Erasmus University Rotterdam

MSc in Maritime Economics and Logistics

2024/2025

From Cost Volatility to Carbon Compliance: Integrating Risk Management and Emission Strategy in Bunker Procurement for International Tanker Fleet Operations

by

Bagus Made Angistra

Acknowledgement

My sincere appreciation goes to PT Pertamina (Persero), PT Pertamina International Shipping, and PT Pertamina Trans Kontinental for granting me the scholarship that enabled me to pursue a Master's degree in Maritime Economics and Logistics at Erasmus University Rotterdam. This opportunity marked a defining stage in both my career and personal life, and I feel privileged to have been entrusted with it.

I am deeply thankful to my thesis supervisor, Dr. Maurice Jansen, whose mentorship, constructive advice, and encouragement were invaluable during the research process. His knowledge and patience greatly influenced the direction of this study and helped me stay focused through its most demanding phases.

To my classmates in the MEL 2024/2025 cohort, thank you for the camaraderie, the exchange of ideas, and the support that made this academic journey as enjoyable as it was rigorous.

I also wish to extend heartfelt appreciation to my family, with special mention to my beloved wife, Fitria Diniarini, for standing by me with unwavering encouragement, understanding, and patience. This thesis is also dedicated to my beloved father, I Wayan Sugiarta, whose love and sacrifices continue to guide and inspire me every day, and my mother (in heaven), Luh Putu Suwastrini. Your blessings have enabled me to honour the promise I once made to you.

Finally, I warmly acknowledge everyone who assisted me in any form along the course of this work. This achievement is as much yours as it is mine.

Abstract

Bunker fuel price volatility remains one of the largest and most unpredictable cost exposures in shipping, often accounting for 40–60% of voyage expenses. At the same time, the European Union's FuelEU Maritime regulation introduces progressively stricter well-to-wake greenhouse gas intensity limits toward 2050. This thesis evaluates compliance over 2025–2044 through an integrated two-stage optimisation framework applied to Pertamina International Shipping.

Stage 1 manages price risk through risk-hedged bunker procurement. Monthly spot and swap price paths for VLSFO, HSFO, and MGO are simulated using a multivariate (DCC) GARCH volatility and correlation model across the company's principal bunkering ports. Hedge ratios are determined via mean–variance optimisation under different levels of risk aversion (λ). The balanced λ = 0.5 strategy is recommended, reducing cost variance by 15.7% at the expense of only a 2.7% rise in mean cost, while generating a USD 17.89 million buffer that is subsequently applied to decarbonisation planning.

Stage 2 incorporates hedge-adjusted costs into a dynamic fuel-mix optimisation that minimises expenditure on fuel, EU ETS exposure, and FuelEU penalties while ensuring annual compliance. Two pathways emerge: LPG–MGO–bio-LPG reaches full compliance at USD 97.62 million, delivering a 74% reduction in regulatory costs versus a fossil baseline; LPG–MGO–bio-MGO achieves compliance at USD 102.25 million, providing an alternative if bio-LPG supply is constrained. The Stage 1 buffer offsets the entire USD 14.12 million premium in the first pathway and 94.06% in the second. Sensitivity analysis confirms robustness, with λ = 0.5 remaining optimal and a 50% VLSFO reduction after 2035 generating a 14,480 tCO_2eq compliance surplus. Consultations with company experts confirmed the practical feasibility and strategic alignment of both pathways.

Overall, the findings demonstrate that integrating financial risk management with decarbonisation planning enables the company to meet FuelEU Maritime requirements without penalties and within budget. More broadly, the thesis contributes to the scientific debate on maritime fuel procurement by showing how price risk hedging can be systematically linked with regulatory compliance, offering a transferable framework for shipping companies confronting the dual challenges of cost volatility and carbon regulation.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

ADF	Augmented Dickey–Fuller test
CII	Carbon Intensity Indicator
CVaR	Conditional Value-at-Risk
(DCC)-	Dynamic Conditional Correlation-
GARCH	Generalized Autoregressive Conditional Heteroskedasticity
DNV	Det Norske Veritas
EEA	European Economic Area
EEXI	Energy Efficiency Existing Ship Index
EU	European Union
EU ETS	European Union Emissions Trading System
ESG	Environmental, Social, and Governance
gCO_2eq/MJ	grams of CO_2-equivalent per mega-joule
GHG	Greenhouse Gas
GWP	Global Warming Potential
HSFO 3.5% S	High Sulphur Fuel Oil 3.5% Sulphur
ICCT	International Council on Clean Transportation
IFO 380	Intermediate Fuel Oil max. viscosity of 380 centistokes
IMO	International Maritime Organization
JB	Jarque–Bera test
LCA	Life Cycle Assessment
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
MGO 0.1% S	Marine Gas Oil 0.1% Sulphur
MPT	Modern Portfolio Theory
MR	Medium Range
MRQ	Main Research question
MT	Metric Tonnes
NO_x	Nitrogen Oxides
OPS	Onshore Power Supply
PIS	Pertamina International Shipping
SD	Standard Deviation
SI	Supplementary Information
MUSD	Million United States Dollar
RFNBO	Renewable Fuels of Non-Biological Origin
SO_x	Sulphur Oxides
SRQ	Sub-Research Questions
tCO_2eq	tonne of carbon dioxide equivalent
TtW	Tank-to-Wake
VaR	Value-at-Risk
VLGC	Very Large Gas Carriers
VLSFO 0.5% S	Very Low Sulphur Fuel Oil 0.5% Sulphur
WtT	Well-to-Tank
WtW	Well-to-Wake

Chapter 1. Introduction

1.1. Research Background

Maritime transport remains the backbone of global trade, carrying most internationally traded goods by volume. The sector is undergoing structural change shaped by volatile fuel markets, the global energy transition, and increasingly stringent climate regulations, including the International Maritime Organization's (IMO) revised greenhouse gas (GHG) strategy and regional carbon pricing schemes such as the European Union Emissions Trading System (EU ETS) and FuelEU Maritime (UNCTAD, 2023). Bunker fuel typically accounts for 40 to 60% of voyage costs and is a dominant operating expense in shipping. Its price is highly sensitive to oil benchmarks, regional supply–demand imbalances, and geopolitical shocks, making cost predictability a persistent challenge (Stopford, 2009).

Academic and industry research underscores the importance of structured fuel price risk management using forward contracts, swaps, and options, often combined with scenario-based decision tools (Alizadeh & Nomikos, 2004; Wang, Meng, & Tan, 2018). However, these approaches focus mainly on cost stability and rarely integrate environmental compliance—an increasingly critical gap as decarbonisation policies reshape shipping economics.

Pertamina International Shipping (PIS), the shipping arm of Indonesia's state-owned Pertamina Group, faces this dual challenge. In 2023 it operated over 50 global routes and conducted nearly 300 international bunker operations, expanding to 65 routes in 2024. Its fleet includes Very Large Gas Carriers (VLGC), Medium Range (MR) tankers, and dual-fuel ammonia-ready Liquefied Petroleum Gas (LPG) carriers such as Pertamina Gas Dahlia and Pertamina Gas Caspia. The company has strengthened its long-term strategy by investing in dual-fuel-ready assets and expanding into Liquefied Natural Gas (LNG), LPG, ammonia, and biofuel transport (PIS, 2024a). Financial performance has been robust, with net profits of USD 330 million in 2023 and USD 558.6 million in 2024 (PIS, 2024b). Its "green business" segment targets 34 percent of revenue within a decade, positioning the firm to capture emerging clean energy cargo demand (PIS, 2024a). Despite these advances, the company lacks a formal bunker hedging policy or integrated procurement framework, leaving it exposed to price volatility and rising compliance costs.

As PIS evolves from a domestic logistics provider into a global carrier, its exposure to fuel price volatility and environmental regulation intensifies. A procurement strategy is no longer only about reducing cost; it must also anticipate carbon compliance and ESG obligations. To sustain growth, the company requires a forward-looking, data-driven model that links cost control with regulatory planning. This makes the question of how international tanker operators can manage both fuel cost volatility and emissions compliance a timely and essential area of research.

1.2. Problem Statement

1.2.1. Managing Cost Volatility in International Bunker Operations

In international shipping, fuel procurement is both the largest cost component and the most volatile. For PIS, which operated more than 50 global routes in 2023 and 65 in 2024 (PIS, 2024a), exposure to fluctuating fuel prices is a strategic risk. The company conducts up to 300 bunker operations annually, yet continues to rely heavily on spot purchases and lacks a comprehensive hedging framework (PIS, 2024b). This short-term approach reduces cost predictability, weakens profit planning, and heightens vulnerability to oil price surges, geopolitical shocks, and supply disruptions.

Fuel markets have become increasingly unstable due to shifts in refining capacity, cyclical demand, and regulations such as the IMO 2020 sulphur cap. Figure 1 shows weekly bunker prices for Marine Gas Oil (MGO 0.1% S) in Rotterdam, Very Low Sulphur Fuel Oil (VLSFO 0.5% S) in Fujairah, and High Sulphur Fuel Oil (HSFO 3.5% S) in Singapore from 2019 to 2025. MGO's prices swung by more than 150% within a single year, peaking above USD 1,300/tonne in 2022, underscoring the unpredictability faced by spot-dependent operators.

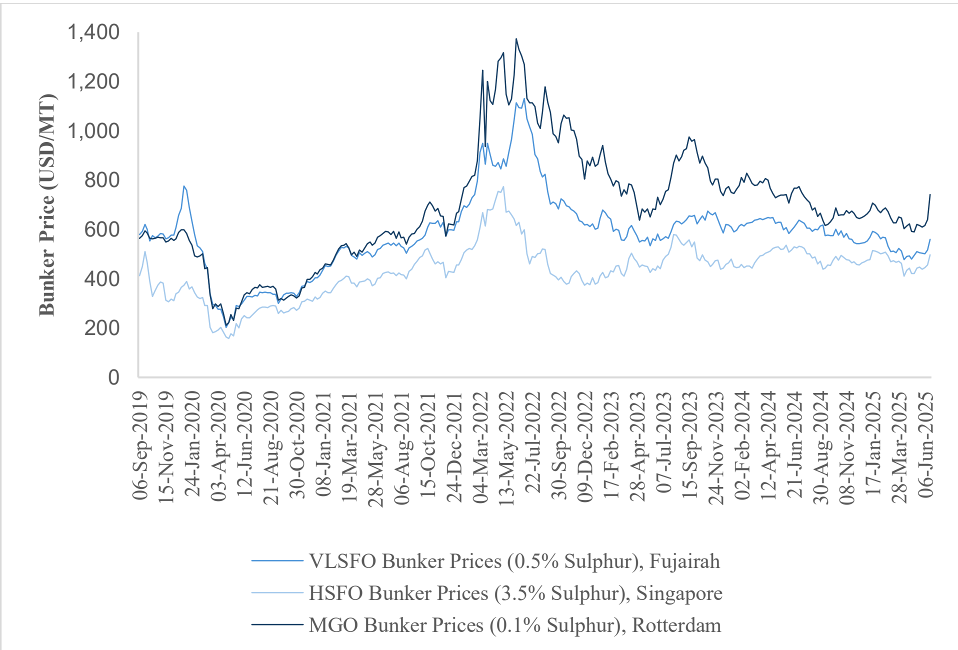


Figure 1: Weekly Bunker Price Trends for VLSFO, HSFO, and MGO (2019-2025)
Source: Author's Compilation based on data of Clarksons Research of PIS's Main Bunkering Ports

Academic research shows that spot-based procurement is suboptimal. Alizadeh and Nomikos (2004) argue that even an inefficient forward bunker market offers cost mitigation opportunities. Wang, Meng, and Tan (2018) demonstrate that quantitative procurement models using scenario-based planning and mean–variance optimisation can reduce exposure and improve cost performance for fleets with predictable demand.

For PIS, the absence of such a framework poses two challenges. First, it limits the ability to strategically time purchases or diversify across ports. Second, it reduces flexibility to capture arbitrage opportunities in price and fuel availability. As the firm expands into competitive international markets, a predictive and resilient strategy becomes urgent. Without it, cost exposure will remain high and opportunities to reinvest buffers into decarbonisation will be lost.

1.2.2. Regulatory Pressures to Reduce GHG Emissions

At the same time, shipping companies face an increasingly strict regulatory landscape. From January 2025, the FuelEU Maritime regulation will impose progressively tighter WtW GHG-intensity reductions for vessels above 5,000 GT calling European Union (EU)/European Economic Area (EEA) ports. Figure 2 shows the trajectory: from 91.16 gCO_2eq/MJ in 2020 to 85.69 in 2030, 62.90 in 2040, and 18.23 by 2050 (DNV, 2024a). Compliance will require not only the use of low-emission fuels but also robust emissions accounting, verified reporting, and possibly the adoption of flexibility mechanisms such as pooling or banking (European Parliament and Council, 2023; DNV, 2024a)

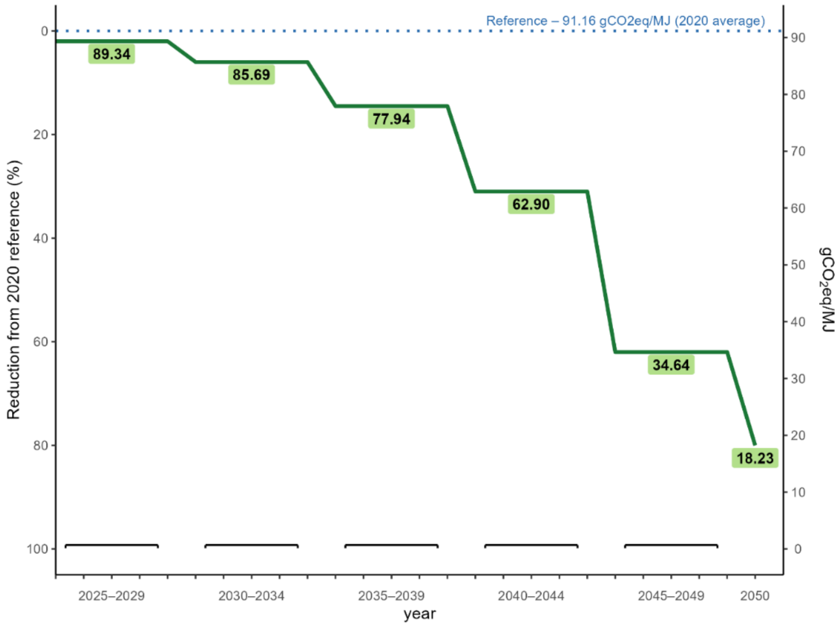


Figure 2: FuelEU Maritime GHG-Intensity Requirements (2025-2050)
Source: Author's Compilation based on data of (DNV, 2024a)

Although headquartered in Indonesia, Pertamina Shipping's growing European exposure places it within scope. Beyond the EU, the IMO is advancing a "basket of measures", including a global fuel standard and possible carbon pricing, targeted for 2027. Fleets that delay transition will face penalties, restricted access, and reduced attractiveness to ESG-conscious stakeholders (DNV, 2024a).

