation
EU Levy on Departing Vessels	Limited – evasive routing still possible via non-EEA ports	Negative – adds cost burden to EU ports and exporters; may cause price inflation	Destination tracking unclear; risk of double charging with ETS
Revised Transshipment Port List	Moderate – closes some loopholes if criteria are revised (e.g., 50% threshold, proximity)	Limited – may not fully resolve cost advantage of non-EEA transshipment ports	Requires clear, regularly updated criteria; political acceptance may vary
FuelEU Scope Expansion	High – includes more ship types and full voyage emissions	Mixed – may trigger diplomatic resistance; could increase rerouting from EEA ports	Challenging for small operators; clean fuel availability and cost are barriers
Container Levy with Fund	Moderate – may discourage evasive transshipment strategies	Generally positive – seen as more neutral and transparent for EU ports	Unclear how to assign emissions fairly to containers; double payment risk with ETS

Table 6.2: Summary of stakeholder feedback on five proposed policy measures to address carbon leakage in maritime transport.

6.3 Summary

Key Takeaways

- Stakeholders confirm that **carbon leakage and competitiveness risks** are emerging due to EU ETS and FuelEU Maritime, with impacts felt through rerouting, transshipment shifts, and potential modal shifts.
- **High-risk areas** include Southern Europe (e.g., Algeciras, Valencia), North-West Europe (e.g., Rotterdam, Hamburg), and Eastern Mediterranean hubs, as well as emerging competition from UK and North African ports.
- **Transshipment relocation** to non-EEA ports such as Tanger Med and Nador West Med is viewed as a likely leakage response, especially where part of the cargo is EU-bound.
- **Feedering is widely seen as economically unviable**, challenging the effectiveness of regulatory strategies aiming to deter leakage through route structures.
- **Modal shifts** from maritime to road transport (especially in Baltic and Iberian regions) may increase due to delayed ETS 2 implementation and low diesel prices in transit countries, risking both leakage and higher GHG emissions.
- **Small and medium-sized enterprises (SMEs)** face disproportionate burdens, with limited fleet flexibility to comply by assigning best-performing vessels.
- **Bunkering location shifts** and ship-to-ship (STS) transfers are not expected to become major avoidance strategies. However, FuelEU Maritime is likely to influence the development of future bunkering hubs by gradually encouraging the use of renewable fuels. Ports that invest early in renewable fuel bunkering infrastructure will likely become more attractive to shipowners over time.
- **Competitiveness loss** is attributed to cost asymmetries with non-EEA ports, uncertain regulation, slower port modernization, and operational disruptions like strikes.
- **Market shifts are already observed**, such as increased UK port calls and reduced traffic in major EEA hubs, with stakeholders noting rerouting and postponed investments.
- Stakeholders stress the need for **supportive mitigation policies**, including ETS revenue recycling, port incentives, and aligning global regulatory frameworks to maintain EU maritime competitiveness.

7 Discussion and Recommendation

This study aimed to explore the mechanisms through which shipping companies might engage in evasive routing under EU climate regulations, and to evaluate the policy effectiveness of proposed countermeasures. The discussion below integrates the quantitative insights obtained from the Panteia liner shipping model with the qualitative findings from stakeholder engagement. This chapter critically reflects on the results, examines their implications for EU policy, and provides a set of informed recommendations

7.1 How and Why Does Evasive Routing Occur?

The scenario analysis revealed that evasive routing, such as calling at nearby non-EEA transshipment hubs like Tanger Med, can significantly reduce a vessel's regulatory exposure under the FuelEU Maritime and EU ETS frameworks. For instance, when a ship calls at a non-EEA port before entering the European Economic Area (EEA), the share of emissions subject to regulation can drop from 100 percent to 50 percent. If the EEA is not the final destination, the regulatory coverage may decrease to zero. These findings provide quantitative evidence that the current 50 percent emission allocation rule creates a clear and exploitable pathway for carbon leakage. This is further illustrated in Chapter 5, Case 1, where incorporating a UK port into the rotation reduced both FuelEU Maritime and EU ETS liabilities by limiting the number of EEA-regulated voyage legs. As a result, the route incurs lower reported emissions and compliance costs compared to a similar route calling only at EEA ports.

Stakeholder interviews confirmed that this is not merely a theoretical risk but a practical concern that is already influencing strategic decisions in the maritime sector. Shipowners and port authorities reported that such routing strategies are increasingly being considered or implemented. Representatives from major ports highlighted that existing regulatory asymmetries between EU and non-EU ports are encouraging shifts in transshipment patterns, potentially undermining the competitiveness of EEA ports. This concern persists even though recent reports from the European Commission do not yet identify significant shifts in port traffic patterns (European Commission, 2025a).

Stakeholders identified cost as the primary driver behind these routing decisions. When the financial burden of compliance at EEA ports becomes too high, shipping companies are likely to seek alternative routes that allow them to reduce exposure to EU climate obligations. This was clearly demonstrated in the case study of the Maersk MECL service discussed in Chapter 5. By avoiding a call at Algeciras, an EEA port, and instead routing through non-EEA ports, the service is able to reduce its regulated emissions and lower its compliance costs. This strategic adjustment shows how even a single port call change can lead to significant savings. If this behavior proves consistently advantageous, it may be replicated by other services, reinforcing the trend of regulatory avoidance and weakening the effectiveness of EU maritime decarbonization policies

7.2 How Do Stakeholders View the Proposed Measures?

The stakeholder engagement activities described in Chapter 6, including structured interviews and a sector-wide survey, provided critical insights into how key maritime actors perceive the feasibility, fairness, and potential consequences of the proposed EU policy measures to mitigate carbon leakage. While the model-based scenarios in Chapter 5 offered quantitative confirmation of carbon leakage pathways, the stakeholder responses added important nuance about practical implementation, behavioral responses, and equity concerns.

Measure 3 (Transshipment Port Criteria Revision) received the broadest support. Stakeholders widely regarded it as a targeted and effective way to close a clearly exploitable loophole. There was general agreement that revising the 300-nautical-mile exemption and tightening the definition of transshipment ports would provide a high-impact yet minimally disruptive policy response. This support is reinforced by the findings in Case 2, discussed in subsection 5.2.3, which highlight the need for revision. Although a transshipment clause already exists to mitigate evasion risks, port avoidance on Non-EEA to Non-EEA routes can still indirectly erode the competitiveness of EEA ports.

Measure 4 (Scope Expansion of FuelEU Maritime) received mixed reactions from stakeholders. While the measure supports the broader regulatory goal of closing loopholes—particularly the exemption for feeder vessels below 5,000 GT—it also exposes structural weaknesses in the current maritime market. Smaller carriers and short-sea shipping operators voiced concerns that expanding the scope without accompanying support mechanisms could lead to disproportionate compliance burdens. These actors often lack economies of scale, access to alternative fuels, or the financial flexibility to upgrade fleets. Critically, this reflects a tension between regulatory ambition and market readiness. Although modeling results indicate that feeder services can currently be used to evade regulation, they also suggest that such services are not economically attractive under present conditions. This raises a key policy dilemma: extending the scope of FuelEU Maritime may theoretically reduce carbon leakage risks, but in practice, it could unintentionally penalize smaller operators and undermine short-sea shipping—a sector often promoted as a sustainable alternative to road transport (Pérez-Mesa et al., 2023). Any expansion of scope should therefore be accompanied by targeted support or exemptions to avoid counterproductive outcomes.

Measure 5 (Levy on Containers) was cautiously welcomed by some respondents, especially port authorities located near non-EEA hubs. They saw it as a transparent and potentially fairer approach to internalize the external costs of carbon emissions without distorting routing decisions. Yet several issues were raised: attribution of emissions remains complex in multi-leg journeys, and stakeholders expressed concern about legal accountability, potential double-charging (with ETS or FuelEU), and whether the levy would target shipping lines, freight forwarders, or cargo owners. These questions suggest that while the measure has conceptual merit, further design clarity is needed.

A similar container levy system is already in place in New Zealand, where charges vary based on vessel type and size (Maritime New Zealand, 2024). However, if a comparable scheme were introduced at EEA ports, it could add yet another layer of compliance costs on top of existing EU ETS obligations and FuelEU Maritime penalties. This may further reduce the attractiveness of EEA ports, especially if competing non-EU ports do not impose similar charges.

Measures 1 and 2 (CBAM extension and destination-based levy) were met with skepticism by stakeholders due to their administrative complexity and potential overlap with the existing EU ETS framework. Many viewed these measures as disproportionate, particularly when layered atop existing compliance mechanisms, and questioned their feasibility in practice. One stakeholder noted that such approaches ”look good on paper but invite retaliation and court challenges.”

Even if CBAM is implemented, applying it uniformly across the EU would pose significant challenges. As highlighted by Zhao and Lin (2025), variations in economic structures, industrial capacities, and development trajectories across member states and regions could lead to unequal impacts. These disparities risk creating internal tensions, potentially undermining both the legal defensibility and political acceptance of the mechanism. Furthermore, a destination-based levy would introduce additional complexity, as ports across the EU apply different methods for calculating associated costs.

The stakeholder responses to the additional scenario questions provide an important lens for interpret-ing the modeling results in Chapter 5. While the simulations focused on operational decisions like transshipment and port call adjustments, stakeholders pointed to longer-term structural risks. Chief among these is the strategic displacement of logistics activities to non-EEA ports such as Tangier Med, Nador, or Jeddah, reflecting not just evasive behavior but a reconfiguration of global shipping networks. This reinforces the model's finding that even small changes in routing can significantly reduce regulatory exposure, raising concerns about the competitiveness of EEA ports.

Stakeholders emphasized that this shift is driven not only by regulation but also by broader cost and infrastructure advantages in non-EU regions. Cheaper fuel, faster permitting, and stronger public investment make non-EEA ports attractive regardless of EU policy. Without safeguards, current measures may inadvertently accelerate this transition. Concerns also extended to modal shifts from maritime to road—especially in cost-sensitive corridors like the Baltics or Iberia—driven by delayed ETS implementation and perceived regulatory imbalance. Underlying these issues is the persistent cost gap between renewable and conventional marine fuels, which remains the most critical barrier to decarbonization efforts (Christodoulou and Cullinane, 2022). Until this gap is addressed, non-EU alternatives may continue to dominate operational decisions.

Across responses, a recurring theme emerged: the risk of losing EU strategic influence over maritime logistics. Rather than viewing leakage as a regulatory loophole, stakeholders framed it as a symptom of deeper global asymmetries and regional vulnerabilities.

7.3 Policy Recommendations

Drawing from the integrated findings of the scenario analysis and stakeholder engagement, the following policy recommendations are proposed to enhance the effectiveness, fairness, and feasibility of EU maritime decarbonisation measures.

- **Prioritize the tightening of transshipment port criteria:** Revise the current exemption rules by setting stricter distance thresholds and requiring that transshipment ports handle a substantial share of EU-destined cargo. Consider introducing targeted incentives for vessels that utilize EEA transshipment ports, particularly those competing with nearby non-EEA hubs, as these ports appear to be at greater risk of carbon leakage based on stakeholders feedback and one of the case studies.
- **Phased Expansion of FuelEU Maritime:** Begin by applying expanded regulatory coverage to high-risk routes—particularly those involving nearby non-EEA transshipment hubs—where the risk of evasion is highest. To avoid disproportionately burdening smaller carriers and short-sea operators, introduce transitional measures such as temporary exemptions or targeted financial support. This approach maintains momentum in decarbonization while ensuring fair and manageable implementation across different market segments.
- **Avoid duplicative measures**: Rather than introducing additional instruments such as CBAM or destination-based levies on top of the EU ETS, policy efforts should focus on better alignment between existing EU regulations and the upcoming IMO Net-Zero Framework. Since the IMO framework will be integrated into MARPOL—with 108 signatory states covering 97% of global merchant shipping by tonnage—harmonization would enhance legal defensibility, reduce administrative burdens for operators, and provide greater regulatory certainty for shipowners.
- **Engage stakeholders in continuous dialogue:** Close and ongoing engagement with stakeholders is essential to ensure that regulatory frameworks are both effective and practically implementable. Operational insights from port authorities, shipping lines, and industry associations can help identify regulatory loopholes, technical barriers, and unintended consequences at an early stage. For instance, the Port Authority of Valencia has raised concerns that the EU ETS could undermine the competitiveness of EU transshipment hubs, potentially diverting traffic to non-EU ports (Valenciaport, 2023). Similarly, the Malta Port Authority has warned that the combined impact of the EU ETS surcharge and rising shipping costs could threaten the viability of national maritime sectors (Redazione, 2023). With the introduction of FuelEU Maritime expected to add further compliance burdens, a structured and transparent stakeholder dialogue is necessary to align decarbonization objectives with market realities and maintain EU port competitiveness.

- **Strengthen clean fuel and power infrastructure:** The Alternative Fuels Infrastructure Regulation (AFIR) mandates the installation of OPS electricity and LNG bunkering at EU ports (Transport & Environment, 2023b), complementing FuelEU Maritime. However, there is currently no EU policy promoting the production or supply of emerging renewable fuels such as green ammonia or hydrogen. Introducing a supply or production mandate—similar to the UK's Sustainable Aviation Fuel (SAF) obligation aimed at incentivizing supply—could enhance the availability of renewable marine fuels and improve routing flexibility. This is particularly relevant given the current limited availability of such fuels (Christodoulou and Cullinane, 2022), and aligns with stakeholder feedback presented in chapter 6.
- **Introduce positive incentives for early adopters:** Encourage voluntary compliance through port fee discounts and operational incentives. For instance, the Port of Hamburg offers reduced port fees for vessels using OPS, with discounts scaled based on gross tonnage (GT). Similar schemes across EU ports could accelerate clean fuel adoption and reward proactive operators. This is particularly important given that fuel price is considered the most critical economic criterion for decision makers, as noted by Hansson et al. (2019), and therefore financial incentives can play a key role in offsetting the high costs of alternative fuels.

8 Conclusion

The maritime sector faces growing pressure to decarbonize, yet investment decisions remain challenged by uncertainty in fuel costs, regulatory developments, and technological readiness. This thesis examined how such uncertainty influences shipowners' strategic and operational behavior, with a particular focus on the implications of the FuelEU Maritime and EU ETS regulations. Chapter 4 presented the modeling methodology developed to simulate route-level compliance impacts under different scenarios. Chapter 5 applied this model to analyze how regulatory design affects route selection and cost exposure, while Chapter 6 incorporated stakeholder perspectives to ground these findings in practical considerations from industry actors. Together, these chapters offer a comprehensive view of how regulatory uncertainty shapes investment strategies in the maritime energy transition. This final chapter summarizes the main conclusions for each research subquestion and reflects on their policy and practical implications.

To what extent does the FuelEU Maritime Regulation lead to carbon leakage risks in the maritime sector, and what strategies can mitigate these risks while maintaining EU competitiveness?

This question will be addressed by answering four sub-questions as outlined below.

1. **What are the key mechanisms contributing to carbon leakage in maritime transport under the FuelEU Maritime and EU ETS regulations?**

   This thesis has examined the regulatory context of the FuelEU Maritime and EU ETS regulations to identify mechanisms through which carbon leakage may occur in maritime transport. A key finding is that certain operational and routing strategies allow ship operators to reduce their regulatory exposure without proportionally reducing actual emissions. These mechanisms have been extensively documented through scenario modeling and stakeholder insights.

   The first major mechanism is evasive routing, where vessels include port calls in nearby non-EEA countries such as Morocco, the United Kingdom, or Egypt to reduce the share of voyage legs subject to EU regulations. Another prominent mechanism is transshipment shifting, in which cargo is transferred to or from non-EEA ports using smaller vessels that are not covered by FuelEU Maritime or EU ETS. Port call optimization is also observed, where minor adjustments to service rotations, such as adding a short stop at a non-EEA port, can reduce regulatory obligations while maintaining access to EU destinations.

   Additional carbon leakage risks stem from the use of high-volume non-EEA transshipment hubs, such as Tanger Med or East Port Said. While these ports do not exempt entire voyage segments from regulation, they concentrate cargo flows just outside EU borders, potentially undermining the intent of EU policies. Another evasion mechanism involves speed adjustments—operators may reduce sailing speeds within EEA waters to limit emissions, but then increase speeds outside the EEA to maintain schedules. This shift results in higher emissions outside EU jurisdiction and can lead to underreporting of actual CO_2 output, thereby reducing the overall environmental effectiveness of the regulation.

While modal shifts to road or rail are mentioned as a possibility to reduce maritime compliance costs, their overall impact is likely limited due to infrastructure constraints and higher carbon intensity in land transport. Finally, strategic port selection based on OPS grid emission intensity allows operators to favor ports with cleaner electricity grids in order to improve GHG intensity scores without changing vessel fuel technology.

Together, these practices illustrate how regulatory loopholes and geographic flexibility enable carbon leakage in the maritime sector under current EU climate policies.

2. **How can the cost impact of the FuelEU Maritime Regulation on shipowners be assessed?**

   The assessment of the cost impact of the FuelEU Maritime Regulation on shipowners was conducted through a combination of literature analysis and model-based cost evaluation. This approach allowed for a detailed understanding of the financial implications arising from compliance with GHG-related maritime policy. The first aspect examined was the introduction of both operational and capital expenditure components. Operating expenses increase due to higher fuel prices from cleaner alternatives and electricity usage during OPS, while capital expenditures emerge from necessary retrofitting for fuel-switching capabilities or OPS installation.

   Emission-linked penalties constitute a second major factor in the cost model. These penalties are calculated based on the deviation between the actual fuel mix of a vessel and the regulatory GHG intensity thresholds. The inclusion of RFNBOs introduces further variability, as their high cost and multiplier effect in the accounting scheme significantly influence the penalty outcomes.

   The third cost element identified is the OPS-related variation between ports. Since Well-to-Tank (WtT) emissions from shore power depend on the national electricity grid's carbon intensity, the same fuel and OPS setup may result in differing compliance costs depending on the port of call. This spatial variation is captured in the modeling using port-level WtT emission factors.

   Furthermore, the cost impacts of similar regulations—such as the EU ETS—have been analyzed using cost analysis frameworks, as demonstrated in the works of Lagouvardou and Psaraftis (2022) and T. Wang et al. (2025). These frameworks quantify compliance costs under various regulatory strategies and evasive behaviors. Similarly, the newly introduced FuelEU Maritime Regulation can be assessed using comparable cost analysis methods to better understand its financial implications for shipowners.