While PIS has begun commissioning dual-fuel vessels and exploring low-carbon fuels, it lacks an integrated emissions roadmap that quantifies fleet-wide intensity, benchmarks against thresholds, and embeds compliance into procurement. Without such a framework, the company risks penalties, competitive disadvantage, and loss of credibility in global markets.

1.2.3. Strategic Interdependence of Cost Volatility and Emissions Compliance

Cost volatility and emissions compliance are interdependent risks. Escalating fuel price swings add cost uncertainty, while tighter environmental regulations increase financial exposure through penalties and carbon pricing. For PIS, these pressures reinforce one another: high prices constrain resources for clean fuel adoption, while delayed compliance leads to additional regulatory costs.

Most research treats these challenges separately, focusing on either hedging or compliance. This siloed view risks fragmented decisions and missed opportunities to link risk management with compliance. The core problem is not only the magnitude of each challenge but the lack of an integrated approach to manage them jointly.

1.3. Research Objectives and Questions

This thesis develops a quantitative and integrated bunker procurement strategy for PIS that addresses the dual challenges of fuel price volatility and tightening GHG compliance. The framework balances cost efficiency with environmental responsibility by combining structured hedging with scenario-based optimisation, while aligning procurement decisions with FuelEU Maritime thresholds. The analysis focuses on the company's EU-bound voyages between 2025 and 2044, examining how procurement planning can improve cost predictability and secure regulatory compliance in a low-carbon shipping environment. To address this objective, the thesis is guided by the following main research question:

"How can Pertamina International Shipping (PIS) optimise its international bunker procurement strategy to manage fuel price volatility, reduce GHG emissions, and comply with FuelEU Maritime regulation?"

To support a structured and detailed analysis, the main question is divided into five sub-questions:

1. How can Pertamina International Shipping (PIS) apply financial instruments and quantitative models to manage bunker price volatility?
2. How do procurement strategies influence well-to-wake GHG emissions across its fleet?
3. How can the cost buffer generated through optimised hedging be reallocated to finance clean-fuel adoption?
4. How can procurement strategies reduce fleet GHG intensity in line with FuelEU targets?
5. How can trade-offs between cost minimisation and GHG compliance be evaluated?

Each sub-question addresses a specific component of the problem: modelling, emissions impact, reinvestment potential, compliance alignment, and cost-compliance trade-offs. They collectively form the foundation of the thesis's methodological and analytical framework.

1.4. Research Relevance

This research addresses a timely challenge in international shipping: how to manage bunker fuel procurement under price volatility while meeting tightening GHG regulations. Its relevance spans both practical decision-making for industry stakeholders and academic debate in maritime economics and logistics.

Practical relevance:

1. Strategic guidance for shipping companies. The study provides procurement managers and shipowners with a structured framework that integrates fuel price risk management and GHG compliance planning, directly aligned with the requirements of the FuelEU Maritime Regulation.
2. Integrated perspective on cost and compliance. It demonstrates how financial risk management and environmental targets can be addressed jointly within a unified procurement model, overcoming the conventional separation between cost efficiency and sustainability strategy.

Academic relevance:

3. Contribution to maritime logistics literature. By combining fuel procurement optimisation with GHG-intensity constraints in a real-world case study of PIS, the thesis addresses a gap in existing research and contributes to the scientific debate on procurement. It advances understanding of how environmental, social, and governance

(ESG)-aligned strategies can be operationalised in tanker shipping, particularly in emerging economies.

1.5. Research Design

This thesis adopts a hybrid research design that combines quantitative modelling with an embedded single-case study to examine how international shipping companies, specifically PIS, can optimise bunker procurement under price volatility and tightening environmental regulations. The framework integrates financial risk management and GHG-intensity constraints into a single decision-support system, enabling procurement planning aligned with FuelEU Maritime decarbonisation objectives.

The research is structured around four interconnected components: quantitative modelling, emissions benchmarking, case study calibration, and methodological grounding. The modelling framework simulates multi-fuel price dynamics and supports scenario-based optimisation of procurement strategies under different risk aversion levels. Emissions benchmarking evaluates the environmental implications of each fuel mix against WtW GHG-intensity thresholds established by FuelEU Maritime. Case study calibration applies the framework to PIS's international operations, drawing on operational, financial, and emissions data to ensure contextual accuracy and managerial relevance. Finally, methodological grounding situates the study within a pragmatic paradigm, combining insights from case study research and operations research to balance analytical rigour with practical applicability.

This integrated design delivers both theoretical contribution and managerial relevance, providing a structured basis for procurement decisions at the intersection of cost management and environmental compliance.

1.6. Thesis Structure

This thesis is organised into six chapters that build the analysis step by step and address the research objectives.

Chapter 1 introduces the research background, problem statement, objectives and questions, relevance, research design, and overall thesis structure.

Chapter 2 reviews academic, regulatory, and industry literature on bunker procurement, price risk management, financial hedging instruments, WtW GHG-intensity modelling, and regulatory compliance strategies in maritime transport. It concludes by identifying gaps in the literature and positioning the thesis within the broader field.

Chapter 3 sets out the research methodology, combining multivariate Dynamic Conditional Correlation (DCC)-Generalized Autoregressive Conditional Heteroskedasticity (GARCH) price simulation, scenario tree construction, and a two-stage optimisation framework within an embedded single-case study of PIS, supported by operational and financial data.

Chapter 4 presents the results from Stage 1 (spot–swap procurement optimisation) and Stage 2 (fuel mix optimisation under emissions constraints), concluding with an integrated cost–GHG trade-off analysis.

Chapter 5 conducts sensitivity analyses on risk aversion, fuel availability, regulatory tightening, and fleet composition changes, incorporating practitioner validation to assess operational feasibility.

Chapter 6 concludes the thesis by summarising key findings, outlining theoretical and managerial contributions, providing recommendations for PIS, and suggestions avenues for future research.

Chapter 2. Literature Review

2.1. Literature Review Approach

This chapter adopts a semi-systematic literature review to examine scholarly, regulatory, and technical sources relevant to bunker fuel procurement under price volatility and tightening GHG-compliance constraints. The aim is to establish a clear conceptual and methodological basis for the thesis and to identify theoretical and empirical gaps that motivate an integrated optimisation model tailored to PIS.

A semi-systematic approach is appropriate given the interdisciplinary scope of the research, spanning maritime fuel economics, stochastic price modelling, environmental life-cycle assessment, and decarbonisation policy. These fields are characterised by rapid regulatory change, heterogeneous data, and diverse academic and institutional contributions. According to Snyder (2019), semi-systematic reviews suit cross-cutting topics where exhaustive protocols are impractical but structured synthesis is essential for theory-building and model design.

The literature reviewed includes peer-reviewed journals (*e.g. Maritime Policy & Management, Transportation Research Part D, Energy Economics, Sustainable Production and Consumption*), together with grey literature from the European Commission, CE Delft, and Det Norske Veritas (DNV), to capture real-world policy mechanisms, market instruments, and decarbonisation benchmarks. Operational and strategic materials from PIS are used to ground the review in practical realities.

The review is organised around five themes aligned with the sub-research questions: (1) marine fuel procurement and cost volatility; (2) stochastic price modelling and optimisation of procurement decisions; (3) WtW GHG emissions of marine fuels; (4) regulatory frameworks under the FuelEU Maritime Regulation and related EU measures; and (5) integration of cost efficiency and environmental compliance in shipping operations. These themes provide the analytical basis for the modelling framework and the case study developed in later chapters.

2.2. Search Strategy

This thesis applies a structured and academically grounded search strategy to identify and synthesise sources relevant to bunker fuel procurement under the dual pressures of price volatility and tightening decarbonisation mandates. The search was designed to ensure thematic coherence, methodological relevance, and balanced coverage of both academic research and institutional perspectives.

The literature search was conducted across major scholarly databases, including *Scopus, ScienceDirect, SpringerLink,* and *Google Scholar*, and supplemented by targeted searches on publisher platforms (*e.g. Elsevier, Taylor & Francis*) and institutional websites such as the European Commission and the International Council on Clean Transportation (ICCT). Grey literature, including white papers from *Transport & Environment* and reports from CE Delft and DNV, was also reviewed to capture industry perspectives and to reflect evolving regulatory frameworks.

Keywords were constructed using Boolean operators to reflect the five thematic domains. These included terms such as *"bunker procurement strategy", "marine fuel price volatility", "GARCH modelling shipping fuel"*, *"well-to-wake emissions", "FuelEU Maritime", "alternative bunker fuel",* and *"stochastic optimisation maritime".* Filters were applied to include English-language sources published between 2000 and 2025, with a focus on studies from the last decade to reflect current market dynamics and regulatory developments.

The final evidence base comprised about 35 academically and thematically significant works. Of these, ten were designated as core sources for their methodological robustness, high citation frequency, and direct alignment with the research questions and modelling framework. These are presented in Table 1, while the remaining 25 sources provide complementary empirical evidence and contextual background, cited in relevant thematic subsections.

This selective but comprehensive approach ensures methodological rigour, provides a solid theoretical foundation for the study, supports the design of the quantitative procurement framework, and reflects the interdisciplinary nature of contemporary maritime decarbonisation research.

Table 1: Key Contribution Sources to the Literature Review

No	Year	Author(s)	Research Subject	Significance
1	2014	Stefanakos & Schinas	Forecasting bunker prices: a non-stationary multivariate methodology.	Proposes a multivariate time-series approach using cointegration with related energy markets to enhance forecasting accuracy. Crucial for generating realistic price scenarios in procurement optimisation.
2	2015	Ghosh, Lee, & Ng	Bunkering decisions for liner shipping under uncertainty with service contracts.	Introduces dynamic programming and simulation to optimise bunkering with fixed contracts under uncertainty. Finds partial hedging strategies to be cost-effective—important for managing risk under variable demand and port availability.
3	2018	Wang, Meng, & Tan	Short-term bunker procurement with swap contracts (mean-variance optimisation using multivariate GARCH).	Demonstrates integration of multivariate GARCH-based scenario generation with quadratic mean–variance optimisation. Key methodological foundation for this thesis's modelling approach.
4	2020	Pavlenko et al. (ICCT)	The climate implications of LNG as a marine fuel (life-cycle GHG analysis).	Independent life-cycle assessment (LCA) warns of limited GHG benefit of LNG under short-horizon metrics due to methane slip. Provides important caution for evaluating LNG in a compliance-sensitive procurement strategy.
5	2022	Bai & Kavussanos	Hedging IMO 2020-compliant fuel price exposure using futures.	Applies copula-GARCH to analyse hedging strategies for VLSFO using Brent and gasoil futures. Demonstrates viable cross-hedging mechanisms applicable to post-IMO 2020 fuel volatility scenarios.

6	2022	DNV	Maritime Forecast to 2050–industry scenarios for decarbonisation.	Provides scenario-based projections for marine fuel transitions and carbon compliance. Informs the future constraints, fuel mix assumptions, and policy pathways embedded in the thesis model.
7	2022	CE Delft	Technical and economic assessment of the FuelEU Maritime and EU ETS proposals.	Provides authoritative policy benchmarks including GHG intensity targets, compliance mechanisms, penalties, and cost impacts on shipping. Serves as a regulatory parameter source for the Stage 2 optimisation model in this thesis, ensuring that GHG targets, penalty costs, and compliance pathways are accurately modelled for PIS.
8	2023	Roux et al.	Life-cycle assessment of maritime fuels: a critical review.	Reviews more than 40 LCA studies, exposing variability in emissions estimates across fuel types. Justifies the use of FuelEU Maritime's standardised WtW benchmark in the thesis.
9	2023	European Commission	FuelEU Maritime Regulation (EU Reg 2023/1805).	Introduces binding emissions-intensity reductions, onshore power supply (OPS) mandates for compliant port calls, and mandatory targets and incentives for renewable fuels of non-biological origin (RFNBOs). These elements are directly integrated into the scenario tree and emissions constraints of the optimisation model.
10	2024	DNV	FuelEU Maritime: requirements, compliance strategies, and commercial impacts.	Interprets the technical, commercial, and compliance implications of the FuelEU Maritime Regulation. Used to translate policy goals into procurement scenarios and benchmark emissions thresholds in the thesis model.

2.3. Cost and Risk Dynamics in Bunker Procurement

Bunker fuel continues to represent a dominant share of operational expenses in shipping, often comprising 40–60% of total voyage costs depending on fuel type and route structure (Stopford, 2009). Such high exposure to fuel price fluctuations creates substantial financial risk for shipowners and operators, making effective procurement strategies critical for maintaining profitability and operational stability.