   Finally, the interaction between regulatory design and ship operations is modeled to understand how variations in fuel mix, RFNBO blending requirements, OPS exemptions, and vessel type influence total cost burdens. This modeling provides a comprehensive picture of the financial impact of the FuelEU Maritime Regulation and highlights the importance of regulatory parameters in shaping cost outcomes for shipowners

3. **How can the Panteia Liner Shipping Model be used to assess potential carbon leakage under the FuelEU Maritime Regulation?**

   To understand how the Panteia Liner Shipping Model can be used to assess potential carbon leakage under the FuelEU Maritime Regulation, several model enhancements were implemented. The model was first expanded to simulate real-world liner operations, including total cost, fuel use, CO_2 emissions, and voyage segmentation. By assigning compliance factors to each voyage leg (EEA–EEA, EEA–non-EEA, or non-EEA–non-EEA), the model accurately isolates which portions of a service fall under EU regulatory scope. This enables targeted calculation of both FuelEU Maritime and EU ETS obligations. The FuelEU component computes Well-to-Tank and Tank-to-Wake emissions, applies GHG intensity thresholds, and determines compliance penalties or credits. In parallel, the model includes EU ETS carbon pricing on CO_2-only emissions, aligning with regulation-specific scopes. In addition, the model integrates Onshore Power Supply (OPS) use at berth, applying country-specific electricity grid emission factors and related costs. It also incorporates diverse fuel types (e.g., LNG, RFNBOs, methanol), enabling scenario testing of fuel strategies against cost and emissions targets. To simulate evasive behaviors, the model evaluates transshipment scenarios involving non-EEA hubs or smaller feeder vessels that are exempt from regulation. Sensitivity tools enable users to test how variations in speed, port selection, or carbon pricing affect route profitability and regulatory exposure. These features collectively support the model's ability to quantify carbon leakage and assess mitigation strategies under current and evolving maritime policies. It is important to note, however, that the model operates under fixed rotation patterns and does not currently simulate changes in service frequency or real-time rerouting behavior.

4. **How can carbon leakage risks on key container shipping routes to and from the EU be mitigated?**

   To identify effective strategies for mitigating carbon leakage risks on container shipping routes to and from the EU, this study combined insights from scenario analysis and stakeholder engagement. The quantitative results showed that routing adjustments—such as calling at nearby non-EEA ports like the UK or skipping EEA transshipment hubs like Algeciras—create clear incentives for shipowners to reduce their regulatory exposure under both FuelEU Maritime and the EU ETS. These behaviors allow shipowners to reduce their regulatory exposure under both FuelEU Maritime and the EU ETS. Stakeholder interviews confirmed that such strategies are already influencing route planning and investment decisions, particularly in services avoiding ports like Algeciras. Among the proposed policy responses, revising transshipment port eligibility criteria received the broadest support. Stakeholders viewed this measure as targeted, feasible, and effective in closing a known regulatory loophole. Expanding the scope of FuelEU Maritime to include smaller vessels and designing a levy on containers were considered promising but raised concerns related to fairness, complexity, and administrative burden. On the other hand, measures like extending CBAM or applying destination-based levies were met with skepticism due to their potential for legal disputes and overlap with existing frameworks. Beyond regulation, stakeholders emphasized the importance of infrastructure investment and economic incentives. They pointed out that the attractiveness of non-EEA ports is also shaped by lower fuel costs, faster permitting, and public subsidies. Therefore, policy efforts should not only aim to reduce evasive behavior but also strengthen the competitiveness of EU ports. This can be achieved by supporting OPS adoption, expanding access to renewable fuels, and introducing reward mechanisms such as port fee discounts for compliant vessels. Finally, ongoing monitoring and stakeholder consultation are essential to ensure that policies remain responsive to emerging trends and do not unintentionally shift global shipping patterns away from the EU.

8.1 Recommendation for Future Studies

Given that this thesis is part of an ongoing research project contributing to the development of maritime decarbonisation policies, several directions are recommended for future studies:

- **Incorporate Dynamic Behavioral Modeling**

  This study relied on static scenarios to explore potential responses to EU climate regulations. Future research could implement agent-based models or game-theoretic frameworks to better capture the dynamic interactions between shipping lines, ports, and regulators. This would enable analysis of how actors adapt over time in response to changing fuel availability, cost signals, or policy adjustments. As such modeling requires detailed historical and behavioral data, it is more feasible as more empirical evidence becomes available.

- **Evaluate the Effectiveness of RFNBO and OPS Adoption**

  A focused assessment of RFNBO and OPS could provide insights into the practical feasibility of decarbonisation pathways promoted under FuelEU Maritime. Future studies could analyze fuel availability, infrastructure readiness at ports, and cost competitiveness across different vessel types and routes.

- **Engage Stakeholders Using Quantitative and Participatory Methods**

  While the current study included rich qualitative input through interviews and surveys, further research could employ quantitative tools such as stated choice experiments, multi-criteria decision analysis, or Participatory Value Evaluation (PVE). These methods can elicit structured insights into trade-offs, willingness to pay, and policy preferences from a broader and more diverse set of stakeholders.

- **Conduct Port-Level Resilience Assessments**

  As the results indicated regional disparities in exposure to carbon leakage, future studies could conduct port-specific vulnerability and resilience assessments, especially for southern and eastern EEA ports. This could inform the design of tailored mitigation strategies, infrastructure investment needs, and regional compensation mechanisms under EU climate policy.

Contribution to Research

This study serves as a preliminary contribution to an ongoing research project on maritime decarbonisation and regulatory impacts in the EU shipping sector. Its main contribution lies in developing an integrated framework that combines quantitative modeling using the Panteia Liner Shipping Model with qualitative stakeholder insights to explore the mechanisms and risks of carbon leakage under the FuelEU Maritime Regulation and EU ETS.

The thesis extends the Panteia model to account for regulatory factors such as GHG intensity thresholds, OPS usage, fuel-specific emission profiles, and route-based compliance differentiation. These enhancements enable the simulation of evasive routing strategies, transshipment behavior, and fuel switching, offering an analytical basis for evaluating how shipowners may respond to climate regulation.

By incorporating feedback from industry stakeholders, the study adds practical perspectives to the scenario analysis and offers early insights into potential behavioral responses, fairness concerns, and implementation challenges associated with EU regulatory measures. While these behavioral responses are informative, they should be interpreted as indicative rather than predictive, given the static nature of the modeling. The study also examines the perceived effectiveness of proposed policy instruments aimed at closing regulatory loopholes and mitigating carbon leakage risks.

As a first-stage investigation, this research provides a foundation for more advanced modeling efforts and deeper policy evaluations in future phases of the project.

Final Thoughts

This thesis has explored how current EU maritime climate regulations, specifically FuelEU Maritime and the EU ETS, can unintentionally incentivize carbon leakage through evasive routing and transshipment strategies. By combining a tailored liner shipping model with stakeholder insights, the study sheds light on how shipping lines respond to regulatory costs and how such behavior may undermine EU decarbonization goals. Such carbon leakage not only shifts emissions geographically but also compromises the environmental integrity of EU climate policy, limiting its overall effectiveness in reducing global maritime emissions.

Although the results are based on defined assumptions and static scenarios, they provide valuable early evidence for policy makers and researchers alike. As the regulatory landscape evolves, so too will the strategies of maritime actors. Continued monitoring, stakeholder engagement, and model refinement will be essential to ensure that climate policies remain effective, equitable, and adaptive.

Ultimately, reducing emissions in the shipping sector requires not only regulation, but also collaboration, investment in clean infrastructure, and a careful understanding of the operational realities shaping global trade. This study provides a step toward that understanding, and serves as a foundation for more comprehensive analyses in the years to come.

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A

Panteia Data Requirement

A.1 Data Collection

This study requires comprehensive data to parameterize the Panteia Liner Shipping Model, both in its original form and with modifications for EU ETS and FuelEU Maritime compliance. Data are sourced from public databases, industry reports, regulatory documents, and stakeholder input and are classified as follows:

A.1.1. Ship and Service Characteristics Data

This category includes the technical and operational specifications of the vessels used in the model (see Table A.1). The data is essential to estimate fuel consumption, operational costs, and voyage characteristics.

Data Required	Description	Source
Vessel Type	Mainline vessel or feeder vessel	Shipping reports, vessel databases (e.g., Clarkson, Equasis)
Ship Capacity (TEU)	Container capacity of vessels in the study	Shipping company fleet data
Ship Speed (knots)	Different speeds used inside and outside the EEA	AIS Data, vessel specifications
Gross Tonnage (GT)	To determine EU ETS/FuelEU applicability	IMO databases, fleet data
Port Rotation & Routes	List of ports per service	Maersk network maps
Port Call Duration (hours)	Estimated time spent per port call	Port Authority Data, shipping timetables

Table A.1: Required data for ship and service characteristics

A.1.2. Fuel Consumption and Emissions Data

This data is critical to compute fuel costs and environmental impact under different regulatory scenarios (see Table A.2). The modified model also requires Well-to-Wake (WTW) emissions factors for FuelEU Maritime compliance.

A.1.3. Cost Data

Cost data is essential for evaluating the financial impact of different routing and fuel scenarios, including compliance with EU ETS and FuelEU Maritime (see Table A.3).

Data Required	Description	Source
Fuel Consumption (tons per mile/km)	Fuel consumption at different speeds	IMO MEPC reports, shipping fleet databases
Fuel Prices ($ per ton)	Bunker fuel prices for different fuels	Ship & Bunker, Argus Media
TTW CO_2 Emission Factors (gCO_2 per MJ)	Tank-to-Wake emissions for different fuels	FuelEU Maritime Annex II
WTT CO_2 Emission Factors (gCO_2 per MJ)	Well-to-tank emission for different fuels	FuelEU Maritime Annex II

Table A.2: Required data for ship fuel consumption, emissions, and pricing

Data Required	Description	Source
Bunker Fuel Costs ($ per ton)	Costs for HFO, VLSFO, LNG, methanol, ammonia	Ship & Bunker, market reports
Vessel Operating Costs ($ per day)	Crew wages, maintenance, insurance	Clarkson Shipping Intelligence
Port Handling Charges ($ per TEU)	Terminal handling fees	Port Authorities, carrier tariffs
EU ETS Carbon Price ($ per ton CO_2)	Varies annually	European Emissions Trading System (EU ETS) reports
Feeder Vessel Costs	Additional costs for feeder transshipment	Shipping company rate sheets

Table A.3: Required cost data for evaluating the financial impact of different routing and different fuel scenarios

A.1.4. Route and Speed Variation Data

This data accounts for ship sailing speed and sea distances between ports (see Table A.4).

Data Required	Description	Source
Sea Distances (km)	Distance per leg	Panteia Shipping route databases
Ship Sailing Speed (knots)	Higher or Slower speeds to reduce costs	AIS Data, historical voyages, literature research

Table A.4: Required distance and speed Data for the model

B

Panteia Model Explanation

B.1 Cost Component in the Model

The model includes a detailed cost breakdown, with each variable and cost category summarized in Table B.1. However, the analysis will focus specifically on the Fuel and Energy Costs as well as the FuelEU Maritime-related costs, since these fall within the scope of this study. It is assumed that the remaining cost components, as implemented in the original Panteia model, are accurate and reliable.

Cost Category	**Model Variable(s)**	**Paid By**
Fuel & Energy	`totalBunkerCost`, `totalAuxiliaryCost`, `OPSConsumptionCost`	Charterer (or Shipowner in spot)
Lube Oils	`totalLubeCost`	Shipowner
Port Charges	`totalPortCost`	Charterer or Line
Capital Cost	`annualCapitalCost`	Shipowner
Crew Cost	`annualCrewCost`	Shipowner
Insurance	`annualInsuranceCost`	Shipowner
Maintenance	`annualMaintenanceCost`	Shipowner
Container (Box) Cost	`annualBoxCost`	Shipowner or Line
EU ETS / FuelEU (To be integrated)	`ETS_cost`, `fuelEU_penalty`	Charterer / Line

Table B.1: Cost Category, Model Variables, and Responsible Party

B.2 Model Structure

B.2.1. Module Overview and Interactions

The model is built using multiple Python modules, each responsible for a specific function (see Table B.2).

Module	Purpose
`main.py`	Runs the model, loads services, and generates cost outputs.
`Services.py`	Defines liner shipping services, including vessel and route details.
`Schedule.py`	Computes voyage schedules, distances, and port stays.
`LinerCost.py`	Calculates the total voyage cost, including fuel, port, and operational costs.
`PortCost.py`	Stores fixed and variable port handling fees.
`VesselCost.py`	Defines vessel operational costs, including fuel prices and maintenance.

Table B.2: Description of Python Modules for Liner Shipping Cost Model

B.2.2. Model Flow

A simplified flowchart representing the interaction between the modules is provided in Figure B.1

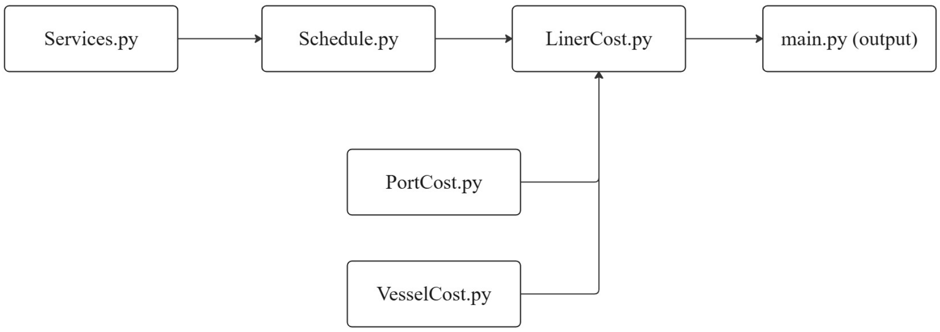

Figure B.1: Model Flow

1. `Services.py` provides liner service details (ship capacity, speed, route, etc.)
2. `Schedule.py` computes the sailing times and port call durations for the given route.
3. `LinerCost.py` estimates the total cost per voyage, using:
    - **Port fees** from `PortCost.py`.
    - **Fuel, maintenance, and crew costs** from `VesselCost.py`.
4. `main.py` runs all calculations and prints the final results.

B.3 Key Model Components & Functions

B.3.1. main.py (Main Execution Script)

This script executes the entire model workflow, performing the following steps:

1. **Loads necessary data:**
    - Reads `m_sea_net` from a CSV file, which contains the sea distances between ports.
    - Retrieves service details from `Services.py`.
2. **Calls the `liner_service()` function:**
    - Iterates over the defined services and retrieves key inputs from `Services.py`.
    - Calls `Schedule.py` to compute the **total sailing time and port call durations** for each service.
    - Calls `LinerCost.py` to compute **total voyage cost**, passing:

- **Vessel cost parameters** from `VesselCost.py`.
- **Port handling fees** from `PortCost.py`.

3. **Processes and outputs key results:**
   - Number of ships required to maintain frequency.
   - Total annual service cost.
   - Cost per TEU transported.
   - Voyage duration and total distance.

Inputs and Outputs of `main.py` is provided in Table B.3

Step	Inputs from Other Modules	Outputs
Load service data	`Services.py` (route details)	Service-specific parameters
Compute schedules	`Schedule.py` (distance, time)	Voyage duration, port calls
Compute costs	`LinerCost.py` (cost functions)	Total cost per TEU, voyage cost
Retrieve vessel cost	`VesselCost.py` (fuel, crew, maintenance)	Annual running cost per ship
Retrieve port cost	`PortCost.py` (handling fees)	Total port handling fees
Display results	Combined data from all modules	Cost breakdown, efficiency

Table B.3: Overview of Module Inputs and Outputs

B.3.2. Services.py (Liner Service Definition)

Defines the shipping routes and vessel characteristics. The service entry is provided in Table B.4.

Parameter	Description	Example
`m_serviceName`	Name of the shipping service	`"MAERSK AE1"`
`m_shipSpeedKnots`	Ship speed in knots	`14.5`
`m_shipCapacityTEU`	Vessel TEU capacity	`21,000`
`m_desiredFrequencyPerYear`	Departures per year	`52`
`m_hoursPerPortCall`	Average time spent per port	`15`
`m_portRot`	List of ports in the route	`['CN_SHA', 'NL_ONLRTM']`

Table B.4: Shipping Service Parameters

B.3.3. Schedule.py (Voyage Scheduling)

This module calculates port rotations, voyage distances, and travel times. It determines:

- Total sailing days required for a complete rotation.
- Total distance covered per route.
- Time spent per port call.

Key Functions in

`Schedule.py`

```
def build_schedule(m_portRot, m_sea_net, m_shipSpeedKnots, m_hoursPerPortCall)
```

How the schedule is built:

1. **Retrieves port rotation**

   `m_portRot`

   This is a list of ports in sequence for a liner service.
2. **Looks up sea distances**

   `m_sea_net`

   The model extracts distances between consecutive ports from a CSV file.
3. **Calculates sailing days**: Using the formula:

   ```
   saild = round((dist / 1.852) / m_shipSpeedKnots / 24.0, 2)
   ```

   - Converts **distance (km)** to **nautical miles (NM)**.
   - Divides by **ship speed (knots)** to get total travel hours.
   - Converts hours into **days**.
4. **Adds port call time**

   `m_hoursPerPortCall`

   ```
   saild += m_hoursPerPortCall / 24.0
   ```

   - Converts **port stay duration (hours)** into **days** and adds to the voyage time.
5. **Compiles schedule output**: Returns a dictionary containing:
   - **Total distance of the voyage (km)**
   - **Total sailing days**
   - **Time spent at each port**
   - **List of ports in the rotation**

B.3.4. LinerCost.py (Cost Calculation)

This module calculates **the total cost of operating a liner service**, including **fuel costs, port charges, and operational expenses**.

B.3.5. PortCost.py (Port Fees)

This module defines the **port-related costs** associated with a ship's port calls.

Key Parameters in `PortCost.py`, provided in Table B.5.

Parameter	Description	Example
`mFixedFeePerVessel`	Fixed fee per vessel per port call.	1500.0 USD
`mCapacityFeePerVesselTeu`	Fee per TEU capacity of the vessel.	2.0 USD/-TEU
`mStevedoringChargePerContainer`	Cost per container for loading/unloading operations.	80.0 USD
`mHandlingRate`	Number of containers handled per hour.	60.0 TEU/hr
`mCastOffAndMoorTime`	Additional time **required** for mooring and casting off.	3.0 hours

Table B.5: Port Cost Parameters and Their Descriptions

B.3.6. VesselCost.py (Vessel Operational Costs)

This module defines **the cost parameters** related to vessel operation, including fuel consumption, crew wages, and maintenance costs.

Key Parameters in `VesselCost.py`, provided in Table B.6.

Parameter	Description	Example
`mBunkerCostPerTonne`	Cost of bunker fuel per metric tonne.	339 USD
`mFuelGramsPerHPPerHour`	Fuel consumption per horsepower per hour (grams).	130 g/hp/hr
`mLubeLitresPerHPPerHour`	Lubricant consumption per horsepower per hour (liters).	0.0015 L/hp/hr
`mLubeLitreCost`	Cost per liter of lubricant.	0.75 USD/L
`mCrewVsTeuPower`	Crew size dependency on TEU capacity.	0.35
`mCostsPerCrewMember`	Annual cost per crew member.	70,000 USD
`mInsuranceCostsVsCapitalCosts`	Insurance **cost** as a percentage of capital costs.	1.25%
`mMaintenanceCostsVsCapitalCosts`	Maintenance **cost** as a percentage of capital costs.	2.5%

Table B.6: Vessel Cost Parameters and Their Descriptions

B.4 Cost Calculation Methodology

This section outlines the key components involved in the cost calculation, excluding regulation costs from FuelEU Maritime and EU ETS.