Early research highlighted the vulnerability of shipping profitability to bunker price volatility. Ghosh, Lee, and Ng (2015) modelled bunkering decisions under uncertainty using a dynamic programming framework combined with Monte Carlo simulation. Their analysis showed that contracting fuel volumes below expected total consumption at a fixed price lower than the anticipated spot average could deliver significant cost advantages. This partial hedging approach enabled operators to achieve price stability while retaining flexibility in volatile markets.

Parallel research has examined the role of financial instruments in mitigating price risk. Alizadeh and Nomikos (2009) pioneered the use of shipping derivatives, including bunker swaps and forward contracts, to manage fuel cost variability. Bai and Kavussanos (2022) extended this by applying a copula-GARCH framework to demonstrate strong statistical dependencies between VLSFO and broader oil markets, including Brent and gasoil futures. Their findings validate cross-hedging as a viable strategy for managing fuel cost exposure in the post-IMO 2020 landscape.

Operational strategies also play a role in procurement resilience. Notteboom and Vernimmen (2009) observed that liner operators adopted slow steaming—reducing vessel speeds—to reduce fuel consumption during price spikes. While not a direct hedging tool, this adjustment complements procurement planning by lowering exposure to fuel cost shocks.

Taken together, these studies indicate that effective bunker procurement under uncertainty involves a multi-pronged approach: combining long-term contracts, spot-market flexibility, financial hedging instruments, and operational adaptations. As fuel markets evolve with the growing adoption of alternative fuels and tightening emissions regulations, procurement strategies must become increasingly dynamic, risk-aware, and aligned with environmental compliance.

2.4. Econometric Modelling of Marine Fuel Prices

A core component of this thesis is the ability to quantitatively anticipate and manage cost volatility in bunker procurement. Marine fuel prices, heavily influenced by global oil markets, refinery economics, and regional demand-supply imbalances, display well-documented patterns of volatility clustering and market shocks. Understanding and modelling this behaviour is essential for informed decision-making, particularly under tightening decarbonisation constraints. Econometric approaches, especially multivariate time-series models and GARCH-family frameworks, provide robust tools for forecasting and simulating fuel prices for integration into stochastic optimisation models.

One foundational contribution in this domain is by Stefanakos and Schinas (2014), who developed a multivariate non-stationary framework for forecasting bunker fuel prices, such as Intermediate Fuel Oil with a maximum viscosity of 380 centistokes (IFO380). By incorporating related energy indices like crude oil and diesel, their model improved forecast accuracy by capturing both long-run co-movement and short-run volatility. This multivariate structure remains especially relevant as bunker price dynamics are increasingly tied to broader energy markets and environmental regulation.

Further advances involve the application of GARCH models, widely used to capture volatility clustering in commodity markets. Wang, Meng, and Tan (2018) extended this approach by calibrating a multivariate GARCH model to simulate spot and swap bunker prices. They used these simulated price paths to generate a scenario tree that reflected joint price uncertainty and applied a mean–variance quadratic programming model to determine optimal procurement strategies. Their findings showed that price scenario modelling is integral to bunker procurement under risk, demonstrating how hedging between spot purchases and swap contracts can reduce volatility exposure. This approach provides a direct methodological foundation for the modelling framework in this thesis.

Although machine learning techniques—such as neural networks or hybrid explainable AI models—are beginning to appear in energy and shipping research, their adoption in peer-reviewed maritime economics remains limited. While they may offer enhanced predictive accuracy, these methods often reduce interpretability and demand extensive datasets, making them less suitable for policy-sensitive and risk-averse contexts such as PIS's procurement planning. For this reason, the thesis prioritises established econometric models, which are more transparent, robust, and compatible with scenario-based optimisation and compliance modelling.

In summary, the literature confirms that multivariate time-series and GARCH-family models are well-suited to simulate marine fuel price behaviour under both market and regulatory uncertainty. These tools provide the quantitative foundation for the scenario-based optimisation framework developed in this thesis. For PIS, the ability to model volatility with precision supports the design of a procurement strategy that minimises expected costs, reduces risk exposure, and embeds compliance with FuelEU Maritime targets.

2.5. Environmental Constraints and Decarbonisation Regulations

2.5.1. Environmental Performance of Marine Fuels

As the maritime sector advances towards decarbonisation, the environmental performance of marine fuels—measured on a WtW basis—has become a critical factor in procurement strategy. This perspective accounts for the full life cycle of emissions: upstream production and transport (well-to-tank) and downstream combustion during vessel operation (tank-to-wake). The WtW approach is increasingly embedded in regulatory frameworks such as the FuelEU Maritime Regulation (CE Delft, 2022; European Parliament and Council, 2023; DNV, 2024a).

Among conventional fuels, VLSFO and HSFO remain widely used but exhibit high WtW carbon intensity. LNG has been promoted as a transitional fuel, offering lower carbon content and significantly reduced emissions of sulphur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter. Industry-commissioned life-cycle assessments, such as SEA-LNG and thinkstep (2019), suggest that LNG can deliver 14–21% GHG reductions compared with HFO on a WtW basis, particularly when deployed in high-efficiency two-stroke engines. However, these reductions are highly sensitive to methane slip and upstream leakage.

Independent studies present a more cautious view. The ICCT (Pavlenko et al., 2020) found that, when evaluated under a 20-year global warming potential (GWP), some LNG engine types, especially low-pressure dual-fuel engines, can produce 70–82% higher GHG emissions than MGO due to unburned methane. This finding challenges the notion of LNG as a long-term climate solution.

Attention has therefore shifted to truly low-carbon alternatives, such as methanol, ammonia and hydrogen produced from renewable electricity, collectively classified as RFNBOs under EU legislation. These fuels offer negligible tank-to-wake (TtW) emissions and, when produced via electrolysis with renewable energy, low well-to-tank (WtT) emissions. Yet, as Roux et al. (2024) note, their benefits depend heavily on production methods, and current costs remain two to five times higher than conventional fuels, constraining large-scale uptake.

Roux et al. (2024) also reviewed more than 40 LCA studies and identified substantial variation in reported emissions results, driven by differences in assumptions, system boundaries and data quality. Such inconsistencies have prompted efforts to standardise emissions accounting. In 2023, the IMO adopted formal guidelines for calculating WtW GHG intensity, providing a basis for comparability and transparency across fuels and propulsion technologies (IMO, 2023).

2.5.2. Regulatory Frameworks Shaping Fuel Procurement

Fuel procurement decisions are now shaped not only by economics but also by an expanding set of climate regulations at both international and regional levels.

At the international level, the IMO's Revised GHG Strategy commits to reaching net-zero GHG emissions by or around 2050, with indicative checkpoints of at least –20% by 2030 and –70% by 2040 compared with 2008 levels (IMO, 2023). These long-term goals are supported by technical and operational measures, notably the Energy Efficiency Existing Ship Index (EEXI) and the Carbon Intensity Indicator (CII), which indirectly affect procurement by rewarding more efficient fuels and penalising carbon-intensive operations.

At the regional level, the EU has introduced binding measures that directly regulate fuel procurement. The FuelEU Maritime Regulation (Regulation EU 2023/1805) mandates progressive reductions in WtW GHG intensity of the energy used on board ships calling at EU/EEA ports, starting with –2% in 2025 and culminating in –80% by 2050, relative to the baseline of 91.16 gCO_2eq/MJ. In addition, FuelEU introduces OPS obligations for containerships and passenger ships at berth from 2030, and sets out mandates and incentives for RFNBOs. RFNBOs benefit from a double-counting mechanism until 2034, and if uptake remains below 1% by 2031, a binding 2% sub-target will apply from 2034 (CE Delft, 2022; European Parliament and Council, 2023; DNV, 2024a).

Complementing FuelEU Maritime, the EU ETS was extended to shipping in January 2024. The ETS requires shipping companies to purchase allowances for verified CO_2 emissions on voyages within the EU and for 50% of emissions on voyages into or out of the EU. Coverage is phased in at 40% in 2024, 70% in 2025, and 100% in 2026. From 2026, methane and nitrous oxide emissions will also be included, creating additional exposure risks for LNG-fuelled ships (European Parliament and Council, 2023; DNV, 2024a).

Together, these policies reshape the cost–benefit calculus of fuel procurement. While clean fuels such as RFNBOs and advanced biofuels are more expensive, they can offset carbon pricing liabilities and ensure long-term regulatory compliance. For PIS, this suggests a strategic shift towards blended procurement strategies—combining VLSFO with biofuels, securing forward contracts for renewable fuels, and investing in vessels with OPS capability and alternative-fuel readiness.

In summary, fuel procurement is no longer determined by cost alone. It must now incorporate lifecycle environmental performance and explicit regulatory compliance. The literature confirms that a multi-criteria evaluation—balancing cost, emissions, and compliance—is essential for building resilient procurement strategies under the climate transition.

2.6. Optimisation Models for Bunker Procurement under Uncertainty

Optimising bunker procurement under uncertainty is a complex but essential task for shipping companies operating in volatile fuel markets under tightening environmental regulations. Traditional cost-minimisation approaches are increasingly inadequate. Firms now require dynamic, integrated decision-support models that capture stochastic price fluctuations, incorporate emissions compliance, and allow operational adaptability. This section synthesises academic and institutional literature that provide the theoretical basis for the stochastic, risk-aware optimisation model developed for PIS.

Stochastic programming has emerged as the dominant methodology in this domain, enabling procurement decisions to be evaluated under multiple plausible future states. One of the most influential studies is by Wang, Meng, and Tan (2018), who developed a scenario-based bunker procurement model incorporating a multivariate GARCH process to simulate the joint dynamics of spot bunker fuel prices and swap contracts. These correlated price paths were used to generate a scenario tree, serving as the foundation for a quadratic mean–variance optimisation framework. The model minimized the variance of procurement costs for a given expected cost, allowing operators to determine optimal hedge ratios between spot purchases and financial instruments. This approach demonstrated strong potential for managing cost volatility in uncertain market conditions.

Complementing this, Ghosh, Lee, and Ng (2015) proposed a dynamic programming model to optimise bunkering strategies in liner shipping, where long-term contracts and port-specific spot prices coexisted. Their simulation-based analysis showed that partial hedging—contracting for fuel volumes below the expected total requirement at fixed prices—outperformed both full hedging and spot-only strategies by preserving flexibility and reducing overcommitment risk. This highlights the critical importance of procurement contract design, especially in multi-port networks with heterogeneous price structures.

In another key contribution, Pedrielli, Lee, and Ng (2015) introduced a bilevel stochastic optimisation model for bunker contract negotiation between ship operators and fuel suppliers. Their game-theoretic approach captured the interaction between buyer and seller objectives under fuel consumption and price uncertainty. The resulting optimal contract structures reflected a shared-risk model, showing that collaborative contracting under uncertainty can yield efficient outcomes for both parties—particularly when market liquidity is limited and volatility is high.

Across these contributions, common elements include rigorous scenario generation, typically combining Monte Carlo simulation, econometric forecasting (e.g. GARCH models), and scenario-tree construction to capture fuel price distributions and operational uncertainties. Optimisation formulations range from quadratic mean–variance models, which assume symmetric risk preferences, to Conditional Value-at-Risk (CVaR) models, which prioritise downside risk protection and are particularly suited to risk-averse shipping operators.

Institutional foresight reinforces the need for robust procurement optimisation. DNV anticipates rising fuel price uncertainty, uneven adoption of alternative fuels, and stronger regulatory effects from FuelEU Maritime and the EU ETS. These developments imply that procurement models must adapt to carbon cost internalisation, binding emissions limits, and constrained fuel availability—especially with the emergence of e-methanol, biofuels, and RFNBOs (DNV, 2024b).

For PIS, these insights emphasise the value of a multi-period stochastic optimisation model that not only hedges price risk but also embeds emissions-related costs and decarbonisation targets. This thesis builds on the reviewed literature by proposing a two-stage framework: Stage 1 focuses on generating a cost buffer through risk-hedged procurement, while Stage 2 reallocates that buffer to meet FuelEU Maritime GHG-intensity constraints. In this way, price-risk management becomes a direct enabler of compliance strategy, producing a procurement model that is both financially resilient and regulation-compliant.

2.7. Summary and Research Gaps

This literature review has integrated scholarly, regulatory, and industry perspectives across five critical domains shaping contemporary marine bunker procurement: (1) fuel cost and risk dynamics, (2) econometric fuel price modelling, (3) well-to-wake environmental performance, (4) international and regional decarbonisation policies, and (5) optimisation models under uncertainty. These interrelated strands collectively establish a comprehensive conceptual and methodological foundation for this thesis, which aims to construct a stochastic, regulation-compliant bunker procurement model for PIS.

The reviewed literature confirms that bunker procurement is no longer driven by cost alone. Increasing price volatility—driven by market fluctuations, fuel market fragmentation, and regulatory uncertainty—has shifted attention towards risk-mitigating strategies such as dynamic hedging and forward contracting. At the same time, fuel procurement decisions are being reshaped by emissions-related policies, such as the FuelEU Maritime Regulation, which imposes explicit WtW carbon intensity thresholds and links compliance to carbon pricing mechanisms.

Econometric methods, particularly multivariate time-series and GARCH-family models are validated as effective for simulating and forecasting marine fuel prices. These tools are widely applied in fuel cost modelling but are rarely embedded into decision-support models for procurement planning. Likewise, optimisation approaches—ranging from dynamic programming to mean–variance and CVaR-based formulations—offer flexible techniques for navigating price risk, but their application to decarbonisation-constrained procurement remains limited.

Despite these contributions, several critical research gaps remain. First, cost and compliance are often treated in isolation, with few studies integrating procurement models that simultaneously address fuel price volatility and regulatory GHG-intensity thresholds. Second, most optimisation frameworks do not incorporate the evolving carbon cost structures introduced by FuelEU Maritime and the EU ETS. Third, a contextual bias persists, since empirical research has focused largely on European liner operators, leaving a gap in understanding procurement strategies in vertically integrated tanker companies such as PIS, which manage fuel procurement internally across global networks. Finally, scenario-based integration remains underdeveloped: although multivariate GARCH and scenario-tree generation are recognised tools for fuel price forecasting, their integration with stochastic optimisation for procurement planning is limited, particularly under dual cost–compliance constraints.

By addressing these gaps, this thesis contributes to the scientific debate on procurement by demonstrating how hedging buffers generated in Stage 1 risk management can be reallocated in Stage 2 to finance the adoption of cleaner fuels. In doing so, it advances both theory and practice, showing how financial risk control can be explicitly linked to regulatory compliance in maritime fuel procurement.

2.8. Conceptual Framework

Building on literature and identified gaps, this thesis integrates two theoretical strands into a unified conceptual framework. The first is Modern Portfolio Theory (MPT), introduced by (Markowitz, 1952), which underpins the use of mean–variance optimisation to manage price risk in bunker procurement portfolios. The second is environmental economics (Pigou, 1920; Tietenberg & Lewis, 2018), which frames emissions regulation as a constrained cost-minimisation problem, where compliance requires balancing fuel expenditures with carbon pricing mechanisms and FuelEU Maritime intensity thresholds.

These strands converge in a sequential two-stage design. In Stage 1, portfolio risk management principles are applied to generate a hedging buffer, expressed as cost reductions in variance and CVaR relative to a spot-only baseline. In Stage 2, this buffer is reallocated into a dynamic fuel-mix optimisation, constrained by FuelEU Maritime targets and EU ETS exposure. This design positions risk management as a direct enabler of cost-effective compliance, linking financial resilience to decarbonisation objectives.

Figure 3 illustrates this conceptual framework, showing how financial and regulatory pressures converge within the two-stage model. It synthesises insights from the reviewed literature and provides the theoretical foundation for the methodological design presented in Chapter 3.

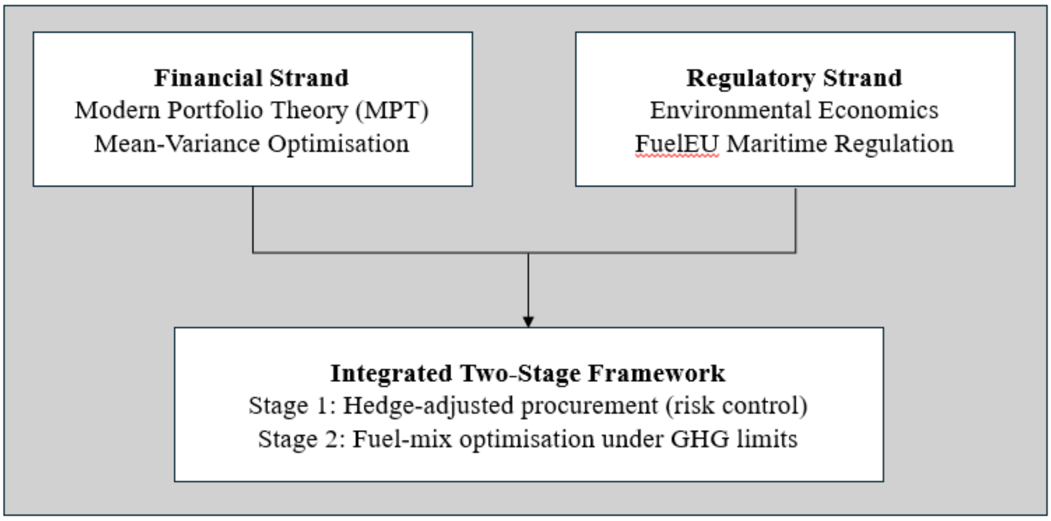


Figure 3: Conceptual Framework of the Two-Stage Bunker Procurement Model
Source: Author's illustration

Chapter 3. Research Methodology

3.1. Methodology Overview

This thesis applies a hybrid methodological framework that combines quantitative modelling with an embedded single-case study to evaluate how PIS can optimise its international bunker procurement strategy under fuel price volatility and FuelEU Maritime compliance. The framework is designed to support decision-making that balances cost efficiency with environmental obligations by integrating price-risk management and emissions benchmarking into a unified procurement model.

The research follows a pragmatic philosophy, which selects methods for their utility in addressing real-world problems rather than adherence to a single tradition (Creswell & Creswell, 2018). This approach is well suited to bunker procurement, where decision-making is shaped by both financial uncertainty and regulatory constraints. Under the FuelEU Maritime Regulation, vessels calling at EU ports must meet progressively stricter WtW GHG-intensity thresholds (European Parliament and Council, 2023). To remain competitive, shipping companies must therefore adopt procurement strategies that are at once cost-effective and regulation-compliant.

To address this challenge, the thesis employs a multi-stage modelling framework. As shown in Figure 4, it consists of three linked layers: inputs, process modules, and outputs, each aligned to sub-research questions (SRQ1–SRQ5) and collectively addressing the main research question (MRQ). Inputs include historical spot and swap bunker prices, monthly fuel demand by port and fuel type, the PIS fleet profile, WtW emission factors, and FuelEU Maritime intensity thresholds.

The first process module applies a multivariate (DCC) GARCH model to simulate monthly bunker fuel price dynamics. This captures volatility clustering and cross-fuel co-movements that are characteristic of global fuel markets (Wang, Meng, & Tan, 2018). The simulated price paths are then embedded in a stochastic scenario tree (Heitsch & Römisch, 2009), which represent a range of plausible market and policy developments.

On this basis, the framework evaluates cost buffers from swap-based hedging strategies. These buffers are measured as reductions in variance and CVaR relative to a spot-only baseline. The associated hedging gains are then allocated as inputs to a fuel-mix optimisation module, where a quadratic program minimises expected cost variance subject to monthly demand and FuelEU GHG-intensity constraints.

The emissions benchmarking module computes fleet-level carbon intensity using well-to-wake factors. Compliance is tested against FuelEU thresholds, with the logic incorporating penalties, EU ETS exposure, and flexibility mechanisms such as banking, borrowing, and pooling. A sensitivity module extends the analysis by varying key assumptions, including levels of risk aversion and access to low-carbon fuels.

The modelling framework is embedded in a single-firm case study of PIS. Calibration uses firm-specific data on bunker volumes, port calls, and procurement patterns, ensuring that model assumptions reflect actual operational practice. This design enables analytical generalisation to other firms with similar regulatory exposure (Eisenhardt, 1989) while maintaining methodological rigour (Gibbert, Ruigrok, & Wicki, 2008).

The hybrid approach provides both analytical depth and managerial value. Methodologically, it integrates the forecasting strength of multivariate (DCC) GARCH models, the scenario-planning capability of stochastic optimisation, the precision of quadratic programming, and the policy logic of FuelEU compliance (Birge & Louveaux, 2011). Substantively, it establishes a mechanism for linking risk management with ESG alignment by translating hedging gains into low-carbon fuel adoption.

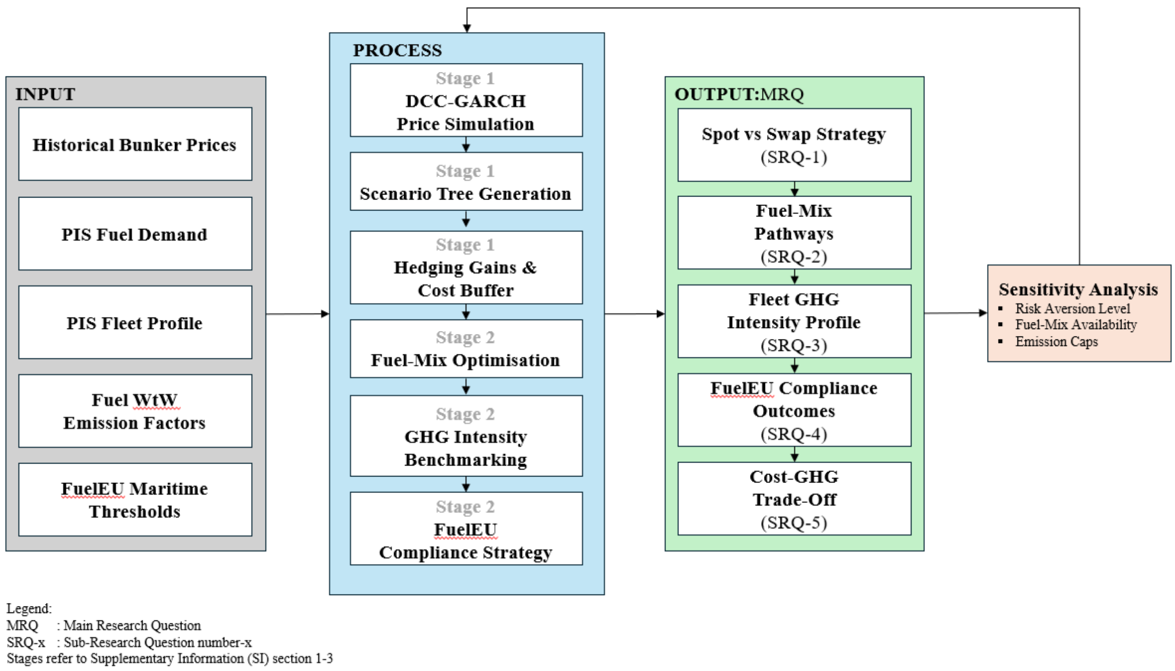


Figure 4: Methodological Framework Diagram
Source: Author's illustration

From a managerial perspective, the framework enables procurement professionals to evaluate cost–compliance trade-offs and to identify strategies that reduce both financial and regulatory risk. It therefore contributes to evidence-based, ESG-aligned planning in the transition to low-carbon shipping.

In sum, this study delivers both theoretical and applied contributions. It extends maritime fuel procurement literature by demonstrating how financial and environmental objectives can be modelled jointly, and it offers a transferable decision framework that shipping firms can use to design forward-looking, regulation-resilient procurement strategies.

3.2. Input Data

This study integrates both primary and secondary data sources to calibrate a quantitative model that reflects PIS's international bunker procurement environment. The dataset is structured to support the four methodological components: price simulation, scenario generation, optimisation, and emissions benchmarking. Together, these inputs create a decision-support framework aligned with both commercial practice and regulatory compliance. Preprocessing details, file schemas, and run order are documented in the Supplementary Information (SI) file in section S0.2–S0.4, with exact script execution listed in Appendix B (Replication Checklist) and Appendix C (R-File Map).

3.2.1. PIS Operational and Procurement Data

Primary data were obtained from PIS's internal bunker procurement logs (2023–2024), including port-specific volumes, fuel types, and transaction timing. These records form the basis for the monthly demand constraints in the optimisation model. Where gaps existed, assumptions were benchmarked against prevailing tanker fleet practices.

The case study focuses on bunker purchases at major refuelling hubs such as Singapore, Rotterdam, Fujairah, and Houston, reflecting PIS's international footprint. Port-level access to alternative fuels (e.g. e-methanol, biofuels, ammonia) was discretised based on infrastructure readiness and supplier presence. These operational data ensure that the optimisation model reflects PIS's actual procurement demand and hub structure.

3.2.2. Fuel Price Data

Historical spot prices were sourced from Clarkson's SIN, Platts Bunkerwire, AFI-DNV, and Ship & Bunker. Data are expressed in USD/tonne and compiled weekly. The fuel set includes VLSFO (0.5% S), HSFO (3.5% S), MGO (0.1% S), LPG, bio-LPG, bio-MGO, e-methanol, and blue ammonia. These fuels were selected for their commercial relevance and regulatory recognition under FuelEU Maritime. The price sample spans September 2019–June

2025, providing sufficient depth to calibrate the multivariate (DCC) GARCH price simulation in Section 3.3.

3.2.3. Emission and Regulation Data

Emission factors were drawn from FuelEU Maritime Regulation and supporting studies (CE Delft, 2022; European Parliament and Council, 2023; DNV, 2024a) and harmonised with life-cycle assessment data (Bouman et al., 2017). The model adopts WtW GHG-intensity factors (gCO_2eq/MJ), distinguishing between higher- and lower-intensity fuels. FuelEU's carbon intensity threshold begins at 89.34 gCO_2eq/MJ in 2025 and declines progressively toward 2044. Thresholds are implemented in the optimisation model both as binding constraints and as penalty triggers, consistent with SI Stage 2 (S17–S19).

3.2.4. Scenario Parameters and Forward Assumptions

Probabilistic assumptions on future prices, clean-fuel availability, and regulatory tightening were informed by DNV's Maritime Forecast to 2050, EU implementation reports, and maritime decarbonisation roadmaps. These assumptions are not empirically calibrated but provide structured uncertainty inputs for the stochastic scenario tree in Section 3.3.2. This ensures that scenario generation reflects expert forecasts of long-term market evolution rather than extrapolations from the calibration dataset.

3.2.5. PIS Fleet Exposure

PIS's exposure to FuelEU Maritime was modelled by mapping fleet operations against EU/EEA port calls. Based on 2023–2024 operations, PIS conducted approximately 300 international voyages outside Indonesia, with a subset calling at EU compliance ports (PIS, 2024a). Vessels were assigned route-level FuelEU exposure, and dual-fuel capacity was coded where applicable. Fuel-type constraints reflect PIS's current spot-based procurement practice, adjusted for anticipated access to cleaner fuels at major hubs. These mappings establish which portions of PIS's bunker demand fall under FuelEU jurisdiction, forming the exposure basis for the optimisation model.

Table 2: Summary of Data Sources and Usage

No	Data Type	Variables	Sources	Model Use
1	Operational Data	Bunker volumes; fuel types; ports; timing.	PIS internal reports (2023–2024); PIS Annual Report (2023-2024).	Demand constraints.