Service Parameters

Each service is defined by the following key parameters:

- Ship capacity in TEU ($mCapacity$)
- Sailing speed in knots ($mMaxSpeed$)
- Load factor (percentage of capacity utilized)
- Port rotation (ordered list of visited ports)

- Desired frequency of service (departures per year)
- Average port call time per port (in hours)

Propulsion Power Estimation

The propulsion power requirement P_{total} for container ships is estimated using a regression-based formula adapted from Cepowski (2019), which relates required power to vessel capacity and speed:

$$\text{Power Output} = \left(\frac{10}{9} \cdot V\right)^{\gamma_s} \cdot C^{\gamma_c} \cdot \kappa \tag{B.1}$$

where:

- Power Output is the estimated total propulsion power requirement (in kW-equivalent),
- V is the maximum vessel speed in knots,
- C is the ship capacity in TEU,
- γ_s is the power-speed exponent (typically 3 (S. Wang and Meng, 2012)), representing cubic relationship with speed,
- γ_c is the power-capacity exponent (typically 0.5), capturing scale economies in size,
- κ is a calibration coefficient derived from ship performance data.

The coefficients γ_s, γ_c, and κ are based on the Panteia Liner Shipping Model, calibrated using stakeholder input, operational data, and sector research.

Schedule and Rotations

To determine the number of rotations a vessel can perform annually, the total duration of one complete roundtrip rotation is calculated. This includes both the sailing time between ports and the time spent at each port during loading, unloading, and mooring operations. The number of rotations per year is then derived by dividing the total number of days in a year by the total duration of one rotation:

$$\text{RotationsPerYear} = \frac{365}{\text{Total Sailing Days per Rotation}} \tag{B.2}$$

This value is essential for estimating the frequency of service a single vessel can provide and for calculating the total fleet size needed to meet the desired service frequency.

To maintain a given service frequency, the total number of vessels required is calculated as:

$$\text{NumShips} = 0.5 + \frac{\text{Desired Frequency}}{\text{RotationsPerYear}} \tag{B.3}$$

The additional 0.5 accounts for operational buffers, such as maintenance, delays, or scheduling flexibility. This ensures that the actual number of ships deployed is sufficient to meet the desired number of departures per year.

Port Cost

Since each port applies different methods to calculate general port costs, the model adopts the fee structure and calculation methodology from the Port of Patreksfjörður (Port of Patreksfjörður, 2024). All rates and charges used in the model are based on this port's published tariffs.

For instance, the Port of Hamburg offers a discount of €0.02 per GT if a vessel's OPS consumption exceeds 50 MWh (Hamburg Port Authority, 2025). However, as not all ports provide such incentives, this discount is not currently included in the model. Nonetheless, it could be incorporated in future iterations to reflect more port-specific policy mechanism.

$$\text{PortCost} = \sum_{\text{ports}} (C_{\text{onetime}} \cdot \text{GT} + C_{\text{pilot}} \cdot \text{GT} + C_{\text{mooring}} + C_{\text{pier}} \cdot \text{GT} + \\ C_{\text{waste}} \cdot \text{GT} + C_{\text{disposal}} + C_{\text{stevedoring}} \cdot \text{HandledTEU}) + C_{\text{cargo}} \cdot \text{CargoTons} \tag{B.4}$$

Where:

- C_{onetime} is the one-time fee charged per GT of the vessel.
- C_{pilot} includes the pilot service fee per GT, plus a flat component.
- C_{mooring} is the mooring service fee, calculated based on number of servants and hours required.
- C_{pier} is the pier dues charged per GT.
- C_{waste} is the waste handling fee charged per GT.
- C_{disposal} is a flat waste disposal charge per vessel call.
- $C_{\text{stevedoring}}$ is the stevedoring fee charged per container move, depending on the ship's load factor and handling assumptions.
- HandledTEU is the number of containers handled per port call.
- C_{cargo} is the cargo-based tariff per ton.
- CargoTons is the estimated cargo weight, based on average tons per loaded TEU.

This formulation captures the total port-related expenses that contribute to the overall service cost.

TEU Handling and Cost per TEU

The number of TEUs handled per ship per year is given by:

$$\text{HandledTEU} = mCapacity \cdot \text{LoadFactor} \cdot \text{HandlingFactor} \tag{B.5}$$

Where the handling factor is defined as:

$$\text{HandlingFactor} = \frac{2}{N} \tag{B.6}$$

and N is the number of ports in the rotation (each port assumed to involve loading and unloading).

Annual Cost Per Ship

The total annual cost per ship is calculated based on the Panteia model, incorporating operational expenditures, fuel and energy consumption, and annualized capital costs. This approach is consistent with the cost structure outlined by Stopford (2009).

$$\begin{aligned} \text{AnnualCostPerShip} = (&\text{BunkerCost} + \text{AuxiliaryCost} + \text{LubeCost} + \text{PortCost} \\ &+ \text{OPS\_CostAnnual}) \cdot \text{RotationsPerYear} \\ &+ \text{CapitalCost} + \text{CrewCost} + \text{InsuranceCost} \\ &+ \text{MaintenanceCost} + \text{BoxCost} \end{aligned} \tag{B.7}$$

Explanation of each term:

- **BunkerCost**: Fuel cost for main engine operation during sailing.
- **AuxiliaryCost**: Calculated using auxiliary engine usage at sea and in port:

$$\text{AuxiliaryCost} = \text{FuelMix} \cdot \text{FuelPrice} \cdot (\text{AuxAtSea} \cdot \text{SailingTime} + \text{AuxAtPort} \cdot \text{PortTime}) \tag{B.8}$$

- **LubeCost**: Lubricant oil cost based on power, days at sea, and unit price:

$$\text{LubeCost} = \text{LubeRate} \cdot \text{Power} \cdot \text{SailingDays} \cdot \text{LubePrice} \tag{B.9}$$

- **PortCost**: Total port handling and call-related costs per rotation.
- **OPS_CostAnnual**: Onshore Power Supply cost while at berth:

$$\text{OPS\_CostAnnual} = \text{OPS\_EnergyCost} + \text{ConnectionFees} \tag{B.10}$$

- **CapitalCost**: Annualized capital cost of the vessel, derived from:

$$\text{CapitalCost} = (\text{HullCost} + \text{MachineryCost} - \text{Subsidy}) \cdot \left(\frac{r}{100} + \frac{1}{\text{Lifetime}}\right) \cdot \text{AdjustmentFactors} \tag{B.11}$$

- **CrewCost**: Based on number of crew required:

$$\text{CrewCost} = \text{CrewSize} \cdot \text{CostPerCrewMember} \tag{B.12}$$

- **InsuranceCost**: Proportional to the capital cost:

$$\text{InsuranceCost} = \text{InsuranceRate} \cdot \text{CapitalCost} \tag{B.13}$$

- **MaintenanceCost**: Also a function of capital value:

$$\text{MaintenanceCost} = \text{MaintenanceRate} \cdot \text{CapitalCost} \tag{B.14}$$

- **BoxCost**: Annual container cost based on TEU capacity:

$$\text{BoxCost} = \left(\text{InsurancePerTEU} + \text{MaintenancePerTEU} + \frac{r}{100} + \frac{1}{\text{Lifetime}}\right) \cdot \text{CostPerTEU} \cdot \text{Capacity} \tag{B.15}$$

Cost per TEU

The final cost per transported TEU is obtained by dividing the total annual service cost by the total number of loaded containers carried across the fleet:

$$\text{CostPerTEU} = \frac{\text{ServiceCost}}{\text{TotalLoadedTEU}} \tag{B.16}$$

The total number of loaded TEUs is derived as:

$$\text{TotalLoadedTEU} = \text{NumShips} \cdot \text{TEUHandledPerShipPerYear} \cdot (1 - \text{EmptyShare}) \tag{B.17}$$

Where:

- TEUHandledPerShipPerYear is the number of total (loaded + empty) TEUs handled by one ship in a year.
- EmptyShare $= 0.25$ represents the assumed proportion of empty containers.
- NumShips is the total number of ships assigned to the service.

This cost per TEU reflects the operational cost attributable to carrying one loaded container, excluding the cost impact of empty repositioning.

C

Determining Compliant Fuel Mass

Before calculating Well-to-Tank (WtT) and Tank-to-Wake (TtW) emissions, it is necessary to determine the **portion of the fuel mass** that contributes to FuelEU Maritime compliance. This step ensures that only the fuel used for the **covered share** of the voyage is included, based on the compliance factor and the share of renewable fuels (RFNBOs) blended **by energy**.

Let:

- M_{adj} be the total adjusted fuel mass consumed during the leg (including berth fuel if applicable), in grams.
- r be the blend ratio of RFNBO *in terms of energy*, and $(1 - r)$ the share of non-RFNBO energy.
- f_c be the compliance factor (1.0, 0.5, or 0.0) as defined in Step 4.
- LCV_{rfnbo} and LCV_{non} be the Lower Calorific Values (MJ/g) of RFNBO and non-RFNBO fuels, respectively.

Step 0: Determine Adjusted Fuel Mass

The total adjusted fuel mass per leg, M_{adj}, consists of the voyage fuel (bunker fuel) and additional fuel used at berth, depending on the port of arrival:

$$M_{\text{adj}} = \begin{cases} M_{\text{bunker}}, & \text{if destination is EEA port (OPS enforced)} \\ M_{\text{bunker}} + M_{\text{berth}}, & \text{if destination is Non-EEA port} \end{cases} \tag{C.1}$$

- M_{bunker} is mass fuel consumed during voyage, calculated using Equation 4.1.
- M_{berth} is mass fuel consumed at berth, calculated using Equation 4.3.

If the port of destination is in the EEA and the regulation year is 2030 or later, Onshore Power Supply (OPS) is assumed to replace berth fuel. In such cases, $M_{\text{berth}} = 0$ and electrical energy is accounted for separately.

Step 1: Split Fuel Mass by Energy-Based Blend

Since FuelEU Maritime requires blending to be done by energy, the split of fuel mass is derived by applying inverse LCV weighting.

First, compute the weighting factors:

$$w_{\text{rfnbo}} = \frac{r}{LCV_{\text{rfnbo}}}, \qquad w_{\text{non}} = \frac{1 - r}{LCV_{\text{non}}} \tag{C.2}$$

$$w_{\text{total}} = w_{\text{rfnbo}} + w_{\text{non}} \tag{C.3}$$

Then, compute the fuel mass for each component:

$$M_{\text{RFNBO}} = M_{\text{adj}} \cdot \frac{w_{\text{rfnbo}}}{w_{\text{total}}}, \qquad M_{\text{non-RFNBO}} = M_{\text{adj}} \cdot \frac{w_{\text{non}}}{w_{\text{total}}} \tag{C.4}$$

Step 2: Convert to Energy Content

$$E_{\text{RFNBO}} = M_{\text{RFNBO}} \cdot LCV_{\text{rfnbo}}, \qquad E_{\text{non-RFNBO}} = M_{\text{non-RFNBO}} \cdot LCV_{\text{non}} \tag{C.5}$$

$$E_{\text{total}} = E_{\text{RFNBO}} + E_{\text{non-RFNBO}} \tag{C.6}$$

Step 3: Allocate Compliant Energy and Fuel Mass

If $f_c = 1.0$: The entire voyage energy is within FuelEU scope.

$$M_{\text{RFNBO, compliant}} = M_{\text{RFNBO}}, \qquad M_{\text{non-RFNBO, compliant}} = M_{\text{non-RFNBO}} \tag{C.7}$$

If $f_c = 0.5$: Only 50% of the voyage energy counts. Apply a cap on total compliant energy.

$$E_{\text{limit}} = 0.5 \cdot E_{\text{total}} \tag{C.8}$$

$$\text{If } E_{\text{RFNBO}} \geq E_{\text{limit}}: \quad \begin{cases} E_{\text{RFNBO, compliant}} = E_{\text{limit}} \\ E_{\text{non-RFNBO, compliant}} = 0 \end{cases}$$

$$\text{Else:} \quad \begin{cases} E_{\text{RFNBO, compliant}} = E_{\text{RFNBO}} \\ E_{\text{non-RFNBO, compliant}} = \min(E_{\text{non-RFNBO}}, E_{\text{limit}} - E_{\text{RFNBO}}) \end{cases}$$

Convert compliant energy values back to mass:

$$M_{\text{RFNBO, compliant}} = \frac{E_{\text{RFNBO, compliant}}}{LCV_{\text{rfnbo}}}, \qquad M_{\text{non-RFNBO, compliant}} = \frac{E_{\text{non-RFNBO, compliant}}}{LCV_{\text{non}}} \tag{C.9}$$

If $f_c = 0$: The voyage leg is outside FuelEU scope.

$$M_{\text{RFNBO, compliant}} = 0, \qquad M_{\text{non-RFNBO, compliant}} = 0 \tag{C.10}$$

Only these compliant fuel masses ($M_{\text{RFNBO, compliant}}$ and $M_{\text{non-RFNBO, compliant}}$) are passed to the GHG intensity and emissions calculations in Equation 4.7 and Equation 4.8.

D

Scoping Interview Result

This annex presents summarized responses from stakeholder interviews conducted to understand the perceived impacts of regulatory developments (FuelEU Maritime, EU ETS, and CBAM) on the maritime sector. The interviews also aimed to explore concerns regarding carbon leakage and competitiveness of EU ports. Responses have been anonymized.

Question 1: How have regulatory developments (e.g., FuelEU Maritime, ETS, CBAM) influenced the decisions of your organization in recent years?

- **Stakeholder 1:** Actively involved in FuelEU Maritime and ETS since their inception. Not very active on CBAM, as it does not cover shipping.
- **Stakeholder 2:** Highlights port rerouting in the Mediterranean and Northern Europe towards the UK. Supports ETS.
- **Stakeholder 3:** Notes regulatory impacts since 2020. Focus on ensuring port infrastructure is used to avoid stranded investments. Highlights risks of port call reordering and transshipment rerouting.
- **Stakeholder 4:** Regulatory developments were a high priority. Their members are committed to decarbonising shipping and engaged in regulatory design processes.

Question 2: How would you define carbon leakage within the maritime industry?

- **Stakeholder 1:** Change in routing to avoid regulatory costs; also mentions modal backshift from sea to road/rail.
- **Stakeholder 2:** Loss of business for ports due to policy; rerouting that results in longer voyages.
- **Stakeholder 3:** Defined as changing port calls or transshipment routes to evade regulatory costs.
- **Stakeholder 4:** Refers to established UNFCCC/IPCC definitions: increase in GHG emissions outside regulated areas due to reductions within.

Question 3: Is there a risk of carbon leakage and competitiveness loss for EU ports?

- **Stakeholder 1:** No rerouting patterns identified yet; mentions scope extension to Tanger and Said.
- **Stakeholder 2:** Real risk exists beyond the Mediterranean.

- **Stakeholder 3:** Confirms risks of both carbon leakage and competitiveness loss.
- **Stakeholder 4:** Outside the scope of comment due to inability to represent member competitiveness.

Question 4: Where do you see geographical risks of carbon leakage or competitiveness loss?

- **Stakeholder 1:** Not applicable.
- **Stakeholder 2:** Mediterranean, Northern Europe, Middle East, parts of Africa, and UK.
- **Stakeholder 3:** South Mediterranean (Spain, Portugal, Italy), Northern Range ports (e.g., Rotterdam, Antwerp).
- **Stakeholder 4:** Cites Commission documents identifying Mediterranean nations as high-risk.

Question 5: Do you foresee operational changes such as bunkering, feeder services, or port evasion?

- **Stakeholder 1:** FuelEU may shift bunkering hubs due to lower energy content of clean fuels.
- **Stakeholder 2:** Skipped.
- **Stakeholder 3:** Predicts more reliance on hub-and-spoke models, fewer direct EU calls, and increased risk of port evasion.
- **Stakeholder 4:** If renewable fuels are not available on current trade routes, this could shift bunkering hubs and alter trade patterns.

Question 6: Relevant scenarios for carbon leakage and competitiveness risks?

- **Stakeholder 1:** Mentions complexity of customs procedures between non-EEA and EEA countries.
- **Stakeholder 2:** Will supply a list of relevant scenarios from their organization.
- **Stakeholder 3:** Emphasizes relevance of feeder and transshipment scenarios, especially in the Mediterranean.
- **Stakeholder 4:** Raised general considerations on proposed case studies.

Question 7: Policies in third countries affecting maritime routes or competitiveness?

- **Stakeholder 1:** Advocates for a global framework under the IMO.
- **Stakeholder 2:** Not applicable.
- **Stakeholder 3:** Mentions a fuel levy as a possible alternative to ETS, but doubts feasibility.
- **Stakeholder 4:** Global GHG pricing and fuel standards through IMO seen as best to avoid market distortion.

Question 8: Strategies to mitigate carbon leakage while maintaining competitiveness?

- **Stakeholder 1:** Recommends voluntary mandates on fuel suppliers and ETS revenue to subsidize clean fuel costs.
- **Stakeholder 2:** Proposes expanding the port exemption list and reviewing investments via the Global Gateway initiative.
- **Stakeholder 3:** Recommends expanding port exemption list.

- **Stakeholder 4:** Advocates for global alignment with EU ETS to reduce leakage risks.

Question 9: Availability and cost-effectiveness of alternative fuels?

- **Stakeholder 1:** Currently 4 times more expensive than conventional fuels; suggests ETS revenue could help bridge the gap.
- **Stakeholder 2:** Skipped.
- **Stakeholder 3:** Suggests consulting shipping associations for fuel insights.
- **Stakeholder 4:** Members are investing in renewable ships, but fuel supply remains limited compared to potential demand.

E

Survey & Questionnaire Result

E.1 Survey Result

Scenario 1: Relocation of Transshipment Operations

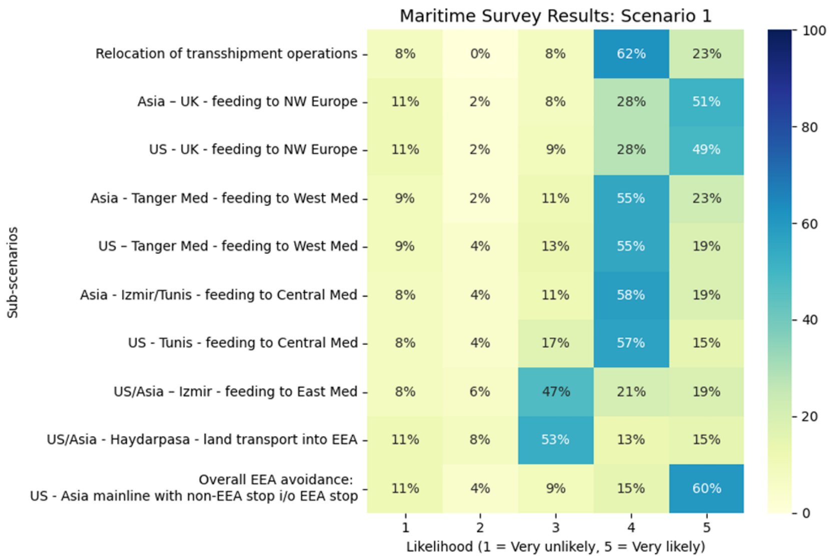

Figure E.1: Stakeholder-rated likelihood of scenario 1: relocation of transshipment operations

The overall scenario involving the relocation of transshipment activities to non-EEA ports is considered likely by many stakeholders as a response to the implementation of the EU ETS and FuelEU Maritime regulations. This shift is expected to negatively affect the competitiveness of European transshipment hubs and could have adverse economic impacts on local port economies.