2	Fuel Price Data	Fuel Prices (USD/tonne).	PIS reports; Clarkson's SIN; Platts Bunkerwire; AFI-DNV; Ship & Bunker.	Multivariate (DCC) GARCH simulation input.
3	Emissions Factors	Lower Heating Value (LHV); WtW GHG intensity (gCO_2eq/MJ).	Regulation (EU) 2023/1805; CE Delft; DNV; Bouman et al. (2017).	Fleet emissions benchmarking.
4	Regulatory Benchmarks	FuelEU thresholds; penalties rate; EU ETS prices.	Regulation (EU) 2023/1805; CE Delft; DNV; Clarkson's SIN.	Compliance constraints and penalty modelling.
5	Scenario Assumptions	Risk aversion levels; fuel-mix availability; regulatory tightening.	PIS reports; DNV; Maritime decarbonization roadmaps.	Define scenario and sensitivity analysis.

Source: Author's compilation; preprocessing and file integration in SI S0.2–S0.4.

By integrating quantitative datasets with case-specific context, this section ensures that the optimisation framework is grounded in operational reality while embedding the regulatory rigour required under FuelEU Maritime. Full preprocessing logic, file structures, and replication steps are documented in the SI (S0.2–S0.4, Appendix B–C).

3.3. Price Simulation and Scenario Tree

This section models marine fuel price volatility using a multivariate (DCC) GARCH structure and constructs a discrete-time stochastic scenario tree. Together, these form the uncertainty layer of the optimisation framework, enabling forward-looking procurement planning under cost and availability risk. Model specification, diagnostics, and simulation steps are documented in SI Stage 1 (S1–S4).

3.3.1. Fuel Price Simulation Using Multivariate (DCC) GARCH

Fuel prices in international bunkering markets display sharp volatility, driven by macroeconomic shocks, supply disruptions, and regulatory changes. To capture this uncertainty, the model applies a multivariate (DCC) GARCH approach (Engle, 2002), which models both time-varying volatilities and dynamic cross-fuel correlations. Each fuel series is estimated as a univariate GARCH (1,1) process, with margins specified under a skewed Student-t distribution to reflect the fat-tailed nature of fuel price returns (see SI S1.2). The conditional variances are coupled through the DCC structure, producing a time-varying covariance matrix that captures co-movements across fuels.

Let $r_t \in \mathbb{R}^n$ denote the *n*-dimensional vector of fuel returns at time *t*. The conditional covariance matrix H_t as:

$$H_t = D_t R_t D_t$$

where $D_t = diag(\sqrt{h_{1t}}, \sqrt{h_{2t}}, \ \ldots, \ \sqrt{h_{nt}})$ is the diagonal matrix of conditional standard deviations from univariate GARCH (1,1) processes, and R_t is the time-varying correlations matrix. Each variance h_{it} evolves as:

$$h_{it} = \ \omega_i + \ \alpha_i \epsilon_{i,t-1}^2 + \ \beta_i h_{i,t-1}$$

where $\omega_i > 0$, $\alpha_i \geq 0$, and $\beta_i \geq 0$ are parameters estimated for each fuel series *i,* and $\epsilon_{i,t-1}$ is the lagged residual return.

The dynamic correlation matrix R_t is obtained by normalizing the conditional covariance matrix Q_t:

$$R_t \ = \ diag\ (Q_t)^{\left\{-\frac{1}{2}\right\}} Q_t diag(Q_t)^{\left\{-\frac{1}{2}\right\}}$$

with Q_t updated as:

$$Q_t \ = \ (1 \ - \ a \ - \ b)\bar{Q} + \ a\, z_{\{t-1\}}\, z_{\{t-1\}}^{\top} \ + \ b\, Q_{\{t-1\}}$$

where $Z_t = \ D_t^{-1} \epsilon_t$ are standardised residuals, $\bar{Q}$ is the unconditional covariance matrix of Z_t, and a and b are scalar DCC parameters.

The model is calibrated on weekly spot prices (USD/tonne) for HSFO, VLSFO, and MGO from September 2019 to June 2025, aggregated to monthly frequency. Simulation produces 500 Monte Carlo paths of monthly prices (2025–2044), capturing realistic cross-fuel volatility and co-movement.

This approach extends the multivariate GARCH-based procurement models of Wang, Meng, and Tan (2018) embedding them in a multi-fuel, emissions-constrained context relevant under FuelEU Maritime.

3.3.2. Scenario Tree Generation

The simulated price paths are used to generate a stochastic scenario tree, discretising the uncertain future into a finite set of decision-relevant trajectories. The scenario tree consists of a finite set of paths $\boldsymbol{S} = \{1, 2, \dots, S\}$, where each scenario s represents a sequence of monthly fuel price realizations over the planning horizon **T**. For each scenario $s \in S$, the model assigns a probability p_s, where:

$$\sum_{s=1}^{S} p_s = 1$$

Each scenario is defined by a time-indexed fuel price vector:

$$\boldsymbol{P}_s^t = \left[P_{s,1}^t, P_{s,2}^t, \dots, P_{s,n}^t\right]^T \in \mathbb{R}^n$$

where $\boldsymbol{P}_s^t$ represents the vector of simulated spot prices (USD/tonne) at time t under scenario s, and n is the number of fuel types considered. These vectors form the basis of the cost structure input into the procurement model.

To manage dimensionality, the model applies backward scenario reduction (Heitsch & Römisch, 2003; Heitsch & Römisch, 2009), retaining a subset of paths that preserve the first and second moments of the full simulation. Each node corresponds to a monthly market state, defined by the fuel price vector. While prices are stochastic, FuelEU Maritime thresholds are deterministic constraints imposed along all paths.

The expected cost of procurement across all scenarios is computed as:

$$\mathbb{E}[C] = \sum_{s=1}^{S} p_s \sum_{t=1}^{T} C_s^t$$

where C_s^t is the cost of the fuel mix procured at time t under scenario s, based on the scenario-specific prices $\boldsymbol{P}_s^t$. This structure allows the optimiser to choose fuel procurement strategies that are robust to a range of market futures.

3.4. Optimisation Framework

At the core of this thesis is a two-stage optimisation model that guides monthly bunker procurement under fuel price uncertainty and FuelEU Maritime compliance. The model is formulated as a multi-stage stochastic quadratic program, where procurement decisions are made dynamically across time and scenarios.

In the first stage, the model determines the optimal split between spot and swap contracts by minimising a mean–variance objective. This formulation balances expected procurement costs against risk exposure and generates a cost buffer, expressed as reductions in variance and CVaR, rather than absolute cost savings.

The second stage reallocates the hedging gains from Stage 1 into a fuel-mix optimisation problem. Here, the objective is to construct a procurement strategy that satisfies operational demand while meeting WtW GHG-intensity thresholds imposed by FuelEU Maritime. In this way, financial risk protection from Stage 1 is directly linked to regulatory compliance in Stage 2.

The evaluation of risk follows the framework of Rockafellar & Uryasev (2000). Risk metrics including mean, variance, Value-at-Risk (VaR), and CVaR are calculated for the simulated procurement costs. Detailed formulations and implementation are provided in SI Stage 1 (S1.4.–S1.5). The portfolio and port-sum CVaR buffer is defined in SI S15–S16, and the complete optimisation run, including outputs, is documented in the SI replication checklist.

3.4.1. Stage 1: Spot Vs. Swap Cost Optimisation

The first stage evaluates procurement strategies across scenarios by minimising a risk-adjusted expected cost function. Let the following variables and parameters be defined:

$x_{f,t,s}$: volume (in metric tonnes) of fuel type *f* procured at time *t* in scenario *s*

$\boldsymbol{P}_{f,t,s}$: unit price of fuel *f* at time *t* in scenario *s* (USD/tonne)

d_t: total bunker demand at time *t* (tonnes)

p_s: probability of scenario $s \epsilon \boldsymbol{S}$

λ : risk aversion parameter

C_s^t : procurement cost at *t, s*

The expected procurement cost across all scenarios is expressed as:

$$\mathbb{E}[C] = \sum_{s \epsilon S} p_s \sum_{t=1}^{T} \sum_{f=1}^{n} P_{f,t,s} \cdot x_{f,t,s}$$

To capture risk aversion and volatility in procurement expenditure, a quadratic penalty on cost variance is introduced. The objective function becomes a mean–variance formulation, as commonly applied in fuel procurement literature (Wang, Meng, & Tan, 2018):

$$min\, x_{f,t,s} \, \{\mathbb{E}[\boldsymbol{C}] + \lambda \,. Var\, [C]\}$$

where $\lambda \geq 0$ is the risk aversion coefficient. The variance term is estimated over the scenario set using the weighted standard deviation of total procurement costs. The decision variables are subject to the following constraints:

1. Demand balance:

$$\sum_{f=1}^{n} x_{f,t,s} = d_t, \quad \forall t, \forall s$$

2. Fuel mix capacity:

$$x_{f,t,s} \leq \bar{x}_{f,t}, \ \ \forall f, t, s$$

3. Non-negativity:

$$x_{f,t,s} \geq 0, \ \ \forall f, t, s$$

The output of Stage 1 is a scenario-dependent hedge strategy that balances expected procurement cost and expenditure risk across ports and fuel types.

3.4.2. Stage 2: Fuel-Mix Optimisation Under Emission Constraints

Stage 2 builds on Stage 1 by reallocating hedging gains into cleaner fuels to achieve FuelEU compliance. The objective is to minimise total cost, defined as:

$$Total\ Cost = Fuel\ Expenditure + ETS\ Liabilities + FuelEU\ Penalties$$

subject to annual WtW GHG-intensity and feasibility constraints.

Each fuel type *f* included in the procurement model is assigned a WtW GHG-intensity value e_f (gCO_2eq/MJ). The average fleet GHG intensity is:

$$\boldsymbol{GHG}_{avg} = \frac{\sum_{s \in S} p_s \sum_{t=1}^{T} \sum_{f=1}^{n} e_f \cdot x_{f,t,s}}{\sum_{s \in S} p_s \sum_{t=1}^{T} \sum_{f=1}^{n} x_{f,t,s}}$$

The compliance constraint imposed by the FuelEU Maritime Regulation is:

$$\boldsymbol{GHG}_{avg} \leq \tau_t$$

where τ_t is the FuelEU threshold. This constraint ensures that any selected procurement plan remains compliant over the regulatory horizon. If $\boldsymbol{GHG}_{avg} > \tau_t$, penalty costs are applied, consistent with SI Stage 2 (S20–S21).

Stage 2 produces optimised fuel-mix pathways, fleet GHG-intensity trajectories, and regulatory cost implications. These results provide the basis for the cost–GHG trade-off analysis in Chapter 4 and the sensitivity tests in Chapter 5.

3.5. Cost-GHG Trade-Off and Sensitivity Testing

This section extends the optimisation framework to evaluate how bunker procurement strategies balance financial efficiency and GHG compliance. The model integrates cost and emissions accounting to generate a cost–GHG frontier, and it subjects the results to systematic sensitivity analysis. Energy, emissions, and compliance mechanics are implemented in SI Stage

2 (S17–S21), while sensitivity modules are documented in SI Stage 3 (S23–S26). Outputs and replication steps are listed in the SI replication checklist.

3.5.1. Cost-GHG Trade-Off Analysis

Each procurement strategy yields two scenario-weighted outcomes: the expected cost and the associated fleet WtW GHG intensity. Together, these define a strategic trade-off space in which PIS must operate. The underlying GHG intensity formula and compliance condition are introduced in Section 3.4.2 and detailed in SI S17–S19, where FuelEU thresholds are embedded as constraints or penalty triggers.

By solving the model under progressively stricter FuelEU intensity thresholds, the optimisation produces a cost–GHG frontier. This frontier quantifies how financial outlays rise as emissions are reduced, illustrating the marginal cost of compliance. It provides decision-makers with a structured basis for comparing optimal fuel portfolios not only in terms of procurement expenditure but also by their regulatory alignment and environmental performance.

3.5.2. Sensitivity Testing Design and Scenarios

The robustness of the optimisation framework is assessed through a suite of sensitivity analyses that vary critical assumptions. The first-dimension concerns risk aversion (λ), shifting from a cost-minimising stance ($\lambda = 0$) to highly risk-averse settings, thereby capturing the transition from aggressive cost minimisation toward stability-focused procurement. The second dimension adjusts fuel availability, restricting or expanding access to low-carbon fuels in order to test operational feasibility under alternative supply and infrastructure conditions, as implemented in SI S24. A third dimension explores regulatory stringency, tightening FuelEU thresholds beyond the baseline trajectory to simulate accelerated decarbonisation scenarios, consistent with SI S19. Finally, changes to fleet composition, including dual-fuel capability and alternative-fuel readiness, are introduced to evaluate the influence of technological transition pathways, as documented in SI S23–S26.

In addition to these four principal dimensions, further scenarios capture corporate or charterer-driven measures, such as a post-2035 VLSFO reduction, to assess voluntary decarbonisation commitments. Each of these modules is executed using batch scripts in SI Stage 3, ensuring transparency and reproducibility. Together, they produce a forward-looking risk map of procurement outcomes under varying assumptions of market volatility, regulatory tightening, and fleet transition, thereby confirming whether the procurement strategy remains resilient under deep uncertainty.

3.6. Case Study Calibration

To ensure that the optimisation framework reflects operational reality, the model is calibrated through an embedded single-case study of PIS. This case study design grounds the model in practice and ensures that its results are consistent with the firm's regulatory exposure and procurement behaviour.

PIS has expanded internationally, with up to 300 bunker operations outside Indonesia recorded in 2023 (PIS, 2024a). A growing share of its fleet calls at ports in the EU/EEA bringing the company under the FuelEU Maritime Regulation. Although dual-fuel vessels are being introduced, procurement remains dominated by the spot market, leaving the firm highly exposed to price volatility and emissions risk.

Calibration integrates monthly fuel demand profiles based on historical procurement data, segmented by vessel type, port cluster, and fuel type. FuelEU thresholds and WtW emission factors are embedded as constraints, consistent with SI Stage 2 (S17–S19). Compliance zones are assigned using 2023–2024 routing data, ensuring that fleet deployment is correctly mapped to FuelEU jurisdiction.

Constraints are customised to PIS's procurement practices. These include monthly procurement caps per fuel–port pair, cashflow ceilings for swap contracts, and compatibility restrictions linked to vessel propulsion systems. The constraint set was developed using internal policy documents and technical fleet data.

Through this calibration, the optimisation model becomes a firm-specific decision-support tool that reflects PIS's operating environment while retaining a transferable structure applicable to other shipping firms with similar regulatory and cost exposures.

3.7. Tools and Computational Environment

The quantitative analysis in this thesis relies on a reproducible, open-source computational environment. All models, simulations, and visualisations were developed in R (version 4.5.0), an established statistical computing environment widely used in econometrics and finance (R Core Team, 2024). The R ecosystem provides robust libraries for time-series modelling, stochastic optimisation, and graphics, which were critical to implementing the hybrid methodology.

To support transparency, Table 3 summarises the computational tools and packages used in this thesis. Each tool is mapped to its primary function within the modelling framework, ranging from econometric estimation to data handling, risk metric computation, and figure production. Detailed package versions, script order, and replication steps are provided in the SI (S0.1–S0.4; Appendix B–C).

Table 3: Tools and Packages Used in the Thesis

Tool/Package	Purpose in Thesis
R 4.5.0	Statistical computing environment for all modelling and analysis.
rugarch / rmgarch / fGarch	Multivariate (DCC) GARCH estimation of bunker price dynamics.
PerformanceAnalytics / FinTS / tseries	Risk metrics (mean, variance, VaR, CVaR) and diagnostic testing (JB, ADF, ARCH-LM).
dplyr / tidyr / readxl / readr / lubridate / xts / zoo	Data preprocessing, transformation, and time-series structuring.
ggplot2 / cowplot / magick / grid	Data visualisation, figure assembly, and multi-panel graphics for thesis figures.
Replication controls	set.seed(12345) for reproducibility; sessionInfo() log for package versions.

Source: Author's compilation based on (R Core Team, 2024)

3.8. Reproducibility and Execution

This thesis is fully reproducible from raw inputs to final figures. All analyses are executed in R 4.5.0 using fixed random seeds and relative paths. Package versions and system details are logged with sessionInfo() as documented in SI S0.1. The project structure assumes a single root directory, with data/ for inputs and output/ for results, ensuring portability across machines.

Randomness is controlled by calling set.seed(12345) at the start of each stochastic procedure, including price simulation and scenario sampling. This guarantees that identical results are obtained when scripts are re-run. Environment logs and run metadata are stored in the output/ directory, following the procedures outlined in SI S0.

Reproducing the results of Chapters 3–5 requires following the Replication Checklist (Appendix B) and the R-File Map (Appendix C). Stage 1 generates simulation and hedging outputs (e.g. sim_all.csv, hedge_optimisation_yearly_all.csv); Stage 2 produces fuel-mix and compliance outputs (fuel_mix_results_*.csv); Stage 3 executes sensitivity scenarios; and Stage 4 assembles all figures. File dependencies and their downstream uses are listed in SI S0.4.

Quality checks are embedded in each stage. These include diagnostics for the multivariate (DCC) GARCH fit, feasibility checks in the optimisation runs, and consistency checks on scenario outputs. Results of these checks are saved alongside outputs, ensuring that every figure and table in Chapters 4 and 5 can be reproduced exactly from the documented inputs, code, and execution order.

3.9. External Validation

To strengthen the methodological robustness of the optimisation framework, the study incorporates external validation through structured consultations with PIS's manager in procurement, commercial, and supply chain functions. These discussions were designed to verify the realism of modelling assumptions, confirm the operational relevance of decision variables, and ensure that the optimisation framework was consistent with actual decision-making contexts.

Validation followed a two-step process. First, assumption checks were conducted on planning horizons, port-level fuel availability, spot-versus-swap contracting structures, and the dual compliance modes applied in the model (strict constraint versus penalty-based). Second, output indicator reviews assessed whether scenario-based cost and compliance projections could be interpreted and applied by managers in practice.

This external validation process established the credibility of the framework and its applicability to PIS's procurement environment, while also clarifying which modelling elements required targeted sensitivity analysis. The detailed design of these sensitivity modules is documented in SI Stage 3 (S23–S26), and the findings from external are presented in Chapter 5.

3.10. Methodological Limitations

While the proposed optimisation framework offers a structured tool for cost–compliance planning in bunker procurement, several simplifying assumptions and methodological limitations must be acknowledged. These relate to demand modelling, price simulation, emissions benchmarking, fuel availability, and generalisability beyond the PIS case.

First, the model assumes deterministic monthly fuel demand across the forecast horizon. In reality, consumption fluctuates with vessel scheduling, cargo flows, and weather conditions. This assumption simplifies optimisation but may understate variability in fleet operations.

Second, the fuel price simulations rely on a multivariate (DCC) GARCH process calibrated to historical data. While this approach captures volatility clustering and cross-fuel correlations, it implicitly assumes that past dynamics persist into the future. Structural breaks such as geopolitical shocks, new fuel taxation regimes, or infrastructure transitions are not fully represented.

Third, emissions intensity factors are treated as fixed values for each fuel, based on FuelEU Maritime benchmarks and published life-cycle assessments. In practice, well-to-wake emissions vary by feedstock, supply chain, and combustion conditions. Benchmarking in this study should therefore be interpreted as indicative rather than precise.

Fourth, fuel availability is represented through deterministic port–fuel access matrices. This reflects current infrastructure but does not adapt dynamically to future port developments or supplier strategies, limiting responsiveness to medium-term market evolution.

Finally, although the model is calibrated to PIS using operational and strategic data, findings may not generalise to all shipping firms. PIS's exposure profile, ownership structure, and procurement strategy differ from those of European container carriers or short-sea operators.

Despite these limitations, the framework provides a robust and transferable foundation. Its integration of stochastic price simulation, optimisation, and regulatory benchmarking enables systematic decision support under uncertainty. Future research may extend the model by incorporating real-time operational data, adaptive learning for price dynamics, and endogenous fuel availability, thereby improving responsiveness and predictive accuracy.

In summary, this chapter 3 has outlined the methodological framework, data sources, optimisation design, and validation approach used to evaluate PIS's bunker procurement strategy under fuel price volatility and FuelEU Maritime regulation. The framework integrates price simulation, hedging optimisation, fuel-mix planning, compliance benchmarking, and sensitivity testing, all calibrated to PIS's operational context and documented in the SI for reproducibility. The following chapter presents the results generated by this framework, beginning with the spot-versus-swap hedging analysis and proceeding to fuel-mix optimisation, emissions benchmarking, and compliance outcomes.

Chapter 4. Results and Analysis

4.1. Introduction

This chapter presents the results of the two-stage integrated optimisation framework developed in Chapter 3, applied to PIS's EU-bound voyages over the 2025–2044 horizon. The analysis evaluates how coordinated bunker procurement and fuel-mix reallocation can jointly address the dual challenges of fuel price volatility and compliance with the FuelEU Maritime Regulation's WtW GHG-intensity limits.

Stage 1 focuses on procurement cost-risk management. Forward price paths for VLSFO, HSFO, and MGO at PIS's primary bunkering ports are simulated using a multivariate (DCC) GARCH model, capturing both volatility clustering and cross-fuel correlations. These simulated prices paths feed into a mean–variance optimisation framework, which determines the optimal allocation between spot purchases and swap contracts under varying levels of risk aversion. The results identify $\lambda = 0.5$ as the most cost-efficient strategy, balancing expected cost minimisation with reduced variability and lower CVaR.

Stage 2 builds on this $\lambda = 0.5$ hedge-adjusted baseline by reallocating fuel volumes across ports and fuel types to meet the annual WtW GHG-intensity thresholds mandated under FuelEU Maritime for 2025–2044. The model incorporates port-level energy demand forecasts, fuel-specific lifecycle emission factors, and the regulation's penalty structure for non-compliance. Results compare a baseline fuel mix, reflecting PIS's 2024 EU voyage profile, with a compliance-oriented strategy that dynamically blends MGO and LPG to close the GHG-intensity gap while maintaining operational feasibility.

The results from Stage 1 are reported in Section 4.2, while Section 4.3 presents the Stage 2 outcomes, including fuel-mix optimisation, compliance performance, and cost implications. These results are examined alongside the FuelEU Maritime flexibility mechanisms and the technical readiness of PIS's fleet to adopt low-emission fuels.

Together, the findings provide an integrated assessment of how PIS can enhance cost predictability and manage regulatory exposure through a unified procurement–compliance strategy. They also form the analytical basis for the sensitivity analysis in Chapter 5. All figures in Chapter 4 are generated through SI Stage 4 (Figures & Assembly) using outputs from SI Stages 1–2, with filenames documented in the Replication Checklist (Appendix B).

4.2. Spot vs. Swap Strategy

This section presents the results of the Stage 1 procurement model, evaluating how spot and swap strategies perform under price uncertainty for PIS's international bunker operations. Monthly spot and swap price scenarios for VLSFO, HSFO, and MGO at PIS's main bunkering ports are simulated over the 2025–2044 horizon using a multivariate (DCC) GARCH model. These simulated paths are embedded in a mean–variance optimisation framework that determines the optimal monthly hedge ratios, balancing expected procurement costs against volatility and downside risk. The analytical structure follows the two-stage methodology proposed by (Wang, Meng, & Tan, 2018), but is adapted to the operational and regulatory context of PIS.

The analysis proceeds in two steps. First, a descriptive assessment of PIS's historical procurement records highlights the variability of bunker prices, the concentration of purchase volumes across ports, and the observed co-movement of fuel price series. Particular attention is paid to the standard deviation of bunker prices, which is used as a statistical indicator of procurement risk and serves as a central input to the optimisation process.

Second, the model results are presented, comparing three procurement strategies: spot-only, swap-only, and dynamically optimised hybrid portfolios. Cost–risk trade-offs are evaluated under varying levels of risk aversion (λ), with emphasis on the $\lambda = 0.5$ configuration that delivers a balanced compromise between expected cost minimisation and reduced variance. Port-specific hedge ratios, efficient frontiers, and risk profiles are reported to illustrate how the buffer generated in Stage 1 can be used as a foundation for Stage 2 fuel-mix optimisation.

All frontiers, hedge-ratio profiles, and risk tables are generated from SI Stage 1 outputs and assembled via SI Stage 4 (Figures & Assembly). Risk metrics—including mean, variance, VaR, and CVaR—are calculated as specified in SI S9–S12, while the portfolio and port-sum CVaR buffer follows SI S13–S16.

4.2.1. Descriptive Statistics of Historical Procurement

Over 2023–2024, PIS executed 547 bunker transactions amounting to 359,649 MT of fuel across its international operations (see Appendix C, Table C1). Figure 5 illustrates the aggregate distribution by fuel type. VLSFO consistently dominated procurement, accounting for 79% of total volume in 2023 before declining to 59% in 2024, reflecting both market availability shifts and deliberate rebalancing towards HSFO, which rose from 16% to 34%.

MGO maintained a marginal but strategically important share (6–7%), primarily to cover operational compatibility requirements.

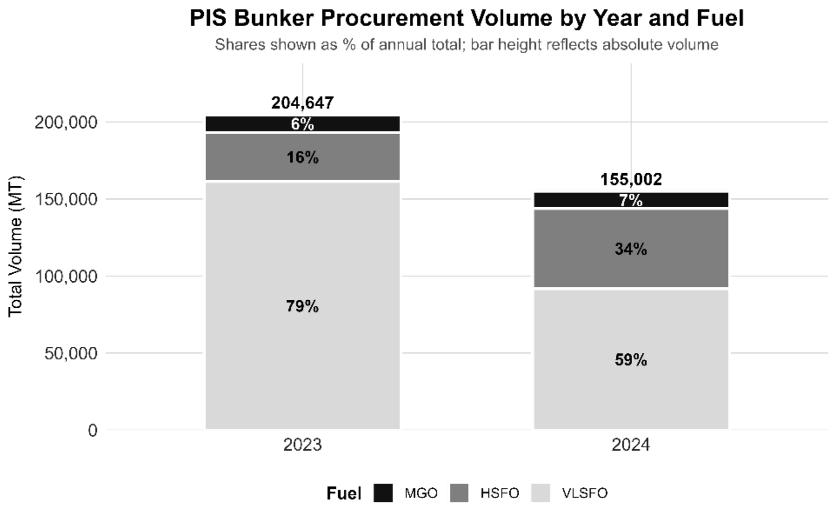


Figure 5: PIS Bunker Procurement Volume by Year and Fuel Type, 2023-2024
Source: Author's compilation based on company procurement records (see Appendix C, Table C1)

Average tender prices and their variability are summarised in Figure 6, with full statistics presented in Appendix C (Tables C1). Across both years, MGO was the most expensive fuel (USD 816/MT in 2023; USD 748/MT in 2024) and displayed the highest volatility, with standard deviations exceeding USD 110/MT in 2023. This made MGO a prime candidate for hedging protection, despite its relatively low share of volumes. By contrast, VLSFO prices were more stable, averaging USD 617/MT in 2023 and USD 611/MT in 2024 with standard deviations below USD 50/MT, but its dominant volume amplified cost exposure. HSFO was consistently the cheapest fuel option (USD 553/MT in 2023; USD 495/MT in 2024), but volatility remained significant, particularly in 2023 (SD = USD 106/MT).