Several stakeholders expressed skepticism about the effectiveness of the 300-nautical-mile rule, particularly in cases where a vessel calls at a single EEA transshipment port. In situations where only a portion of the cargo is destined for the EU and the rest for non-EU markets, operators may be incentivized to shift transshipment to third-country ports entirely.

The rerouting of Maersk's MECL service from Algeciras to Tangier Med is cited by multiple stakeholders as a potential example of this trend, with data indicating a 9.7% decline in container throughput at Algeciras Port between February 2024 and February 2025. Although Tanger Med is nearing capacity, stakeholders noted that the upcoming Nador West Med terminal—with a projected capacity of 3.5 million TEU—may help accommodate additional volumes.

Stakeholders also reported an increase in US–EEA services making intermediate stops at UK ports, with the expansion of London Gateway reinforcing the UK's attractiveness as an alternative to EEA ports. International routes that involve only a single EEA transshipment port (e.g., Non-EEA → EEA → Non-EEA) are considered especially vulnerable to rerouting.

Conversely, some stakeholders consider this scenario unlikely. One respondent emphasized that rerouting would require shipping operators to carry out business operations in additional ports and navigate complex customs procedures—for instance, goods transiting from Tunis (non-EEA) to Spain (EEA) would need to clear EU customs. They argue that such administrative burdens may deter avoidance strategies, further noting that no significant market shifts have been observed according to the DG CLIMA study.

Lastly, multiple stakeholders indicated that feedering strategies are unlikely to be economically viable in this context, as supported by the analysis in section 5.3, which shows that short-sea feeder services between European ports are not economically feasible.

Scenario 2: Evasive Port Calls

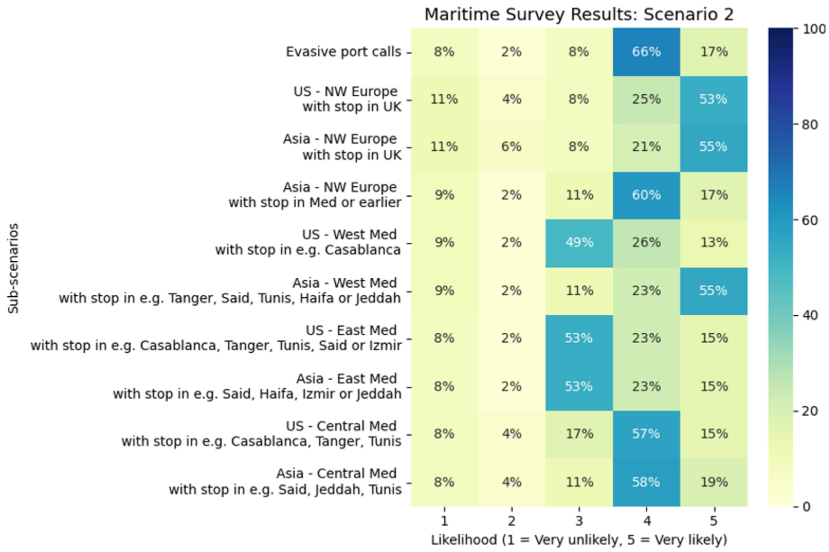

Figure E.2: Stakeholder-rated likelihood of scenario 2: evasive port calls

Similar to Scenario 1, an increase in US–EEA voyages with intermediate stops at UK ports has been observed, with MSC's Britannia service cited as an example. One stakeholder noted that EEA ports such as Antwerp, Rotterdam, and Hamburg are facing direct traffic losses, reduced revenues, weakened connectivity, and diminished attractiveness for future investment. DP World's recent £1 billion expansion of London Gateway further reinforces the appeal of UK ports as alternatives to EEA hubs.

While the UK is introducing its own emissions trading system (ETS), which may lessen the incentive for calls at UK ports, major long-distance routes—such as those between the Far East and Northern or Western Europe—can still easily accommodate an additional non-EEA port call. North African ports like Tanger Med are also seen as likely alternatives to Southern European ports.

Plans announced by major operators, including MSC and Maersk, suggest that relocations to non-EU ports may occur in 2025 and 2026, with Mediterranean services shifting to Tanger Med and UK ports. CMA CGM is also investing in Nador West Med. Additionally, Jeddah has been mentioned as a potential transshipment hub following recent disruptions in the Red Sea.

However, some stakeholders argue that certain recent route changes are driven more by geopolitical factors—such as instability in the Red Sea—rather than by EU climate legislation.

Scenario 3: Reordering of Port Calls

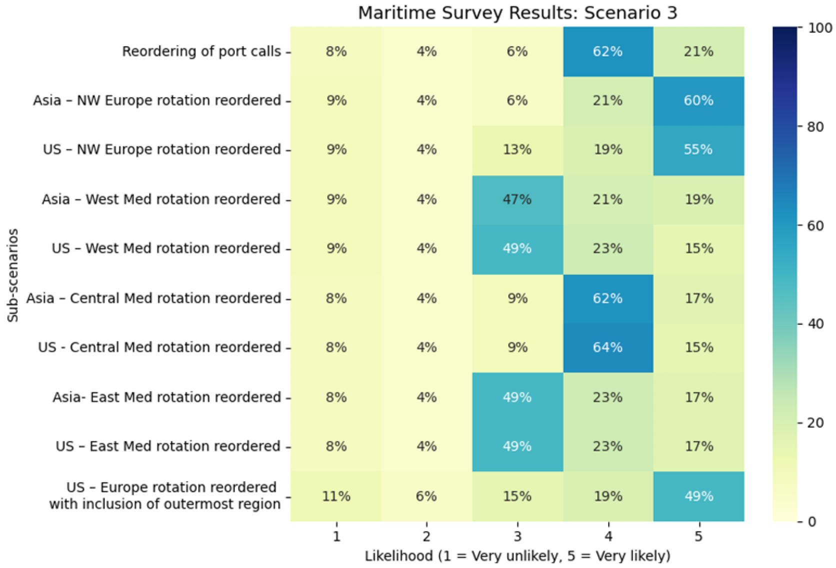

Figure E.3: Stakeholder-rated likelihood of scenario 3: reordering of port calls

Reordering port calls to ensure a stop in a non-EEA port both before entering and after exiting the EU portion of a route is described by stakeholders as a cost-effective alternative to adding additional port calls. Stakeholders indicate that routes involving ports located near major export and import destinations—such as UK ports in Northern Europe and North African ports in Southern Europe—are particularly likely to be affected by such adjustments. As in previous scenarios, stakeholders noted that major operators including MSC and Maersk are planning to relocate services to non-EU ports. However, some stakeholders continue to argue that observed changes in port call patterns may not be directly attributable to EU climate legislation, citing geopolitical developments as a significant influencing factor.

Scenario 4: Modal Shift

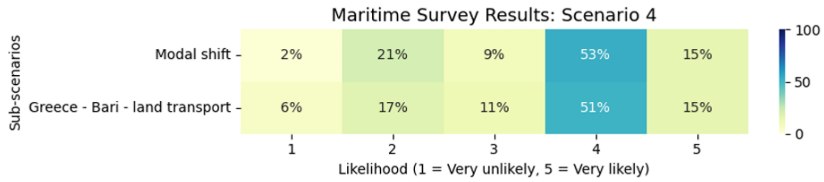

Figure E.4: Stakeholder-rated likelihood of scenario 4: modal shift

Several stakeholders consider the potential modal shift from maritime to road transport, particularly on short sea shipping (SSS) routes, as a likely response to the increased costs associated with the EU ETS and FuelEU Maritime regulations. This shift poses a dual risk: an increase in total carbon emissions due to the higher carbon intensity of road transport, and a loss of competitiveness for northern ports, such as Ancona.

The regulatory asymmetry between the maritime and land transport sectors exacerbates this issue. ETS 2, which will apply to road transport, is scheduled to begin later and may implement a different carbon price than ETS 1. This discrepancy could make road transport a more economically attractive option, leading to a potential backshift from maritime to road and rail.

One stakeholder emphasized that the low diesel prices for road transport in certain transit countries significantly contribute to the risk of modal shift. This risk is expected to increase along the Via Baltica corridor between 2025 and 2026, as maritime operators will be required to surrender EU Allowances

(EUAs) for 100% of their greenhouse gas emissions. The imbalance may persist until the implementation of EU ETS 2 in 2027, which aims to create a more level playing field. EU ETS 2 is a separate cap-and-trade scheme that covers emissions from road transport, buildings, and industrial sectors not included in the original EU ETS (Altaghlibi, 2023).

Despite this, the anticipated price level of ETS 2 is considered relatively low and unlikely to offset the cost increases in maritime transport driven by ETS 1 and FuelEU Maritime. Furthermore, the implementation of these regulations coincides with rising costs from national policies. As a result, the competitiveness of maritime transport—particularly in the Baltic Sea region—is expected to decline.

Stakeholders also anticipate shifts from SSS vessels to rail transport in regions such as Iberia and on routes connecting Türkiye and Italy. Modal shifts from Spanish car carrier routes to land-based alternatives, as well as similar changes in the North and Baltic Sea regions, are foreseen. The Finland–Germany/Poland corridor via the Via Baltica is highlighted as particularly vulnerable.

Scenario 5: Switch to Smaller Vessels

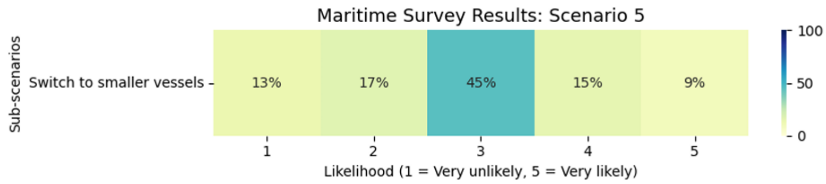

Figure E.5: Stakeholder-rated likelihood of scenario 5: switch to smaller vessels

Generally considered not a realistic scenario on a large scale due to the loss of economies of scale and significant investments in existing terminal infrastructure for larger vessels. A widespread immediate transition is improbable. Potential risk might exist in intra-EU traffic and regional markets like the Baltic Sea. North Africa - Europe and short sea shipping routes with vessels around 5,000 GT are mentioned as potentially relevant.

Scenario 6: Assigning Best Performing Vessels

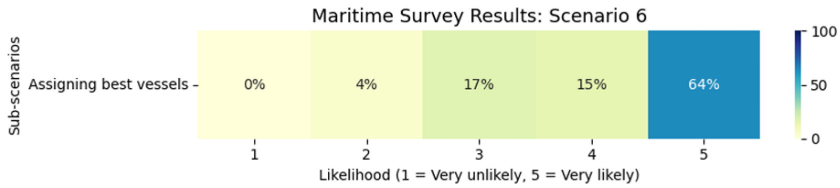

Figure E.6: Stakeholder-rated likelihood of scenario 6: assigning best performing vessels

Assigning best vessels to EU routes is generally considered a positive outcome and a legitimate compliance measure, aligning with the goals of EU climate legislation to drive decarbonisation, rather than a form of carbon leakage.

Relevant on high-frequency or strategically competitive East-West routes (e.g. Far East North Europe, US–North Europe, East Med–West Med), intra-Mediterranean services, and routes frequently transiting Sulphur Emission Control Area (SECA) zones.

This practice is already being observed. Key routes mentioned are Far East - North Europe; Far East - Med; US - Med; and US - Northern Europe.

However, it's noted that applying regional decarbonisation rules can disproportionately harm SMEs with smaller fleets.

Scenario 7: Ship-to-ship (STS) Transfer

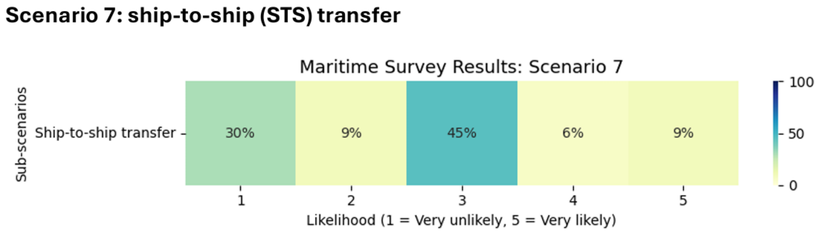

Figure E.7: Stakeholder-rated likelihood of scenario 7: ship-to-ship (STS) transfer

Ship-to-Ship (STS) transfer is not defined as a port of call under the EU ETS framework, which means that conducting an STS activity does not affect the extent to which a particular route is subject to regulatory compliance costs.

This measure is generally not regarded as a likely strategy for avoiding EU ETS obligations, particularly for most liner and short-sea services, due to substantial logistical, regulatory, and safety challenges. STS operations are more commonly associated with tanker and dry bulk trades (Maritime Mutual, 2023), making them less relevant in the context of container shipping.

While there may be increased transshipment activity in North African ports for sea-going services operating between the Far East and Northern Europe or the United States East Coast, this is not necessarily carried out through STS operations for the purpose of avoiding port calls.

Scenario 8: Shift of Bunkering to Outside of EEA

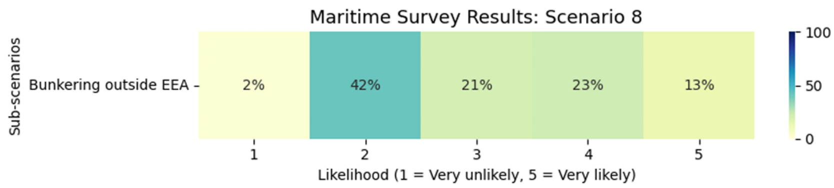

Figure E.8: Stakeholder-rated likelihood of scenario 8: shift of bunkering to outside of EEA

Shifting bunkering activities outside the European Economic Area (EEA) is generally not considered a form of carbon evasion, as the voyages themselves remain subject to EU ETS and FuelEU Maritime regulations. Bunkering locations are primarily influenced by factors such as fuel prices and national tax policies.

FuelEU Maritime is expected to shape the development of bunkering hubs both within and beyond the EEA, particularly due to the additional fuel requirements associated with the use of lower energy density alternative fuels. Proposed bunkering routes include those involving ports in Singapore, Hong Kong, the United Arab Emirates, and potentially the Suez Canal region. Existing non-EU ports such as Tanger Med and Gibraltar already serve as key bunkering hubs, with Mediterranean routes also playing a significant role.

E.2 Additional Questions on Scenarios

The survey included additional questions regarding the proposed scenarios. The responses to these questions are summarized below:

Q1: "Apart from the eight presented scenarios, are there other scenarios you think will be relevant?"

- The stakeholders highlighted the potential displacement of key European logistics hubs,
- especially transshipment ports, to non-EU territories due to decreased competitiveness.

- This could lead to a loss of EU control over critical logistics nodes, impacting supply chain
- security and geopolitical stability.
- The use of non-EU maintenance and lay-up ports was mentioned, potentially resulting in a loss of circular economy opportunities within the EU.
- One stakeholder raised that the 8 scenarios converge into a global scenario involving a loss of control over logistics chains due to business leakage and the loss of direct connections to production centres.
- A decrease in demand for ammonia and methanol bunkering within the EU due to a potential switch to smaller vessels was also noted.

Q2: "Do you consider any additional maritime routes are particularly vulnerable to carbon leakage and loss of competitiveness due to the aforementioned legislation?"

- Routes involving ports in the Canary Islands, Algeciras, Valencia, and Barcelona are considered quite affected by ETS.
- Risks are especially present in North-West Europe (compared to the UK) and the Mediterranean (facing competition from non-EEA Mediterranean ports).
- Key affected routes include those from the Far East to Europe (North and Med) and from the US to Europe (North and Med).
- Routes from South Africa and West Africa to Europe and vice versa.
- Routes using the Hamburg-Le Havre range as a transition point to the Baltic are vulnerable.

Q3: "If possible, please list specific routes/rotations where legislation could have the greatest impact on operational costs, competitiveness, or fuel choice."

- Routes with existing transshipment, such as those in the Baltics.
- Intra-Mediterranean services.
- US or Asia-Europe services via Mediterranean or North European hubs.
- Routes frequently transiting SECA (Sulphur Emission Control Area) zones.
- Far East - East Med - Intra Med (East Med-Adriatic).
- Routes from US to Far East Asia that previously stopped in EEA ports in the West Med (Algeciras, Valencia, and Barcelona) but no longer do.
- Route using the Hamburg Le Havre range as a transition point for going to the Baltic.

Q4: "For which types of vessels do you consider that a risk of carbon leakage and loss of competitiveness may exist as a result of the aforementioned legislation? If any, please indicate the type(s) of vessel likely concerned as well as possible scenarios."

- Ro-Ro/Ro-Pax vessels, particularly due to potential modal shifts towards road transport.
- Containerships engaged in transshipment operations, as mainline operators might reroute
- through non-EU hubs.
- Vessels of older age (20-25 years).
- Short sea vessels (loss of competitiveness).
- Bigger container vessels and ships operating in tramp regime (risk of carbon leakage).
- All vessels below 5000 GT.
- Offshore vessels due to the current "port of call" definition being unsuitable for the offshore sector, leading to EU contractors facing 100% ETS costs for projects outside EU waters while non-EU contractors may face 0%.

- Potentially more impact on tanker and bulker vessels, less on container vessels (according to one stakeholder).

Q5: "Have you noticed any market shifts or preferences towards non-EEA routes or ports/hubs? Please provide examples, ship type and data, if available."

- An increase in services towards the UK and redesigning of service schedules are observed. The first port of call is shifting to UK ports.
- Examples include Maersk's MECL route (USA to India) no longer calling at Algeciras Port from December 2024 and MSC's Britannia service.
- A shift of transshipment business to North African ports is occurring and is expected to continue with new facilities like Damietta II, Abu Qir and Nador becoming operational, other investments in terminals in these areas being announced and investments in the EU being postponed.
- London Gateway in the UK is expanding capacity and becoming a primary hub.
- There's a possible scenario for transshipment in Jeddah and Egypt post-Red Sea crisis.

Q6: "Which EEA ports/hubs are most (if at all) vulnerable to carbon leakage and loss of competitiveness due to the aforementioned legislation?"

- Main Southern European port hubs (Algeciras, Valencia, Sines and Barcelona).
- Ports involved in transshipment to non-EU hubs for non-EU end destinations.
- North West European ports.
- Ports in the Eastern Mediterranean and Malta, especially considering the Red Sea crisis (e.g. Malta Freeport, Piraeus, Gioia Tauro).

Q7: "To what extent (if at all) are passengers/consumers expected to be impacted by carbon leakage related to shipping?"