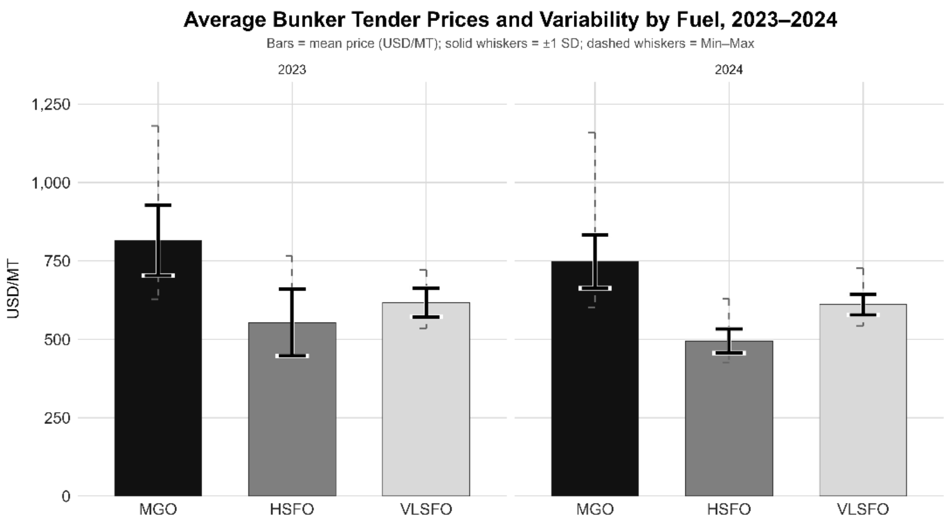


Figure 6: Average Bunker Tender Prices and Price Variability by Fuel, 2023-2024
Source: Author's compilation based on company procurement records (See Appendix C, Table C1)

Procurement patterns were highly port-concentrated (Figures 7; see detailed distributions in Appendix C, Tables C2–C3). Singapore supplied more than 100,000 MT in 2023 and close to 90,000 MT in 2024, reinforcing its role as the anchor hub. Fujairah and Houston emerged as secondary hubs, while smaller ports such as Port Louis, Rotterdam, and Gibraltar accounted for modest but strategically necessary volumes. These secondary locations, however, often presented sharper price instability. For example, Port Louis exhibited extreme volatility (SD = USD 205/MT in 2023; USD 233/MT in 2024; see Appendix C, Table C2–C3), exposing PIS to disproportionate procurement risk relative to its small share of volume.

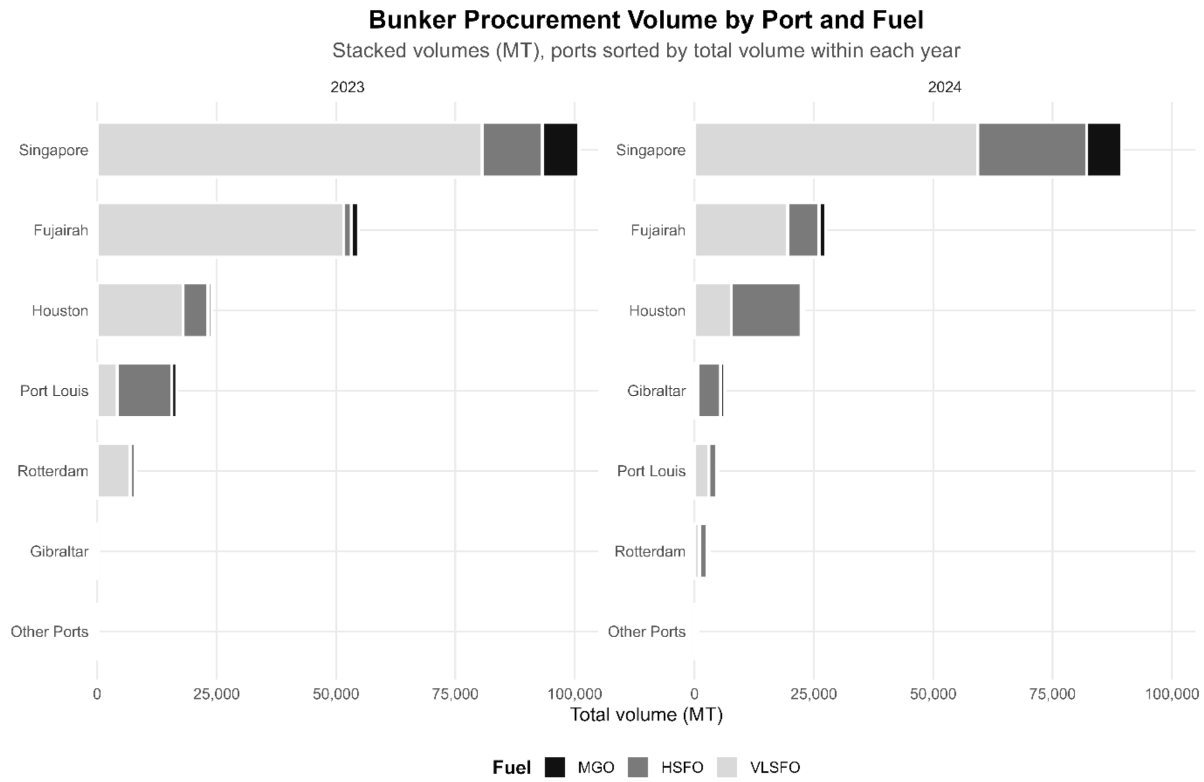


Figure 7: Bunker Procurement Volumes by Port and Fuel, 2023-2024
Source: Author's compilation based on company procurement records (see Appendix C, Table C2-C3)

Figure 8 illustrates the variation in port-level standard deviations of bunker prices, aggregated across fuels. The results confirm that volatility tends to be lower in high-volume hubs (e.g. Singapore) and higher in smaller, supplier-constrained ports (e.g. Port Louis). This heterogeneity underscores the importance of modelling both volume and volatility jointly in the optimisation framework, since exposure depends not only on price stability but also on the scale of procurement at each port.

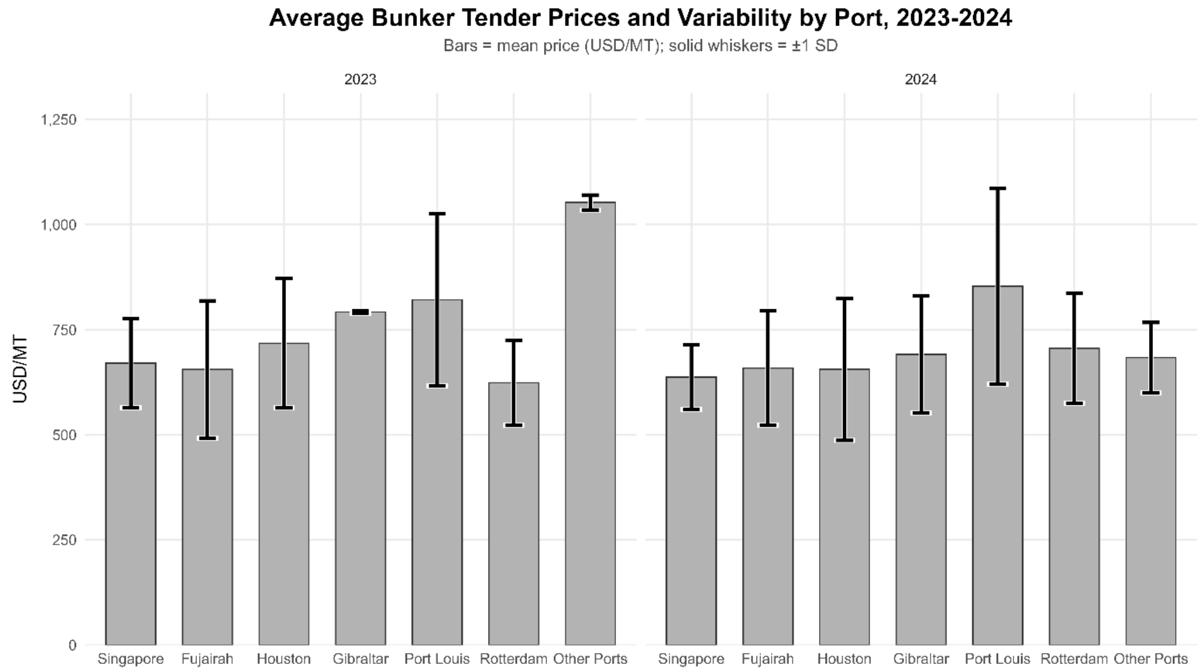


Figure 8: Average Bunker Tender Prices and Price Variability by Port, 2023-2024
Source: Author's compilation based on company procurement records (see Appendix C, Table C2-C3)

In total, PIS spent USD 217.6 million on bunker fuel over 2023–2024 (see Appendix C, Table C1). The evidence indicates that procurement risk is structurally uneven: concentrated volumes in stable hubs amplify the cost impact of relatively small price changes, while smaller ports introduce extreme volatility per tonne. These descriptive insights provide the empirical baseline for the hedging optimisation in Section 4.2.2, where mean–variance trade-offs are evaluated under alternative spot–swap strategies.

4.2.2. Results of Stage 1 Optimisation: Risk-Hedged Bunker Procurement

A. Overview of Optimisation Framework

This section presents the results of the first-stage optimisation model for international bunker procurement, building directly on the methodology outlined in Chapter 3 and detailed in SI Stage 1. The model evaluates the cost–risk performance of alternative hedging strategies over a 20-year horizon (2025–2044), using simulated monthly spot and swap prices for PIS's main bunkering hubs and fuels.

Price dynamics are generated using a multivariate (DCC) GARCH framework with skewed Student-t innovations, which captures both volatility clustering and the fat-tailed return distributions characteristic of marine fuel markets. For each port–fuel combination, 500 forward price paths are simulated, providing a scenario set that reflects plausible market conditions under correlated volatility.

Synthetic swap contracts are modelled with a fixed 5% premium over expected spot levels, consistent with the modest differentials observed in Platts and ICE forward assessments. This uplift reflects the cost of risk transfer to financial counterparties, incorporating financing, liquidity, and credit considerations that are typically embedded in swap pricing. By adopting a transparent and conservative proxy for forward values, the model remains aligned with standard hedging practice in energy markets. These simulated spot and swap prices are then embedded in a rolling quadratic mean–variance programme, where the decision variable is the monthly hedge ratio, the proportion of demand secured through swaps versus the spot market.

The optimisation is parameterised by the risk-aversion coefficient ($\lambda \in [0,1]$), which determines the trade-off between expected cost and risk exposure. A λ value of 0 corresponds to a purely cost-minimising strategy (spot-only), while $\lambda = 1$ corresponds to a fully risk-averse strategy (maximum hedge coverage). Intermediate values (e.g. $\lambda = 0.25, 0.50, 0.75$) reflect blended strategies where stability is prioritised alongside cost efficiency.

For each λ setting, the model computes expected procurement cost, cost variance, and downside risk metrics, including VaR and CVaR. These indicators are consistent with the definitions introduced in Chapter 3.4 and formalised in SI Stage 1 (S9–S12, S13–S16).

The objective is to support PIS in designing forward-looking, risk-adjusted sourcing strategies that strengthen cost predictability across its bunker procurement portfolio. The results of this first-stage optimisation are reported in the subsections that follow: Part B validates the simulated price behaviour, Part C examines the procurement frontier, Part D analyses hedge ratio dynamics across ports and fuels, Part E decomposes costs and evaluates hedging efficiency, and Part F quantifies the CVaR reduction that functions as a cost buffer for clean-fuel transition planning.

B. Simulated Price Distribution and Statistical Validation

Figure 9 presents the simulated monthly price distributions for spot and synthetic swap contracts across all port–fuel combinations for the 2025–2044 horizon. Spot prices were generated using a multivariate (DCC) GARCH model with skewed Student-t innovations, capturing volatility clustering, heavy tails, and asymmetric returns observed in historical marine fuel prices. Swap prices were derived as rolling six-month averages of the simulated spot series, adjusted with a fixed 5% premium to reflect over-the-counter swap market practice, where liquidity costs and transaction margins are embedded in forward pricing.

The comparison highlights the distinct risk profiles of the two procurement modes. Spot prices exhibit wider dispersion and heavier tails, particularly for MGO and VLSFO in Singapore, Fujairah, and Rotterdam, reflecting exposure to short-term supply shocks and thinly balanced markets. Swap prices, by contrast, display tighter and more symmetric distributions, effectively smoothing volatility. This divergence confirms the central premise of the Stage 1 model: greater dispersion in spot prices translates into higher procurement cost variance, while swap contracts compress volatility and reduce left-tail risk. The statistical evidence therefore reinforces the value of hedging as a mechanism to stabilise procurement expenditure across ports.