- Consumers are already paying EU ETS costs through ETS surcharges on freight rates.
- There are increased risks of some EU ports experiencing a decrease in traffic due to the loss of direct connections, potentially causing operational difficulties for inland logistic and ultimately raising transport costs.
- Consumers might end up still paying ETS and BAF surcharges without environmental benefits if carbon leakage occurs.
- One stakeholder anticipates a potential inflation increase.
- One stakeholder suggests that greater consumer awareness might lead to a preference for solutions with fewer emissions.

E.3 Additional Questions on Loss of Competitiveness

The survey additionally asked stakeholders to define loss of competitiveness, and elaborate on the competitiveness of European ports. A summary of the responses to these questions is included below:

Q1: "How would you define loss of competitiveness in the EEA maritime transport sector?"

In short, stakeholders defined loss of competitiveness in the EEA maritime transport sector as a decline in the sector's ability to compete effectively. This is primarily due to higher operating costs and regulatory burdens imposed by EU decarbonisation policies like the EU ETS and FuelEU Maritime, which disadvantage EEA operators compared to non-EEA counterparts. This can lead to diversion of cargo and passenger traffic to non-EEA ports and transport modes, reduced profitability and investment, and ultimately weaken the strategic position of EU maritime transport.

Q2: "Do you foresee an impact on the competitiveness of the EEA maritime market due to decarbonisation policies (e.g. shift in passenger or freight demand due an increase in costs)? Please provide examples or data, if available."

The stakeholders generally do foresee a negative impact on the competitiveness of the EEA maritime market due to decarbonisation policies like the EU ETS and FuelEU Maritime, leading to a potential shift in passenger or freight demand because of increased costs. Examples and data provided by stakeholders in their responses to this question are summarized below:

- Past small increases in costs led to more near-shoring, affecting ton-miles more than cargo transported.
- Risk of declining service quality and frequency for ferry services to islands.
- Potential modal shift from maritime to road transport on short sea shipping routes due to cost advantages of road transport, especially before ETS2 for road transport is fully implemented.
- A 5000 GRT ship might face approximately 12000 EUR in extra costs for a 3-day EU voyage.
- Potential loss of traffic for EEA ports investing in alternative fuel infrastructure if shipping lines reroute.
- Cost differentials due to ETS/FuelEU compliance can make non-EEA ports significantly cheaper.
- Lower employment costs and environmental standards in non-EEA regions can also drive shifts.

Q3: "Do you foresee an impact on the competitiveness of the EEA maritime market from factors other than EU decarbonisation policies (e.g. different levels of automation in ports, port modernisation, labour costs)?."

Stakeholders generally do expect other factors besides EU decarbonisation policies to impact the competitiveness of the EEA maritime market.

- Unequal access to public funding, differing labour and energy costs, lack of automation in ports and the pace of infrastructure modernisation all play a role.
- Trade wars, the Red Sea crisis, lower employment costs in third countries, and generally lower environmental standards outside the EU are significant factors.
- Port investments are being relocated to African ports (Tanger, Nador, Turkish ports) and other non-EEA locations. The lack of adequate port infrastructure for sustainable fuels in the EEA compared to potential developments elsewhere can be a disadvantage.
- Operational disruptions such as repeated dockers' strikes can divert shipping companies away from EEA ports.
- The insecurity relating to the implementation of legislation and increasing operating costs in general affect competitiveness.
- Proximity to production centres and overall environmental costs influence shipping choices.

Q4: "What are the main drivers that could motivate a change in shipping choices (i.e. triggering a shift in demand away for EEA port calls) and lead to loss of competitiveness, if any?"

The main drivers for changes in shipping choices that could lead to a shift away from EEA port calls and loss of competitiveness are primarily related to cost.

- Cost-related factors (compliance, shipping, operating, environmental, employment,transport, incentives)
- Proximity of competing non-EEA ports with sufficient capacity and facilities and lower overall cost.
- Insecurity regarding the implementation of legislation.
- Operational disruptions such as dockers' strikes in EEA ports.
- Strategic repositioning of services by shipping lines to non-EEA hubs to avoid EU compliance costs.

- Availability of cheaper or more flexible alternative fuels in non-EEA ports.
- Transit time optimisation and schedule reliability, especially if EEA ports face congestion or higher regulatory burdens.
- Insufficient port infrastructure, including hinterland connections.
- Geopolitical dynamics.
- Announcements of planned capacity expansions and enhanced service levels at several non-EEA ports.

F
FuelEU Maritime Calculation Flowchart

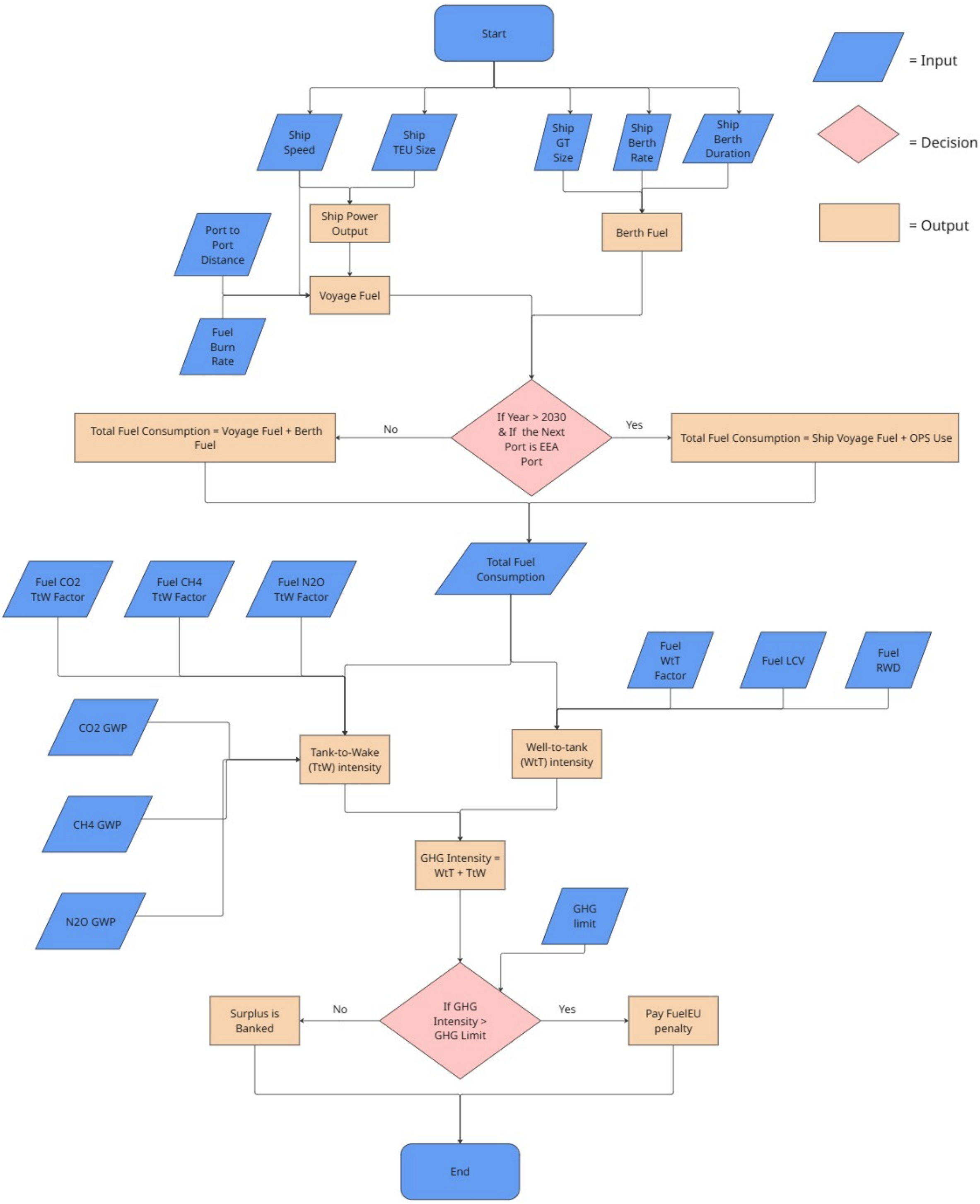

Figure F.1: Flowchart of FuelEU Maritime model calculations

G

Scientific Paper

Carbon Leakage in Maritime Transport: Cost Analysis and Mitigation Strategies under FuelEU Maritime

Ahmad Nabil Maulana
Delft University of Technology

July 7, 2025

***Abstract*—The introduction of FuelEU Maritime and the extension of the EU Emissions Trading System (EU ETS) to maritime shipping mark a significant step toward decarbonizing the sector. However, these regulations may also create unintended consequences, such as cost-driven rerouting and carbon leakage to non-EEA ports. This study investigates the compliance costs and behavioral responses of liner shipping operators through route-based case studies and expert stakeholder interviews. Results indicate that current regulatory designs can incentivize strategic evasive behavior—such as avoiding EEA ports or shifting transshipment hubs—to minimize exposure to EU climate obligations. These strategies risk undermining climate goals and affecting the competitiveness of certain EU ports. To support effective implementation, the study recommends policy measures focused on tightening transshipment rules, improving fuel infrastructure, and aligning EU actions with international frameworks such as the IMO Net-Zero Strategy.**

***Index Terms*—FuelEU Maritime, EU ETS, Carbon Leakage, Liner Shipping, Maritime Policy, Port Competitiveness.**

I Introduction

Maritime transport is the backbone of global trade, responsible for handling nearly 80% of global goods by volume (World Bank Group, 2023). While it plays a vital role in sustaining economic development, the sector is also a growing source of greenhouse gas (GHG) emissions. Shipping contributes approximately 2.9% of global carbon dioxide (CO_2) emissions—a share that is expected to rise in the absence of decisive climate action (European Commission, 2021b).

In response to this challenge, the European Union (EU) has implemented ambitious regulatory measures under the Fit for 55 package, aiming to reduce GHG emissions by at least 55% by 2030 compared to 1990 levels (European Council, 2025). Two major instruments targeting the maritime sector are the EU Emissions Trading System (EU ETS), extended to maritime transport in 2024, and the FuelEU Maritime Regulation, which enters into force in 2025. The EU ETS introduces a carbon price by requiring shipowners to surrender allowances for a share of their emissions, while the FuelEU Maritime Regulation imposes GHG intensity reduction targets on onboard energy use and mandates Onshore Power Supply (OPS) for large vessels at EU ports (European Commission, 2023).

These policies are intended to support the maritime energy transition and promote the uptake of cleaner fuels and technologies. However, they also raise concerns about increased compliance costs. Alternative fuels and OPS infrastructure are typically more expensive than conventional marine fuels and onboard generators, which may impact the cost competitiveness of shipping routes and port operations. As a result, shipping companies may seek to minimize their regulatory exposure through operational strategies such as rerouting via non-EU transshipment hubs or bypassing EU ports entirely.

While these evasive responses are not illegal, they risk undermining the effectiveness of climate policies by shifting emissions geographically rather than reducing them globally. This phenomenon—known as carbon leakage—has been studied in other industrial sectors but remains underexplored in maritime transport (Intergovernmental Panel on Climate Change, 2007).

Although several studies have assessed the economic and emissions impacts of the EU ETS and broader Fit for 55 measures (S. Wang et al., 2021; Faber, Leestemaker, et al., 2022; Berg et al., 2022), fewer have focused specifically on behavioral responses to the FuelEU Maritime Regulation. For example, models developed by Springer (2023) examine fuel consumption trends but do not capture rerouting behaviors. Likewise, techno-economic assessments such as CE Delft (2022) investigate emissions reduction technologies without addressing potential leakage caused by route adjustments.

Recent policy monitoring has not found conclusive evidence of carbon leakage. The European Commission's implementation report on the maritime EU ETS found no major transshipment shifts or strategic port avoidance during its initial phase. Instead, routing changes observed in 2024 were largely attributed to the Red Sea crisis, which disrupted major shipping lanes and triggered emergency rerouting (Bedoya-Maya et al., 2025). Nevertheless, the report highlights the need for ongoing monitoring, especially with FuelEU Maritime taking effect in 2025 (European Commission, 2025b).

In light of these regulatory developments and uncertainties, this paper aims to investigate whether the FuelEU Maritime Regulation could unintentionally incentivize evasive routing or transshipment relocation, potentially leading to carbon leakage. Using Panteia's Liner Shipping Model, several operational scenarios are simulated—such as the use of non-EU hubs like Tanger Med or Port Said—and their impacts on fuel consumption, emissions, and regulatory cost exposure are assessed. In doing so, this study contributes to the emerging literature on carbon leakage in maritime shipping and provides evidence to inform future regulatory design and mitigation strategies.

A. Research Scoping

This study focuses on the container shipping segment as the primary object of analysis, excluding other vessel types such as bulk carriers, oil tankers, and cruise ships. The decision to narrow the scope reflects both methodological practicality and sectoral relevance: container shipping plays a central role in global trade and exhibits high sensitivity to regulatory cost changes. Although it accounts for roughly 16% of total maritime cargo volume, the container sector represents over half of the total cargo value transported and has seen substantial growth in recent decades—from 0.1 billion tons in 1980 to 1.85 billion tons in 2020 (B. Lu et al., 2023). This growth is coupled with increased operational intensity, longer voyages, and higher fuel consumption, making container shipping a key contributor to maritime GHG emissions (Faber, Hanayama, et al., 2020).

In particular, container shipping is characterized by frequent transshipment operations, which are less prevalent in other segments (Lagouvardou and Psaraftis, 2022). This makes it a suitable case for assessing how routing adjustments—such as hub relocation or port avoidance—might contribute to regulatory evasion and carbon leakage.

The analysis concentrates on vessels with a gross tonnage (GT) of 5,000 or more, consistent with the compliance thresholds defined by the FuelEU Maritime Regulation and the EU ETS. These thresholds establish the regulatory boundaries for onboard energy use and emissions reporting in the EU. However, smaller feeder vessels—often below the 5,000 GT threshold—are included due to their critical role in transshipment chains and indirect exposure to regulatory effects. Although not directly regulated, feeder vessels interact closely with mainliners and thus shape the feasibility and cost-effectiveness of evasive routing strategies.

This dual-level focus allows for a more realistic assessment of compliance behavior and routing decisions. The modeling approach remains cost-based and data-sensitive, constrained by the availability of fuel prices, emissions data, and port cost inputs. These constraints may limit generalizability but help ensure the model reflects operational realities.

II Methodology

This study employed a multi-method approach, combining a literature review, quantitative model-based case study analysis, and qualitative expert interviews. The literature review established the theoretical and regulatory context, while the case studies—simulated using Panteia's Liner Shipping Model—enabled a quantitative assessment of fuel usage, emissions, and compliance costs under various routing scenarios. Expert interviews with stakeholders from the maritime and port sectors complemented the analysis by providing practical insights into behavioral responses, regulatory impacts, and feasibility of proposed mitigation strategies.

A. Literature Review

To support the analysis of carbon leakage risks and cost impacts under the FuelEU Maritime Regulation, this study conducted a targeted literature review of both academic and policy sources. Searches were performed using academic databases such as Elsevier and Google Scholar, with keywords including carbon leakage, maritime transport, shipping evasion, and FuelEU Maritime Regulation. Key studies such as Lagouvardou and Psaraftis (2022) and Defour and Afonso (2020) served as anchor points for snowballing to identify additional relevant publications.

The review focuses on three main themes:

1. The concept of carbon leakage in the context of maritime transport;
2. Economic and operational responses to climate regulations—particularly FuelEU Maritime and the EU ETS;
3. Emerging insights on the feasibility of mitigation strategies and regulatory design improvements.

Given the recent adoption of FuelEU Maritime, the review also integrates up-to-date policy documents, implementation reports, and stakeholder position papers to capture early signals of behavioral shifts in the industry. These insights serve as the foundation for the scenario development and modeling analysis conducted in this study.

B. Panteia Liner Shipping Model

To evaluate the risk of carbon leakage and the cost impacts of the FuelEU Maritime Regulation, this study employs the Panteia Liner Shipping Model—a Python-based simulation framework that replicates real-world container shipping operations. The model integrates key operational parameters such as vessel speed, fuel consumption, sailing frequency, and port handling costs, making it suitable for analyzing regulatory exposure and rerouting strategies.

The model has been extended to incorporate FuelEU Maritime and EU ETS compliance logic, with the following key capabilities:

- Voyage segmentation based on port locations (EEA–EEA, EEA–non-EEA, non-EEA–non-EEA) to allocate regulatory obligations with precision.
- GHG emissions estimation, using fuel consumption data to calculate both well-to-tank (WtT) and tank-to-wake (TtW) emissions.
- Scenario simulation of avoidance strategies, including the use of non-EEA transshipment hubs or sub-5,000 GT vessels exempt from FuelEU Maritime.

The model generates detailed outputs such as:

- Total voyage costs (fuel, crew, maintenance, and port handling).
- Annual operating expenditure (OPEX) and cost per TEU.
- Fuel use per voyage and year, serving as the basis for emission calculations.
- Transit time and rotation duration, relevant for service planning.

By simulating multiple compliance and avoidance scenarios, the model enables a structured comparison of economic and environmental trade-offs. This approach provides actionable insights into how current regulatory design may incentivize evasive routing behaviors, and serves as an early indicator of the potential effects of the FuelEU Maritime Regulation on shipping operations.

C. Stakeholder Engagement

To complement the model-based analysis, qualitative insights were integrated using stakeholder engagement conducted independently by Panteia. These consultations targeted key maritime actors within the EEA, including shipping companies, port authorities, regulators, environmental NGOs, and academic experts.

The engagement process consisted of preliminary scoping interviews, a structured survey questionnaire, targeted follow-up interviews, and multi-stakeholder workshops. While the author did not directly conduct these activities, anonymized summaries and outcomes were shared and reviewed as secondary input to contextualize the modeling results and support the policy discussion.

Stakeholder insights served three key purposes:

1. To interpret behavioral responses to FuelEU Maritime and EU ETS in practice, such as rerouting, bunkering, or transshipment changes.
2. To enrich policy recommendations by identifying operational, financial, and administrative concerns voiced by stakeholders.
3. To triangulate model outcomes with real-world views, validating findings and expos-

ing potential blind spots.

Due to confidentiality agreements, individual responses cannot be disclosed. However, aggregated findings were used to substantiate the impact assessment and inform scenario selection.

III Literature Review

A. Carbon Leakage in Maritime Transport

Carbon leakage occurs when climate policy costs incentivize businesses to shift operations to jurisdictions with less stringent regulations, resulting in a geographic displacement rather than an absolute reduction in emissions (European Commission, 2021a; Felbermayr and Peterson, 2020). In the maritime sector, carbon leakage can take the form of evasive routing, transshipment relocation, or shifts in modal transport (Lagouvardou and Psaraftis, 2022; Peng et al., 2024). For instance, routing cargo through non-EU transshipment hubs such as Durban or Tanger Med can reduce regulatory exposure under the EU ETS and FuelEU Maritime frameworks.

The risk is particularly relevant for the maritime sector due to its global operational flexibility and cost sensitivity. When compliance costs surpass certain thresholds—e.g., a 5% increase in gross value added with over 10% trade intensity—the sector may be classified as at risk (European Commission, 2021a). Historical studies, including those on the Kyoto Protocol, confirm that emissions reductions in regulated areas are often offset by increases in imports from less-regulated regions (Grunewald and Martinez-Zarzoso, 2016).

B. Modeling Carbon Leakage: Approaches and Gaps

The literature on carbon leakage in maritime transport employs a range of modeling techniques, including cost-benefit analyses, econometric models, optimization frameworks, and scenario-based simulations. Each offers valuable insights, but none fully captures the complexity of shipowners' operational responses to recent EU climate regulations—particularly under the newly implemented FuelEU Maritime Regulation.

Lagouvardou and Psaraftis (2022) used cost-benefit analysis to show that when carbon prices fall below €25 per ton, it becomes financially attractive for shipping lines to shift port calls to nearby non-EEA hubs. Other studies, such as Vierth et al. (2024) and Faber, Leestemaker, et al. (2022), suggest that evasive behavior is unlikely to be widespread, although these conclusions are based on regulatory contexts that predate critical updates—such as the revision of the EU ETS transshipment clause.

Scenario-based approaches are increasingly used to assess behavioral responses in the absence of historical data. However, most studies do not explicitly model operational avoidance strategies. For instance, while Springer (2023) considers the interaction between the EU ETS and FuelEU Maritime, the study does not examine how these policies might influence route selection, transshipment patterns, or port calls. Similarly, optimization-based models such as those by T. Wang et al. (2025) and Trosvik and Brynolf (2024) evaluate compliance strategies under carbon pricing schemes but often abstract away from real-world operational choices, such as evasive routing, use of exempt feeder vessels, or changes in berthing practices.

C. Evasive Routing and Transshipment Strategies

Cost-driven operational adjustments such as rerouting or transshipment relocation are identified as key mechanisms behind carbon leakage. Evasive routing often involves an intermediate stop at a non-EEA port (e.g., Morocco) to reduce regulatory exposure for the preceding voyage segment (Defour and Afonso, 2020). Though the EU ETS excludes some transshipment ports from counting as full port calls, studies show these exemptions may not be sufficient to prevent evasion (Peng et al., 2024).

Transshipment strategies, such as replacing an EEA hub with a nearby non-EEA alternative, are also effective at avoiding regulatory costs. For example, substituting Piraeus (Greece) with Izmir (Turkey) reduces ETS-covered emissions but increases total emissions (Lagouvardou and Psaraftis, 2022). These cost-minimizing decisions threaten the environmental integrity of the EU's decarbonization measures.

D. FuelEU Maritime Regulation and Policy Interactions

FuelEU Maritime introduces progressively stricter GHG intensity limits for shipboard energy use, starting with a 2% reduction in 2025 and reaching 80% by 2050 (European Commission, 2023). It works alongside the EU ETS and the MRV Regulation to create a multilayered compliance framework. However, its effectiveness depends on shipowners' willingness to invest in low-carbon fuels and Onshore Power Supply (OPS), which often carry higher costs and infrastructure requirements (Rojon et al., 2021).

The combined cost pressures from carbon pricing and energy intensity thresholds can incentivize evasion strategies. Moreover, port competitiveness may be affected as shippers seek to minimize exposure to regulatory burdens (Halim et al., 2019).

E. Global Context and Future Regulation

The upcoming IMO Net-Zero Framework will introduce global GHG intensity targets and market-based measures starting in 2027. While similar to FuelEU Maritime in design, it differs by offering financial incentives for zero-emission fuels and omitting OPS mandates (International Maritime Organization, 2025). The interaction between these frameworks—regional vs. global—raises questions about overlapping compliance and enforcement, especially for ships calling at both EU and non-EU ports.

IV Panteia Liner Shipping Model

To enable policy-oriented analysis, the model has been extended to incorporate regulatory mechanisms under the FuelEU Maritime Regulation and the EU Emissions Trading System (EU ETS). Key modifications include:

- Inclusion of FuelEU Maritime GHG intensity compliance, accounting for fuel- and electricity-based energy use per voyage leg;
- Integration of OPS (Onshore Power Supply) and berth emissions;
- Modeling of evasive routing and feeder vessel strategies, especially those exploiting exemptions for sub-5000 GT ships;
- Calculation of both Well-to-Tank (WtT) and Tank-to-Wake (TtW) emissions and intensity metrics;
- Estimation of FuelEU and ETS-related penalties and costs under different routing and fuel scenarios.

This extended framework allows for a scenario-based assessment of carbon leakage risks, regulatory cost burdens, and mitigation strategies. The model flow is shown in Figure G.1, and the function of each module is explained in Table G.1.

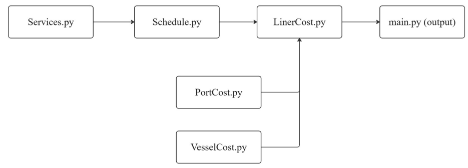

Figure G.1: Model Flow

Module	Purpose
`main.py`	Runs the model, loads services, and generates cost outputs.
`Services.py`	Defines liner shipping services, including vessel and route details.
`Schedule.py`	Computes voyage schedules, distances, and port stays.
`LinerCost.py`	Calculates the total voyage cost, including fuel, port, and operational costs.
`PortCost.py`	Stores fixed and variable port handling fees.
`VesselCost.py`	Defines vessel operational costs, including fuel prices and maintenance.

Table G.1: Description of Python Modules for Liner Shipping Cost Model

A. FuelEU Maritime Regulation Integration

Compliance with FuelEU Maritime is modeled in eight steps:

1. Voyage Leg Classification: Ports and legs are classified as EEA or non-EEA to assign compliance factors (1.0 for EEA–EEA, 0.5 for mixed, 0.0 for non-EEA–non-EEA).
2. Fuel Consumption Allocation: Fuel is allocated per leg based on distance, power output, fuel properties, and vessel load, ensuring correct application of regulatory boundaries.
3. OPS Consumption at Berth: In EEA ports, fuel-based auxiliary power is replaced with OPS electricity, adjusted for efficiency gains and linked to country-specific emission factors and energy prices.
4. Compliance Factor Application: Determines the share of voyage energy subject to GHG intensity limits.

5. WtT Emission Calculation: Includes upstream emissions from fuels and OPS electricity, weighted by the Renewable Energy Directive (RED II) reward factors.
6. TtW Emission Calculation: Combustion and slip emissions (especially relevant for LNG) are calculated using RED II global warming potentials and fuel-specific emission factors.
7. GHG Intensity Determination: The sum of WtT and TtW emissions is divided by total compliant energy to derive the voyage's regulatory GHG intensity.
8. Compliance Balance and Penalty: If GHG intensity exceeds the regulatory threshold, a penalty is calculated based on the excess emissions and a fixed rate per energy unit.

V Scenario Analysis & Case Studies

A. Fuel-Based GHG Intensity Comparison

Before analyzing routing scenarios, it is essential to establish a baseline of fuel-specific greenhouse gas (GHG) intensities. This provides context for why certain fuels may trigger higher compliance costs under FuelEU Maritime and influence ship routing decisions.

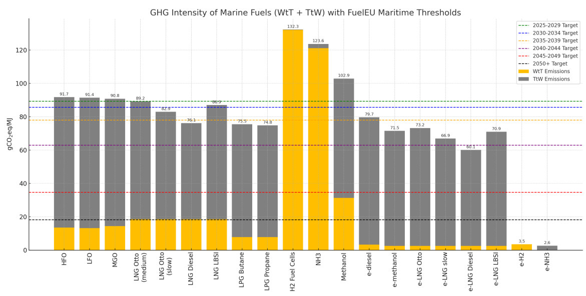

Figure G.2: GHG intensity of marine fuels relative to FuelEU Maritime thresholds.

Figure G.2 shows the total GHG intensity (gCO_{2eq}/MJ) of commonly used marine fuels, combining Well-to-Tank (WtT) and Tank-to-Wake (TtW) emissions as defined in Equation 4.7 and Equation 4.8. These values do not account for regulatory incentives, such as the RFNBO reward factor.

The chart enables preliminary screening of fuel options. Conventional fuels like HFO and MGO already exceed the 2025 FuelEU Maritime limit, meaning compliance would require blending or substitution with cleaner alternatives such as e-LNG, e-methanol, or biofuels.

Note that the chart assumes exclusive use of a single fuel and does not reflect route-specific switching or OPS usage. Additionally, it omits the RWD incentive that temporarily reduces RFNBO intensities between 2025 and 2033. Because WtT intensities are based on current production pathways, comparisons with future GHG limits (e.g., 2040, 2050) may overstate the compliance gap, as fuel supply chains are expected to decarbonize over time.

B. Case Study 1: Case Study 1: Far East Asia - (UK) - Northwest (NW) Europe

This case study examines the MSC Britannia service, a deep-sea container route connecting Far East Asia with Northwest Europe—one of the busiest trade corridors in global liner shipping. This particular service is of interest due to its strategic inclusion of a port call in the United Kingdom, a non-EEA country. As FuelEU Maritime and EU ETS regulations apply only to voyages involving EEA ports, the presence of a non-EEA intermediate stop introduces the potential for carbon leakage.

By inserting a UK port call before entering the EEA, operators can reduce their exposure to regulatory compliance costs, as the segment from a non-EEA origin to a non-EEA destination is exempt from FuelEU Maritime obligations. This makes the MSC Britannia service a relevant example for analyzing evasive routing behavior. In addition to Liverpool, the service connects with key Northern European ports such as Rotterdam, Antwerp, and Hamburg, providing access to Scandinavian and Baltic regions (MSC Mediterranean Shipping Company, 2024). The route passes through the Cape of Good Hope due to ongoing geopolitical tensions. The complete port rotation is listed in Table G.2.

Voyage Leg	Voyage Type
Shanghai → Ningbo	Non-EEA → Non-EEA
Ningbo → Yantian	Non-EEA → Non-EEA
Yantian → Vung Tau	Non-EEA → Non-EEA
Vung Tau → Liverpool	Non-EEA → Non-EEA
Liverpool → Rotterdam	Non-EEA → EEA
Rotterdam → Antwerp	EEA → EEA
Antwerp → Hamburg	EEA → EEA
Hamburg → London Gateway	EEA → Non-EEA
London Gateway → Singapore	Non-EEA → Non-EEA
Singapore → Shanghai	Non-EEA → Non-EEA

Table G.2: Voyage legs and voyage Classification for MSC Britannia service

To analyze how fuel and operational choices interact with regulation, six fuel strategy scenarios are evaluated for the period 2025–2029, during which the FuelEU GHG intensity threshold remains constant:

- Scenario 1: Baseline with 100% Marine Gas Oil (MGO)
- Scenario 2: 98% MGO + 2% RFNBO (e-H_2)
- Scenario 3: Scenario 2 + Onshore Power Supply (OPS)
- Scenario 4: 100% Liquefied Natural Gas (LNG)
- Scenario 5: 98% LNG + 2% e-H_2
- Scenario 6: Scenario 5 + OPS

LNG is included due to its increasing uptake and role as a transition fuel (Solakivi et al., 2022). Results are presented in Table G.3.

Key Findings for UK-inclusive Route

- Scenario 1 (MGO only) is non-compliant, with a GHG intensity of 90.63 gCO_{2eq}/MJ, exceeding the regulatory threshold (89.34 gCO_{2eq}/MJ), leading to FuelEU penalties of $12,965 and ETS costs of $66,805.
- Scenario 2, with 2% RFNBO, lowers GHG intensity below the threshold (87.97 gCO_{2eq}/MJ), avoiding penalties. However, cost savings are limited, and ETS costs remain high.
- Scenario 3 adds OPS and yields the most ETS cost savings ($9,000 reduction) while slightly improving GHG performance. This highlights OPS's cost-effectiveness for ETS rather than FuelEU compliance.
- Scenarios 4–6 show that switching to LNG significantly reduces both GHG intensity and ETS exposure. Blending e-H_2 (Scenario 5) or adding OPS (Scenario 6) leads to marginal improvements. However, Scenario 6 achieves the lowest ETS cost ($44,846) and the lowest emissions (15,593 tonnes CO_2), even though GHG intensity gains are minimal due to the carbon intensity of electricity used for OPS.

Non-Evasive Route

To evaluate the effect of excluding UK ports, an alternative EEA-only route is modeled, replacing Liverpool with Le Havre and London Gateway with Gothenburg. These substitutions ensure geographic and operational comparability (10 legs total). The adjusted voyage legs and map are shown in Table G.4.

Voyage Leg	Voyage Type
Shanghai → Ningbo	Non-EEA → Non-EEA
Ningbo → Yantian	Non-EEA → Non-EEA
Yantian → Vung Tau	Non-EEA → Non-EEA
Vung Tau → Le Havre	Non-EEA → EEA
Le Havre → Rotterdam	Non-EEA → EEA
Rotterdam → Antwerp	EEA → EEA
Antwerp → Hamburg	EEA → EEA
Hamburg → Gothenburg	EEA → EEA
Gothenburg → Singapore	EEA → Non-EEA
Singapore → Shanghai	Non-EEA → Non-EEA

Table G.4: Voyage legs and voyage Classification for Far East Asia - Northwest Europe route

The same six scenarios are applied to this route. Results are presented in Table G.5, with Scenario 1 visualized in Figure G.3.

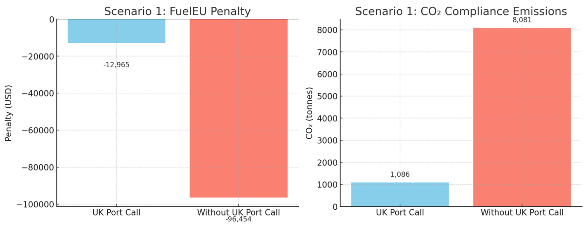

Figure G.3: FuelEU Maritime penalty comparison in Scenario 1 for routes with and without UK port calls.

Key Differences in the EEA-only Route

- Compliance burden sharply increases. In Scenario 1, compliance CO_2 emissions reach 8,081 tonnes—nearly 7.5 times higher than the MSC Britannia case (1,086 tonnes)—resulting in an ETS cost of $497,011 vs. $66,805.
- OPS costs rise due to more EEA port calls, reaching $87,827 compared to $52,696 in the UK route.
- FuelEU penalties also worsen. In Scenario 1, the penalty rises to $96,454, compared to $12,965 previously.
- LNG-based scenarios (4–6) still achieve compliance and generate FuelEU credits (e.g., $1.37 million in Scenario 5), but ETS costs remain 6–7 times higher due to the higher number of regulated segments.

This contrast shows that including UK ports substantially reduces the regulatory exposure of a liner service, despite similar total emissions.

Scenario	OPS Cost	Fuel (ton)	Fuel Cost	WtT (gCO_{2eq}/MJ)	TtW (gCO_{2eq}/MJ)	Average GHG (gCO_{2eq}/MJ)	FuelEU Penalty (2025-2029)	CO_2 Compliance (ton)	Total CO_2 (ton)	ETS Cost
1	$–	6502.95	$ (4,978,005)	57.6	304.93	90.632	$ (12,965)	1086.3	21158.9	$ (66,805)
2	$–	6487.58	$ (4,988,803)	56.1	295.78	87.967	$ 13,961	1035.5	21097.3	$ (63,681)
3	$52,696	6433.78	$ (4,945,173)	81.0	264.70	86.427	$ 28,538	891.2	20923.5	$ (54,811)
4	$–	5678.69	$ (4,832,653)	74.0	230.63	76.129	$ 161,242	826.3	15714.4	$ (50,820)
5	$–	5667.95	$ (4,846,275)	72.0	223.71	73.927	$ 192,021	792.1	15741.4	$ (53,095)
6	$60,147.70	5614.15	$ (4,797,719)	97.8	197.64	73.855	$ 181,480	669.0	15593.1	$ (44,846)

Table G.3: Case Study 1: MSC Britannia scenario comparison of costs and emissions

Scenario	OPS Cost	Fuel (ton)	Fuel Cost	WtT (gCO_{2eq}/MJ)	TtW (gCO_{2eq}/MJ)	Average GHG (gCO_{2eq}/MJ)	FuelEU Penalty (2025-2029)	CO_2 Compliance (ton)	Total CO_2 (ton)	ETS Cost
1	$–	5763.760	$ (4,412,158)	86.4	457.4	90.632	$ -96,454	8081.49	18753.78	$ (497,011)
2	$–	5607.502	$ (4,493,664)	84.4	445.2	88.263	$ 350,356	7619.62	18141.59	$ (468,606)
3	$87,826.70	5517.835	$ (4,420,966)	115.8	405.8	86.9379	$ 423,477	7359.53	17851.94	$ (452,611)
4	$–	5035.851	$ (4,285,509)	111.0	345.9	76.1292	$ 1,177,646	6035.27	13994.93	$ (404,574)
5	$–	4926.686	$ (4,392,910)	108.3	336.7	74.1747	$ 1,369,755	5724.42	13602.09	$ (383,736)
6	$100,246	4837.01	$ (4,311,983)	140.9	303.6	74.0871	$ 1,356,378	5502.52	13354.96	$ (368,861)

Table G.5: Case Study 1: Far East Asia - Northwest Europe scenario comparison of costs and emissions (no UK port calls)

Conclusion: Case Study 1

This case study demonstrates that evasive port strategies—such as inserting a UK call before entering the EEA—can significantly reduce both FuelEU and ETS cost burdens without lowering actual emissions. While the total CO_2 output remains similar between UK-inclusive and EEA-only routes, the volume of emissions covered by EU regulations drops dramatically with evasive routing.

The risk of carbon leakage is most acute in Scenario 1, where MGO use results in both FuelEU penalties and high ETS costs. Given that MGO remains the dominant maritime fuel (60.3% of consumption) (X. Wang et al., 2023), the incentive for evasive routing is strong and widespread.

Furthermore, OPS proves more effective in reducing ETS liabilities than improving GHG scores under current grid emissions. This suggests a need for cleaner electricity to enhance OPS's climate mitigation value.

Finally, the findings reinforce concerns about port competitiveness. Without aligned regulatory frameworks, non-EEA ports like those in the UK could gain a strategic cost advantage—undermining the environmental effectiveness and fairness of EU regulations.

C. Case Study 2: Asia - (Algeciras) - North America

This case investigates a carbon leakage scenario where a liner service between Asia and North America avoids FuelEU Maritime and EU ETS compliance by omitting a call at Algeciras, Spain—an EEA port. Maersk's updated MECL rotation eliminates Algeciras, shifting the voyage outside EU regulatory scope. This has raised competitiveness concerns from the Port Authority of Algeciras (Atalayar, 2024).

According to industry sources, the change is financially motivated: bypassing Algeciras avoids EU ETS costs estimated at €150,000 per vessel (FP Editor, 2025). Panteia's consultations with a stakeholder confirm the shift saves roughly six sailing days. Maersk cites commercial reasons and transit time improvements as the main drivers (Faouzi, 2025).

Table G.6 and Table G.7 list the voyage legs for both routing options

Voyage Leg	Voyage Type
Jebel Ali → Qasim	Non-EEA → Non-EEA
Qasim → Pipavav	Non-EEA → Non-EEA
Pipavav → Nhava Sheva	Non-EEA → Non-EEA
Nhava Sheva → Salalah	Non-EEA → Non-EEA
Salalah → Tanger Med	Non-EEA → Non-EEA
Tanger Med → Newark	Non-EEA → Non-EEA
Newark → Charleston	Non-EEA → Non-EEA
Charleston → Savannah	Non-EEA → Non-EEA
Savannah → Houston	Non-EEA → Non-EEA
Houston → Norfolk	Non-EEA → Non-EEA
Norfolk → Newark	Non-EEA → Non-EEA
Newark → Salalah	Non-EEA → Non-EEA
Salalah → Jebel Ali	Non-EEA → Non-EEA

Table G.6: Voyage legs and voyage classification for Asia – North America route

Voyage Leg	Voyage Type
Jebel Ali → Qasim	Non-EEA → Non-EEA
Qasim → Pipavav	Non-EEA → Non-EEA
Pipavav → Nhava Sheva	Non-EEA → Non-EEA
Nhava Sheva → Salalah	Non-EEA → Non-EEA
Salalah → Tanger Med	Non-EEA → Non-EEA
Tanger Med → Newark	Non-EEA → Non-EEA
Newark → Charleston	Non-EEA → Non-EEA
Charleston → Savannah	Non-EEA → Non-EEA
Savannah → Houston	Non-EEA → Non-EEA
Houston → Norfolk	Non-EEA → Non-EEA
Norfolk → Newark	Non-EEA → Non-EEA
Newark → Algeciras	Non-EEA → EEA
Algeciras → Salalah	EEA → Non-EEA
Salalah → Jebel Ali	Non-EEA → Non-EEA

Table G.7: Voyage legs and voyage classification for Asia – North America route via Algeciras

To quantify the cost and regulatory effects of this adjustment, both routes were assessed under the same compliance scenario: LNG blended with 2% RFNBO e-H_2, with OPS use at the EEA port. Results are summarized in Table G.8.

Metric	No Stop at Algeciras	Calling at Algeciras
Total Sailing Days	54.03	65.89
Total Fuel Consumption (ton)	2814.78	3468.67
Total Fuel Cost ($)	$2,395,380	$3,032,844
Cost Per TEU ($/TEU)	1031.13	1221.49
FuelEU Penalty ($)	$–	$552,713
Total CO_2 Compliance Emission (ton)	0	2122.16
Total CO_2 (ton)	7822.45	9603.48
EU ETS Compliance ($)	$0	$142,259
Omitted CO_2	100%	78%

Table G.8: Case Study 2: Comparison of cost and emissions with and without Algeciras port call

From Table G.8, it is evident that the regulatory cost implications are significant. The route that includes a call at Algeciras falls under the scope of both the EU ETS and the FuelEU Maritime regulation. Since the vessel operates on a compliant blend of LNG with 2% RFNBO e-H_2, and the analysis reflects the 2025–2029 regulatory phase, its average GHG intensity remains below the FuelEU threshold. Consequently, instead of facing a FuelEU penalty, the vessel generates a surplus of $552,713, which can be banked for future compliance use. However, this surplus does not provide immediate financial benefit. In contrast, the EU ETS imposes a mandatory cost of $142,259, which must be paid irrespective of GHG intensity performance.

Avoiding the port call at Algeciras results in 100% of the voyage's emissions falling outside the scope of EU regulations, compared to 78% when Algeciras is included. While the 22% difference may seem modest, it becomes highly significant when considered over repeated voyages and across the global fleet. Without proper safeguards, such evasive routing strategies could undermine the effectiveness of EU climate policies and erode the competitiveness of EEA transshipment hubs like Algeciras.

Conclusion: Case Study 2

The Algeciras case highlights the vulnerability of EU transshipment hubs under the current regulatory framework. While both FuelEU Maritime and the EU ETS include transshipment safeguards, they do not adequately address evasive routing strategies that operate entirely between non-EEA ports. Maersk's route adjustment demonstrates how regulatory incentives can unintentionally encourage rerouting, thereby undermining the competitiveness of EU ports. Targeted policy interventions may be necessary to address this regulatory blind spot and safeguard the strategic role of EU ports. In particular, ports located near non-EEA territories are at heightened risk of carbon leakage, as vessels may choose to bypass EEA ports entirely to avoid regulatory obligations.

D. Case Study 3: Asia - North Europe

This case study investigates a route proposed by the European Commission, focusing on shipping from Asia to Europe. The MSC Swan Sentosa service is selected due to its extensive port coverage across major European hubs. Given that a substantial portion of its voyage legs falls within the scope of the FuelEU Maritime regulation—owing to the high number of EEA port calls—this route presents a relevant opportunity to explore potential compliance strategies. Notably, the introduction of MSC's feeder service in Le Havre (since 2013) (MarineLink, 2013) enables a meaningful comparison between routes that do and do not utilize feeder transport from this port. The objective is to assess whether the use of a feeder from Le Havre can reduce overall shipping costs—including, but not limited to, FuelEU Maritime and EU ETS-related compliance costs, even if it results in partial regulatory evasion or carbon leakage.

The full rotation is shown in Table G.9

Voyage Leg	Voyage Type
Yokohama → Ningbo	Non-EEA → Non-EEA
Ningbo → Shanghai	Non-EEA → Non-EEA
Shanghai → Xiamen	Non-EEA → Non-EEA
Xiamen → Yantian	Non-EEA → Non-EEA
Yantian → Singapore	Non-EEA → Non-EEA
Singapore → Sines	Non-EEA → EEA
Sines → Le Havre	EEA → EEA
Le Havre → Rotterdam	EEA → EEA
Rotterdam → Gothenburg	EEA → EEA
Gothenburg → Aarhus	EEA → EEA
Aarhus → Hamburg	EEA → EEA
Hamburg → Antwerp	EEA → EEA

Table G.9: Voyage legs and voyage classification for the East Asia to Northern Europe service

In this case study, both service configurations—with and without the use of feeder vessels—are evaluated under a consistent compliance scenario. The mainline service is assumed to operate on LNG blended with 2% RFNBO (e-H_2) and utilizes Onshore Power Supply (OPS) at EEA ports. In contrast, the feeder vessels operate exclusively on HFO, as they fall outside the scope of the FuelEU Maritime regulation.

To ensure comparability, the analysis scales the operational performance of the feeder service to match the transport capacity of the mainline vessel, which carries 6,478 TEU. Given that the selected feeder vessel, M.V. Vantage, has a capacity of 354 TEU, approximately 20.64 feeder trips are required to match a single mainline voyage (6,478 ÷ 354 ≈ 20.64). Accordingly, all cost and emissions figures associated with the feeder configuration are multiplied by this factor.

The M.V. Vantage, designed for the North European feeder market, is chosen for its regional suitability and availability (Conoship International, 2019). With a gross tonnage of 3,871 GT, it remains below the regulatory threshold set by FuelEU Maritime, rendering it both compliant and operationally relevant for this analysis.

The detailed results of the model are presented in Table G.10.

From Table 5.9, it is evident that the total CO_2 emissions associated with the Mainline + Feeder configuration are substantially higher—reaching 11,782.20 tonnes—compared to 8,252.72 tonnes for the Mainline-Only scenario. This 43% increase raises environmental concerns, as it may undermine the emissions reduction targets set by the EU Fit for 55 package.

The discrepancy is primarily attributed to the feeder vessel's exemption from FuelEU Maritime and EU ETS obligations due to its gross tonnage being below the 5,000 GT threshold. Consequently, the 4,089.77 tonnes of CO_2 emitted by the feeder leg are excluded from compliance calculations. This creates a regulatory blind spot where a significant share of emissions escapes oversight, weakening both the environmental effectiveness and financial enforcement of EU climate policy.

This exemption also implies foregone revenue for the EU. The feeder leg avoids an estimated EU ETS cost of $488,815.80. While the FuelEU Maritime penalty is not directly applied to the feeder segment, the total FuelEU penalty in the Mainline + Feeder configuration is slightly higher than in the Mainline-Only scenario—suggesting that the evasion of one regulation does not necessarily offset costs under the other.

Economically, the feeder strategy offers no clear advantage. The combined fuel and OPS expenditure in the Mainline + Feeder scenario amounts to $3,301,427—approximately $400,566 higher than the Mainline-Only case. Moreover, total compliance costs (FuelEU + ETS) are also higher by nearly $13,000, further diminishing the cost-effectiveness of this routing strategy.

Conclusion: Case Study 3

The results of Case Study 3 suggest that while routing via feeder vessels may reduce regulatory coverage due to tonnage exemptions, it does not deliver financial savings and significantly increases total CO_2 emissions. Consequently, the risk of widespread carbon leakage via this strategy appears limited under current cost conditions.

However, the findings point to a structural weakness in the regulatory framework: the exclusion of sub-5,000 GT vessels allows for unregulated emissions that could become significant if this strategy were adopted more broadly. Unless operational costs of feeder services are reduced or the regulatory scope is expanded to include smaller vessels, the feeder strategy is unlikely to be economically viable or environmentally sustainable in the long term.

VI Sensitivity Analysis

To evaluate how changes in operational and regulatory variables affect compliance and emissions outcomes, this section conducts a sensitivity analysis focused on two key parameters: sailing speed and electricity emission intensity for Onshore Power Supply (OPS). While the core case

Metric	Mainline Vessel Only	Mainline + Feeder (Mainline)	Mainline + Feeder (Feeder)	Mainline + Feeder (Total)
Total Sailing Days	69.05	60.74	6.57	67.31
Total Fuel Consumption (ton)	3022.4	2816.7	1292.98	4109.68
Total Fuel Cost ($)	$2,900,861	$2,700,190	$601,237	$3,301,427
OPS Cost ($)	$11,613	$3,318	$0	$3,318
Cost Per TEU ($/TEU)	1109.4	1593.7	575.7	–
FuelEU Penalty (2025–2029)	$1,068,628	$1,114,439	$0	$1,114,439
FuelEU Penalty (2040–2044)	$(-584,308)	$-428,950	$0	$-428,950
Total CO_2 Compliance Emission (ton)	3836.15	3302.49	0	3302.49
Total CO_2 (ton)	8252.719	7692.431	4089.77	11782.20
EU ETS Compliance ($)	$235,923.30	$203,103.34	$0	$203,103.34
Omitted CO_2	54%	57%	0%	–

Table G.10: Case Study 3: Comparison of cost and emissions with and without using a feeder service

studies rely on fixed assumptions, real-world shipping conditions are dynamic. This analysis isolates the effects of each parameter by varying one at a time, holding all others constant.

A. Sailing Speed

Sailing speed directly affects fuel consumption, emissions, and fleet requirements. Lower speeds reduce emissions and fuel costs but prolong voyage duration, potentially requiring more vessels to maintain schedule frequency. Drawing on Rodrigue (2024), four speed regimes are assessed: 21, 18, 15, and 12 knots.

Results for the MSC Britannia route (see Figure G.4) show that reducing speed from 21 to 18 knots yields a 24% reduction in FuelEU penalty with a modest 14% increase in sailing time. However, further speed reductions exhibit diminishing returns. At 15 knots, the penalty reduction reaches 44%, but voyage duration increases by 33%. At 12 knots, gains in compliance costs taper off, while sailing time increases 63%. These results indicate that moderate slow steaming (15–18 knots) offers the most efficient trade-off between cost savings and service reliability.

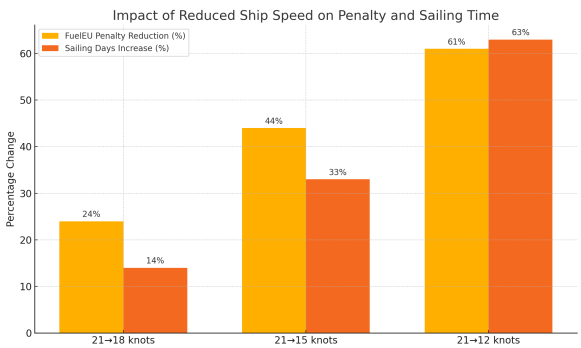

Figure G.4: Impact of sailing speed on FuelEU penalty and sailing time

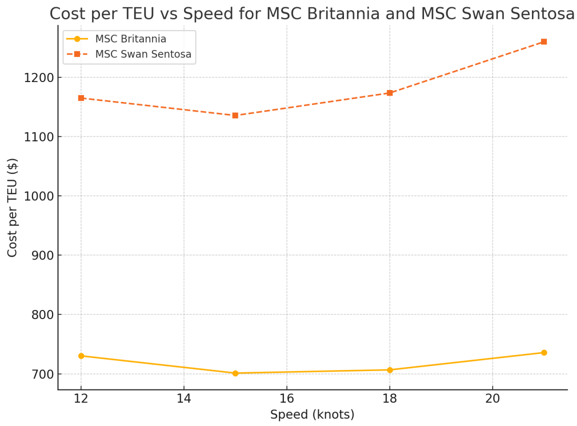

Figure G.5: Impact of sailing speed on cost per TEU

As shown in Figure G.5, cost per TEU initially decreases with slower speeds, but rises again at 12 knots due to increased ship deployment and operational time—highlighting the economic limit of slow steaming.

B. OPS Electricity Emission Intensity

The effectiveness of OPS in reducing GHG intensity depends on the carbon intensity of national electricity grids. While OPS use during berthing contributes only a small portion of total energy consumption, it can meaningfully influence a vessel's GHG profile under stringent FuelEU thresholds.

As seen in Figure G.6, fuels like LNG and LPG remain compliant in low-emission countries (e.g., Norway, Sweden, France) but exceed thresholds in high-emission grids (e.g., Poland, Italy). This suggests a potential strategy: operators may prefer OPS in countries with cleaner grids to optimize compliance. As electricity decarbonizes further, OPS could become increasingly important in reducing lifecycle GHG emissions and avoiding FuelEU penalties.

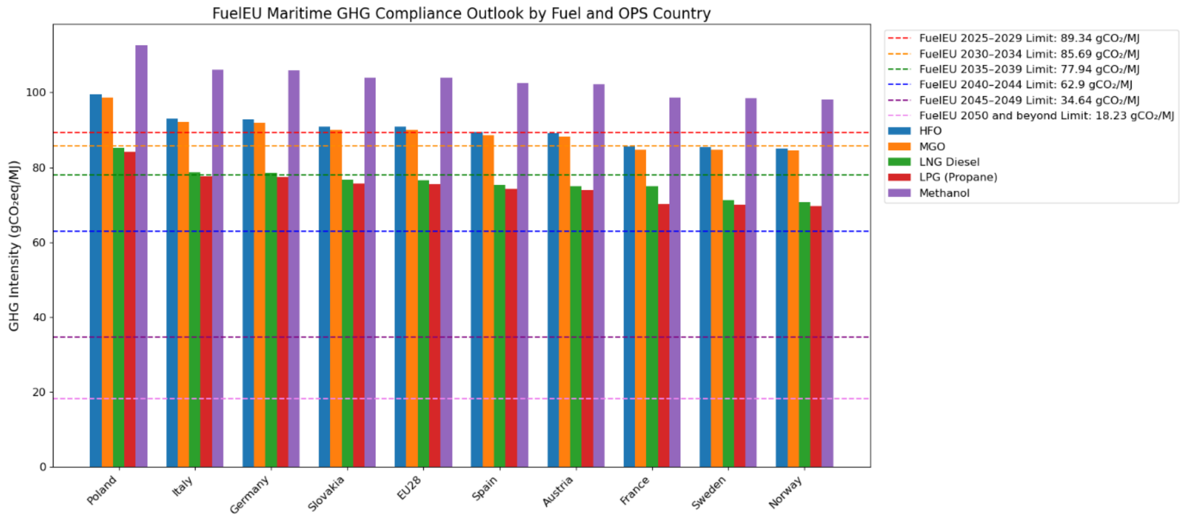

Figure G.6: GHG intensity sensitivity to OPS grid emission factors by country

VII Stakeholder Engagement

A. Targeted Interview

Each stakeholder was asked a series of standardized questions regarding the impact and effectiveness of maritime climate policies.

- Stakeholder 1 has been actively involved with FuelEU Maritime and the EU ETS since their inception but is not actively engaged with CBAM, as it currently does not cover shipping.
- Stakeholder 2, representing port interests, indicated that this topic is especially relevant for the Port of Algeciras. They have observed rerouting in the Mediterranean and shifts in northern Europe toward the UK. Stakeholder 2 expressed general support for the EU ETS.
- Stakeholder 3 noted that since 2020, FuelEU Maritime and the EU ETS have had a clear impact on their members' operations. Their focus has been on ensuring that port infrastructure is utilized, to avoid stranded investments. They also highlighted the risk of changing port call sequences or transshipment routes to reduce regulatory costs. Regarding CBAM, Stakeholder 3 does not currently foresee a significant risk of carbon leakage.
- Stakeholder 4 emphasized that FuelEU and the EU ETS have been of high strategic importance. They reported active involvement in shaping the regulatory frameworks to ensure their effectiveness in supporting shipping decarbonization. Stakeholder 4 also noted that their members are committed to achieving decarbonization goals.

Discussion & Key Takeaways

- Most stakeholders confirm carbon leakage and competitiveness risks—especially due to rerouting, transshipment shifts, and modal backshifts.
- High-risk areas identified: Mediterranean (e.g., Spain, Italy), Northern Europe (e.g., Rotterdam, Antwerp), and even the UK and Middle East.
- Stakeholders anticipate changes in bunkering, feedering, and port call patterns. According to Stakeholder 3, regulatory developments may encourage the adoption of the hub-and-spoke model, resulting in fewer direct EU port calls and a stronger reliance on transshipment hubs. The hub-and-spoke system is a widely used approach for optimizing maritime transport networks by consolidating cargo at central hub ports before distributing it to smaller spoke ports. This model improves operational efficiency, reduces transportation costs, and enables economies of scale through strategic network design (Humang et al., 2025). Major shipping lines such as Hapag-Lloyd and Maersk have begun implementing this model through their joint initiative, the Gemini Cooperation, which will commence in February 2025 (Hapag-Lloyd, 2024).
- Stakeholders note that alternative fuels are approximately four times more expensive than conventional fuels and are not widely available, particularly at traditional bunkering

hubs. This concern is supported by the findings of Solakivi et al. (2022), which indicate that even when accounting for the EU ETS, the projected prices of alternative fuels will remain significantly higher than those of fossil fuels for the foreseeable future.

- Stakeholders propose several mitigation strategies, including expanding the list of exempted ports, implementing fuel supplier mandates, and using EU ETS revenues to subsidize the use of clean fuels. Stakeholder 1, in particular, advocates for a voluntary mandate on fuel suppliers to ensure sufficient production of alternative fuels, noting that no binding obligation currently exists. A comparable policy can be found in the United Kingdom, where the Sustainable Aviation Fuels (SAF) scheme mandates fuel suppliers to progressively increase the share of SAF in the aviation sector. This policy aims to reduce GHG emissions by legally requiring the supply of SAF over time (UK Department for Transport, 2024).
- Stakeholder 3 highlights the risk of stranded port investments if vessels begin to avoid regulated ports. For instance, a study by Jeong et al. (2023) on the implications of the Paris Agreement under carbon pricing found that shipowners could face approximately US$26.5 million in stranded asset risk. This risk could be slightly reduced to US$25.2 million if ships slow down to meet carbon intensity requirements.

B. Survey Questionnaire

As part of the stakeholder consultation, five proposed regulatory measures were evaluated in terms of feasibility, effectiveness, and potential unintended consequences. These include: (1) extending the Carbon Border Adjustment Mechanism (CBAM) to maritime transport; (2) introducing an EU-wide levy on vessels departing the EEA based on final destination; (3) revising the criteria for identifying neighboring transshipment ports under FuelEU Maritime and/or ETS Maritime; (4) amending the scope and coverage of the FuelEU Maritime regulation; and (5) implementing a container-based levy with proceeds directed to a dedicated maritime fund. A synthesis of stakeholder views is presented in Table 6.2.

Measure 1: Extension of CBAM to Maritime Transport

- Stakeholders expressed significant concerns regarding the feasibility of applying CBAM to international shipping. Core issues included:
  - The complexity of monitoring and verifying emissions from global maritime voyages.
  - Risk of administrative duplication with the EU ETS and upcoming IMO measures, potentially resulting in double counting.
  - Limited effectiveness in addressing transshipment relocation, particularly for Non-EU / EU / Non-EU itineraries.
  - Risk of incentivizing port calls just outside the EEA, further undermining EU port competitiveness.
  - Trade risks, such as retaliation from non-EU countries and compatibility with WTO rules.
  - Negative impacts on exporters and consumers, particularly in cost-sensitive or developing markets.

While CBAM was broadly viewed as ill-suited for shipping, stakeholders consistently emphasized the need for alignment with IMO-level instruments. A harmonized global approach was favored over unilateral EU action.

Measure 2: EU Levy Based on Final Destination

This measure proposes a levy on vessels departing from the EEA, indexed to their final destination. Stakeholder feedback highlighted:

- Increased pressure on EU ports and exporters due to compounding costs alongside the EU ETS.
- Ambiguity in defining ”final destination,” especially for liner services with complex multi-stop schedules.
- Risk of double charging and regulatory redundancy.
- Limited deterrent effect on evasive routing, as vessels could continue to call at non-EEA hubs.
- Disproportionate economic impact on developing regions, such as African markets.
- Preference for incentive-based policies rather than additional levies.

Measure 3: Revision of Neighboring Transshipment Port Criteria

There was broad support for refining the criteria used to designate neighboring transshipment ports:

- Suggestions included lowering the transshipment share threshold (from 65% to 50%), considering ports handling other unitized cargo types, and expanding 100% emissions coverage to ports such as Tanger or Nador.
- Stakeholders advocated for the inclusion of geographic proximity to the EEA and regular (e.g., annual) updates to the designation list.
- Nonetheless, many noted that such changes would not fully address competitiveness challenges, particularly when EEA ports are treated less favorably than nearby non-EEA alternatives.
- For instance, calling at Port Said (a non-EEA port on the list) incurs only 50% ETS coverage for the subsequent voyage leg, whereas calling at Valencia (an EEA port) results in 100% emissions coverage—creating a cost-based incentive to bypass EU ports.

Measure 4: Amendments to the FuelEU Maritime Regulation

Multiple stakeholders recommended extending the regulation's scope:

- Covering 100% of international voyage emissions (rather than 50%) and lowering the vessel size threshold from 5,000 GT to 400 GT.
- The upcoming 2025 expansion of the EU MRV system was cited as enabling infrastructure for such an extension.
- While these changes could reduce regulatory loopholes, concerns included:
- Increased risk of rerouting to avoid compliance.
- Financial and administrative burdens on smaller operators with limited fleet flexibility.
- Limited market availability and high costs of alternative fuels, undermining compliance feasibility.

Measure 5: Container-Based Levy and Maritime Fund

This measure attracted a mixed response:

- Some stakeholders viewed it as more equitable and less distortionary than voyage-based penalties—particularly for EU ports near non-EEA transshipment hubs.
- Others cautioned that containers do not emit CO_2; emissions depend on fuel, routing, and vessel performance. Tracking these variables could introduce complexity and administrative cost.
- Uncertainties included how to determine liability for payment, how to differentiate container types (e.g., LCL vs FCL), and how to allocate revenues.
- There was concern that LCL shipments could be disproportionately affected, potentially harming small and medium exporters.
- The risk of overlapping costs—if combined with the ETS—was also raised, along with doubts about the levy's ability to curb cargo re-routing between non-EU ports.

VIII Discussion & Policy Recommendation

A. Drivers and Implications of Evasive Routing

The scenario analysis revealed that evasive routing—such as calling at nearby non-EEA transshipment hubs like Tanger Med—can substantially reduce a vessel's regulatory exposure under the FuelEU Maritime and EU ETS frameworks. For example, if a ship calls at a non-EEA port before entering the European Economic Area (EEA), the share of emissions subject to regulation may drop from 100% to 50%. In cases where the EEA is not the final destination, regulatory coverage can be reduced to zero. This finding demonstrates that the current 50% emission allocation rule provides a clear and exploitable pathway for carbon leakage. This was quantitatively illustrated in Chapter 5, Case 1, where incorporating a UK port into the rotation reduced both FuelEU Maritime and EU ETS liabilities, limiting the number of EEA-regulated voyage legs. The resulting route incurred lower reported emissions and compliance costs than a comparable route calling only at EEA ports.

Stakeholder interviews confirmed that this is not a merely theoretical risk but a practical concern already shaping strategic decisions. Shipping companies and port authorities noted that routing adjustments are actively being considered or implemented to reduce exposure. Representatives from major ports emphasized that regulatory asymmetries between EU and non-EU ports are incentivizing shifts in transshipment patterns, undermining the competitiveness of EEA ports. Although current European Commission monitoring reports have not yet documented substantial shifts in aggregate port traffic volumes, the risk remains significant (European Commission, 2025a).

Cost considerations emerged as the dominant driver behind evasive routing. When compliance costs at EEA ports become excessive, operators naturally explore alternatives that allow them to reduce regulatory obligations. This was clearly demonstrated in the case of the Maersk MECL service, where avoiding Algeciras and rerouting through non-EEA ports resulted in measurable reductions in regulated emissions and compliance costs. This case illustrates how even a single change in port rotation can yield substantial financial savings—potentially encouraging replication across other services and reinforcing systemic regulatory avoidance.

B. Stakeholder Perceptions on Mitigation Measures

The stakeholder engagement activities described in Chapter 6, including structured interviews and a sector-wide survey, provide deeper insight into how maritime actors perceive the feasibility, fairness, and potential impacts of proposed EU measures to mitigate carbon leakage. While the modeling in Chapter 5 quantified routing-based leakage, the stakeholder responses added context regarding implementation feasibility, behavioral responses, and distributional effects.

Measure 3—Revising transshipment port criteria—received the broadest support. Stakeholders viewed it as a targeted and relatively low-disruption approach to close an identifiable regulatory loophole. Most agreed that tightening the 300-nautical-mile exemption and refining the transshipment port definition could yield a high-impact result. This support aligns with the modeling in Case 2, which underscores the need to revise transshipment rules. Although FuelEU already includes a transshipment safeguard, Non-EEA to Non-EEA relay strategies can still indirectly erode EU port competitiveness.

Measure 4—Expanding the scope of FuelEU Maritime—elicited more mixed responses. Stakeholders supported broader coverage, particularly the inclusion of vessels below 5,000 GT to address loopholes exploited via feeder services. However, smaller operators voiced concerns over compliance capacity, especially due to a lack of access to alternative fuels, fewer economies of scale, and limited capital for fleet upgrades. This reflects a broader tension between policy ambition and industry readiness. As shown in the feeder case study, such services may avoid regulation but are not economically superior under current conditions. Thus, while expanding scope may theoretically reduce leakage, in practice it could penalize short-sea shipping—a sector often promoted as an environmentally friendly alternative to road freight (Pérez-Mesa et al., 2023). Any expansion must be paired with support mechanisms or well-calibrated exemptions to avoid counterproductive effects.

Measure 5—Levying containers with revenue directed to a shipping fund—received cautious support, especially from EU port authorities located near non-EEA hubs. The measure was viewed as a more transparent way to internalize shipping emissions costs without distorting routing behavior. Nonetheless, stakeholders raised concerns around emission attribution, legal liability, and operational complexity, especially for multi-leg container flows. There was particular uncertainty about who should bear the levy—shipowners, freight forwarders, or shippers—and how to manage differentiated cargo values or split shipments. A similar container levy system has been introduced in New Zealand, where charges vary based on vessel size and category (Maritime New Zealand, 2024). However, if introduced at EEA ports, this measure could further reduce their attractiveness, particularly if competing non-EU ports do not implement equivalent charges.

Measures 1 and 2—Extending CBAM to maritime and applying a destination-based EU levy—received the most skepticism. Many stakeholders viewed them as complex, duplicative, and difficult to enforce. CBAM was seen as overlapping with existing mechanisms like EU ETS and potentially leading to double counting, administrative burden, and international trade disputes. Stakeholders emphasized that such measures "look good on paper but invite retaliation and court challenges." Indeed, if CBAM were uniformly applied across the EU, it could lead to uneven impacts across member states with differing industrial profiles and maritime exposure (Zhao and Lin, 2025). A destination-based levy presents additional complications, as port operations and route determination can be ambiguous and vary widely across carriers.

The stakeholder responses also reinforce concerns raised in the scenario modeling. While case studies focused on immediate behavioral adjustments—such as port call changes—stakeholders highlighted longer-term structural shifts. Chief among these is the potential strategic displacement of logistics hubs to non-EEA ports like Tanger Med, Nador, or Jeddah. These shifts represent not just regulatory avoidance, but a reconfiguration of global shipping patterns. Interviewees noted that fuel costs, public investment, and permitting speed in non-EU ports often outperform EU options—making such transitions attractive even in the absence of regulatory differences.

Stakeholders also raised the risk of modal shifts, particularly in sensitive corridors like the Baltics or Iberia, where delays in ETS enforcement or perceived asymmetries could push cargo from sea to road. At the core of many of these issues is the unresolved cost differential between conventional and renewable marine fuels—a barrier identified across the literature as the main constraint on sectoral decarbonization (Christodoulou and Cullinane, 2022). Without targeted financial and regulatory support to close this gap, rerouting to avoid EU regulations may remain a rational and persistent strategy.

Across interviews and survey responses, a consistent theme emerged: carbon leakage is not just a policy loophole but a symptom of deeper structural asymmetries between EU and global maritime ecosystems. To avoid erosion of strategic control over maritime logistics, EU policymakers may need to complement regulatory tightening with incentive-based policies and stronger international coordination.

C. Policy Recommendations

Drawing from the integrated findings of the scenario-based modeling and stakeholder engagement activities, this section proposes a set of policy recommendations to improve the effectiveness, fairness, and feasibility of the EU's maritime decarbonisation measures under the FuelEU Maritime and EU ETS frameworks.

- **Tighten Transshipment Port Criteria:** Revise the current exemption mechanism for neighboring transshipment ports by introducing stricter proximity thresholds and requiring that listed ports handle a significant share of EU-destined cargo. Based on both scenario results and stakeholder input, ports competing closely with non-EEA hubs—such as Algeciras, Valencia, and Malta—face elevated carbon leakage risks. In parallel, introduce targeted incentives for vessels that call at EEA transshipment ports to help maintain their competitiveness relative to nearby non-EEA alternatives.
- **Phase-In an Expanded Scope for FuelEU Maritime:** Extend regulatory coverage in stages, prioritizing high-risk routes involving nearby non-EEA ports where the incentive for evasive behavior is strongest. To avoid disproportionately burdening smaller carriers and short-sea operators, implement transitional exemptions or provide targeted financial support. This phased approach allows for enhanced environmental performance without jeopardizing operational or economic viability in sensitive market segments.
- **Avoid Duplicative Instruments—Align with IMO Frameworks:** Rather than layering additional measures such as CBAM or destination-based levies on top of existing instruments, policy coherence should be prioritized. In particular, efforts should focus on aligning FuelEU Maritime and EU ETS with the forthcoming IMO Net-Zero Framework. As this framework will be incorporated into MARPOL—ratified by 108 member states representing 97% of global shipping tonnage—harmonization would improve legal defensibility, reduce administrative burden, and provide greater regulatory certainty for shipowners.
- **Institutionalize Stakeholder Dialogue Mechanisms:** Maintain structured and ongoing engagement with stakeholders across the maritime supply chain. Operational insights from port authorities, shipping lines, and logistics operators are essential to identifying regulatory loopholes, practical barriers, and unintended consequences early in the policy cycle. For example, the Port Authority of Valencia has warned that the EU ETS could erode the competitiveness of EU transshipment hubs and shift cargo to non-EU ports (Valenciaport, 2023), while the Malta Port Authority raised concerns about the viability of small national fleets under combined ETS and FuelEU compliance costs (Redazione, 2023). Given the additional complexity introduced by FuelEU Maritime, formal stakeholder forums are needed to ensure regulatory measures remain responsive to operational realities.
- **Accelerate Clean Fuel and OPS Infrastructure Development:** While the Alternative Fuels Infrastructure Regulation (AFIR) mandates the deployment of OPS and LNG bunkering across EU ports (Transport & Environment, 2023), current policy frameworks lack dedicated support for the production and distribution of emerging renewable fuels such as green ammonia or hydrogen. Introducing supply-side mandates or production incentives—similar to the UK's Sustainable Aviation Fuel (SAF) obligation—could stimulate market development for renewable marine fuels. This is particularly important given

the high cost and limited availability of such fuels (Christodoulou and Cullinane, 2022), as echoed in stakeholder responses.

- **Incentivize Voluntary Compliance Through Port-Based Rewards:** Offer financial incentives for early adopters of low-carbon technologies through reduced port fees or priority berthing. For instance, the Port of Hamburg already provides OPS-related discounts scaled by gross tonnage. Scaling such incentive schemes across EU ports could accelerate adoption of alternative fuels and technologies. This approach aligns with economic preferences reported by decision-makers: fuel price is consistently cited as the dominant consideration in shipowner investment decisions (Hansson et al., 2019). Financial incentives can therefore play a crucial role in overcoming the cost barriers to decarbonisation.

IX Conclusion

This study examined the impact of regulatory uncertainty on investment behavior in the maritime sector, focusing on the EU's FuelEU Maritime and Emissions Trading System (EU ETS) frameworks. Drawing on route-level scenario modeling and stakeholder engagement, the research provides empirical and qualitative insights into how carbon leakage risks emerge, how regulatory design affects cost exposure, and what strategies can mitigate unintended outcomes.

Mechanisms of Regulatory Evasion and Carbon Leakage

The findings demonstrate that current EU climate regulations in maritime transport create several openings for carbon leakage. Vessels can reduce their reported compliance obligations through routing strategies that exploit geographic boundaries and regulatory exemptions. Evasive routing—such as including calls at nearby non-EEA ports like the UK, Morocco, or Egypt—was shown to reduce the share of voyage legs covered by EU regulations from 100% to 50% or even 0%, depending on the final destination. Similarly, transshipment through non-EEA hubs using small vessels exempt from FuelEU Maritime and EU ETS creates a pathway for emissions to bypass regulatory coverage entirely.

These strategies are not merely hypothetical. Stakeholder interviews confirmed that operators are already adjusting port rotations to minimize compliance costs. The inclusion of low-emission ports with favorable grid factors, or the avoidance of EEA transshipment hubs like Algeciras, further illustrates how operational flexibility allows shipowners to optimize routes for regulatory purposes rather than environmental benefit.

Assessing Cost Impacts and Compliance Behavior

The enhanced Panteia Liner Shipping Model developed for this study enabled a detailed quantification of regulatory costs under different routing and fuel use scenarios. Compliance costs were shown to be highly sensitive to fuel mix (e.g., LNG vs. RFNBO), OPS grid intensity, and vessel type. Introducing RFNBOs reduced GHG intensity scores, but at significant cost, highlighting the tension between decarbonization goals and financial feasibility.

OPS use reduced FuelEU penalties but did not necessarily lower EU ETS obligations, as the impact depends on local grid emissions. Moreover, non-EEA feeder vessels below 5,000 GT remained outside the regulatory scope, allowing for large volumes of emissions to be excluded from the EU's carbon pricing system. The simulation results indicate that such design gaps not only distort route competitiveness but may also undermine the integrity of decarbonization objectives.

Modeling Carbon Leakage Pathways

By simulating real-world container routes and cost components, the model demonstrated how regulatory design shapes operational decisions. Assigning regulatory scope by voyage leg enabled clear identification of which emissions are covered or excluded. Incorporating OPS emissions, bunker fuel types, and port-specific electricity factors allowed for comparative analysis between scenarios.

Notably, scenarios involving transshipment through non-EEA hubs (e.g., Tanger Med) led to higher total emissions but lower regulatory cost burdens, revealing how leakage can occur despite rising emissions. While the model does not yet incorporate behavioral feedbacks like frequency shifts or service suspensions, it is capable of highlighting the financial logic behind evasive strategies. These capabilities position the model as a useful tool for policy assessment, especially when evaluating mitigation strategies like scope expansion or new levy designs.

Mitigation Strategies and Stakeholder Support

The combined scenario analysis and stakeholder engagement offer a roadmap for mitigating carbon leakage without compromising EU port competitiveness. Among the proposed measures, revising the eligibility criteria for neighboring transshipment ports received broad support. Stakeholders viewed this option as both practical and effective, particularly if revised thresholds and geographic criteria were applied more dynamically.

Expanding the scope of FuelEU Maritime to include vessels below 5,000 GT was acknowledged as a necessary long-term goal but raised concerns about feasibility, especially for smaller operators. Similarly, container-based levies were seen as promising but complex to implement. In contrast, measures like CBAM extension or destination-based levies drew skepticism, primarily due to concerns over administrative burden, legal complexity, and overlap with existing policies.

Beyond regulatory design, stakeholders highlighted the need for investment in clean fuel infrastructure and positive incentives to encourage early adoption. OPS fee discounts and fuel production mandates were seen as valuable tools to support compliance and level the playing field between EEA and non-EEA ports. A consistent theme across responses was the need to align EU regulations with emerging IMO frameworks to avoid fragmentation and duplication.

Implications for EU Maritime Decarbonization Policy

The findings suggest that the effectiveness of the FuelEU Maritime and EU ETS regulations depends not only on their stringency but also on how well they account for operational realities and strategic behavior. Carbon leakage is driven as much by economic geography and port infrastructure disparities as by gaps in regulatory scope.

To maintain the credibility and competitiveness of EU climate policy in shipping, future efforts should prioritize closing known loopholes, harmonizing with global frameworks, and designing supportive measures that promote compliance without disproportionately burdening smaller actors. Stakeholder engagement must remain central in this process to ensure that measures are practical, accepted, and aligned with broader market trends.

Ultimately, this research reinforces that regulatory ambition must be matched with precision in policy design, flexibility in implementation, and transparency in enforcement. Addressing carbon leakage in maritime transport will require an integrated approach that balances environmental integrity with economic viability across the global logistics chain.

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