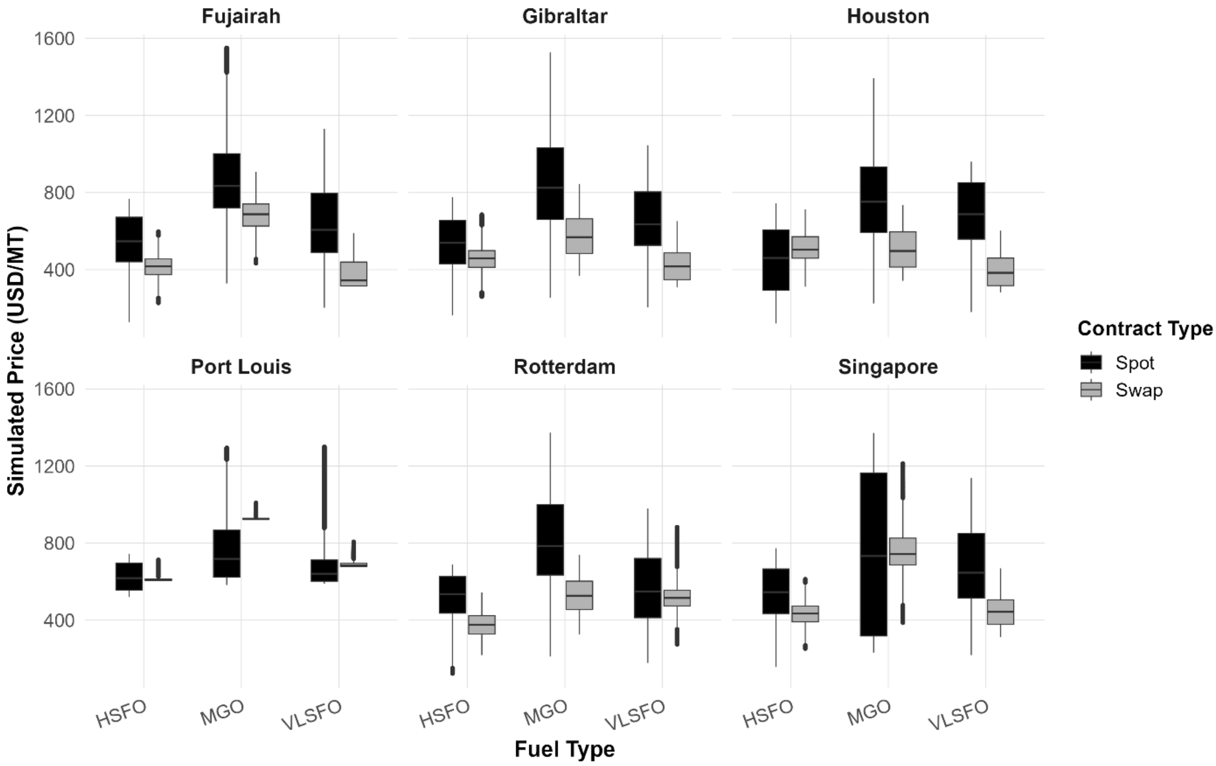


Figure 9: Simulated Monthly Spot and Swap Price Distributions (2025–2044)
Source: Author's simulation by port and fuel type

Fuel-specific dynamics are also evident. MGO shows the highest volatility, especially in Port Louis and Singapore, while HSFO remains relatively stable in Rotterdam and Houston, where deeper liquidity and predictable demand mitigate price swings. These differences explain why the optimisation framework applies port- and fuel-specific hedge ratios rather than a uniform strategy across the fleet (see Section 4.2.2.D).

To ensure statistical rigor, formal validation tests were applied to the simulated log return series. As shown in Table 4, the Jarque–Bera (JB) test strongly rejected the null hypothesis of normality for all fuel–port combinations ($p < 0.01$). This confirms the presence of skewness and leptokurtic behaviour—well-known characteristics of energy price time series—thereby justifying the use of skewed Student-t innovations in the multivariate (DCC) GARCH model.

Table 4: Statistical Test Results for Simulated Log Returns

Port	Fuel	Contract	JB_Statistic	JB_p-value	ADF_Statistic	ADF_p-value
Fujairah	HSFO	Spot	3890.7175	0	-81.1937	0.01
Fujairah	HSFO	Swap	4857.4756	0	-79.0371	0.01
Fujairah	MGO	Spot	1187.2988	0	-84.7322	0.01
Fujairah	MGO	Swap	2665.0672	0	-74.2829	0.01
Fujairah	VLSFO	Spot	542.9274	0	-86.2779	0.01
Fujairah	VLSFO	Swap	20228.8465	0	-79.299	0.01
Gibraltar	HSFO	Spot	679.6159	0	-79.4625	0.01
Gibraltar	HSFO	Swap	7340.2323	0	-71.79	0.01
Gibraltar	MGO	Spot	1015.6929	0	-82.5534	0.01
Gibraltar	MGO	Swap	4954.8893	0	-84.372	0.01
Gibraltar	VLSFO	Spot	1723.5767	0	-76.6553	0.01
Gibraltar	VLSFO	Swap	960.4091	0	-83.8989	0.01
Houston	HSFO	Spot	151.362	0	-97.8102	0.01
Houston	HSFO	Swap	2194.6037	0	-84.6182	0.01
Houston	MGO	Spot	311.5995	0	-81.3553	0.01
Houston	MGO	Swap	1827.0143	0	-78.9151	0.01
Houston	VLSFO	Spot	2030.7654	0	-80.6105	0.01
Houston	VLSFO	Swap	1660.8865	0	-85.7257	0.01
Port Louis	HSFO	Spot	2194.9209	0	-84.0777	0.01
Port Louis	HSFO	Swap	220499.4305	0	-82.4196	0.01
Port Louis	MGO	Spot	48.0015	0	-84.6787	0.01
Port Louis	MGO	Swap	252278.2377	0	-84.9675	0.01
Port Louis	VLSFO	Spot	9308.2375	0	-77.8406	0.01
Port Louis	VLSFO	Swap	44661.7601	0	-88.2266	0.01
Rotterdam	HSFO	Spot	4114.3476	0	-85.9102	0.01
Rotterdam	HSFO	Swap	2865.7199	0	-75.5339	0.01
Rotterdam	MGO	Spot	576.8295	0	-85.8888	0.01
Rotterdam	MGO	Swap	2579.2929	0	-79.9766	0.01
Rotterdam	VLSFO	Spot	60.8611	0	-86.4531	0.01
Rotterdam	VLSFO	Swap	7122.4071	0	-88.86	0.01
Singapore	HSFO	Spot	1990.5708	0	-85.4794	0.01
Singapore	HSFO	Swap	3745.8034	0	-75.5366	0.01
Singapore	MGO	Spot	1983.4691	0	-88.8172	0.01
Singapore	MGO	Swap	9846.1994	0	-81.5269	0.01
Singapore	VLSFO	Spot	717.2601	0	-76.0878	0.01
Singapore	VLSFO	Swap	1074.4708	0	-87.807	0.01

As reported in Table 4, the Augmented Dickey–Fuller (ADF) test confirms that all return series are stationary at the 1% level, a necessary condition for GARCH modelling to ensure stable variance dynamics rather than spurious persistence.

Taken together, the statistical diagnostics demonstrate that the simulated spot and swap series replicate the stylised facts of fuel markets and provide reliable inputs for optimisation. They form the empirical foundation for the procurement frontier analysis in Section 4.2.2.C, where the cost–risk trade-off across different levels of risk aversion is evaluated.

C. Procurement Frontier: Cost-Risk Trade-Off

Figure 10 illustrates the procurement performance frontier across all port–fuel combinations over the 2025–2044 horizon, mapping the trade-off between expected procurement cost and total cost variance under alternative levels of risk aversion (λ). The frontier is constructed from annualised outputs of 500 scenario simulations under the rolling hedge optimisation framework. As λ increases from 0 (spot-only) to 1 (fully hedged), the optimiser progressively reallocates volumes toward swaps, producing the familiar convex shape of quadratic mean–variance optimisation.

The curvature of the frontier highlights the efficiency of hedging. Initial increases in λ deliver substantial reductions in volatility with only modest increases in mean cost. Moving from $\lambda = 0$ to $\lambda = 0.5$ reduces variance by about 15.7%, while mean procurement cost rises by just 2.7%. Beyond $\lambda \approx 0.5$, however, further risk reduction comes at sharply higher cost, with diminishing marginal benefits. This convexity confirms the existence of an “efficient frontier” for bunker procurement under uncertainty.

Fuel- and port-specific dynamics also shape the frontier. Steep curves in Singapore–MGO, Houston–HSFO, and Port Louis–VLSFO/MGO highlight strong volatility–cost trade-offs, while flatter profiles in Rotterdam and Houston–MGO indicate limited hedging gains beyond initial variance reductions. Most curves exhibit a turning point at low λ values, where variance declines sharply before tapering off, underscoring that hedging efficiency is highly context specific. These differences highlight why the model requires disaggregation by port and fuel, with hedge ratios dynamically optimised at the local level (see Section 4.2.2.D).

Table 5 quantifies the trade-off in detail. The mean procurement cost rises gradually from USD 1.654 billion at $\lambda = 0$ to USD 1.701 billion at $\lambda = 1$ (a 2.81% increase). Over the same interval, variance falls from 5.93×10^{15} to 4.99×10^{15}, confirming that hedging significantly compresses volatility. Importantly, downside risk measures exhibit asymmetric behaviour: the 90th percentile Value-at-Risk (VaR_{90}) and Conditional Value-at-Risk ($CVaR_{90}$) increase more slowly than mean cost, demonstrating that hedging reduces left-tail exposure to extreme cost shocks. This means that swap coverage lowers the likelihood of severe procurement overruns, even in periods of correlated global price volatility.

The next subsection examines how these portfolio-level trade-offs are expressed in fuel- and port-specific hedge ratios, providing a granular view of how the optimiser allocates risk protection across the network.

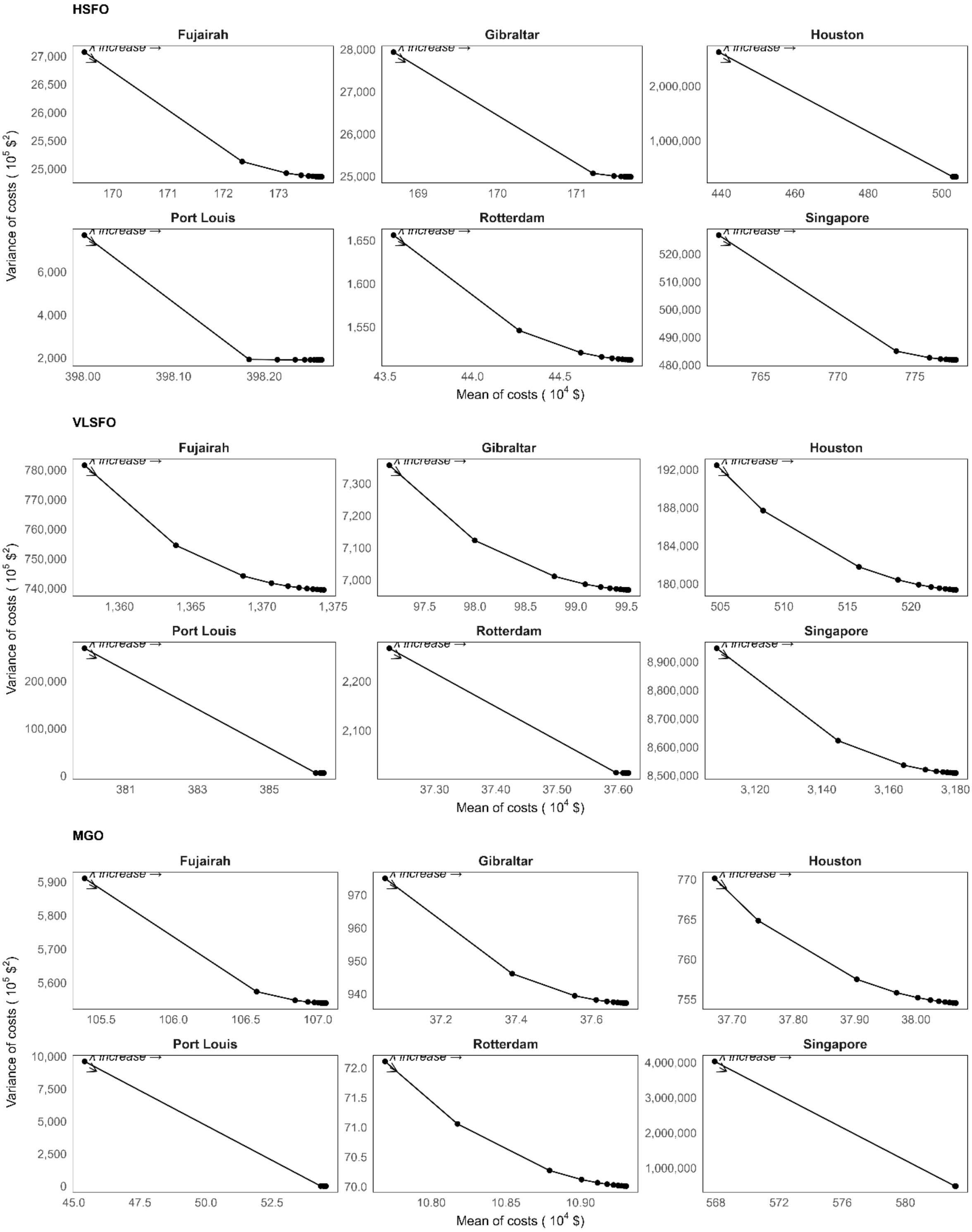


Figure 10: Procurement Performance Frontier Across Risk Aversion Levels (λ)
Source: Author's simulation-expected cost vs. total cost variance, (2025-2044)

Table 5: Simulated Annual Procurement Cost, Variance, Downside Risk Across λ Values

λ	Mean Cost (USD x 10^9)	Cost Increase (%)	Variance (USD^2 in x 10^{15})	Variance Reduction (%)	Std. Dev. (USD x 10^7)	VaR_{90} (USD x 10^9)	$CVaR_{90}$ (USD x 10^9)
0	1.6541	0.00	5.92582	0.00	7.6979	1.7569	1.7975
0.1	1.6864	1.95	5.03207	15.08	7.0937	1.7826	1.8200
0.2	1.6939	2.41	4.99835	15.65	7.0699	1.7859	1.8268
0.3	1.6966	2.57	4.99746	15.67	7.0671	1.7894	1.8294
0.4	1.6980	2.66	4.99622	15.69	7.0670	1.7900	1.8307
0.5	1.6989	2.71	4.99468	15.71	7.0673	1.7903	1.8316
0.6	1.6995	2.74	4.99531	15.70	7.0678	1.7905	1.8321
0.7	1.6999	2.77	4.99588	15.69	7.0682	1.7907	1.8326
0.8	1.7002	2.79	4.99634	15.69	7.0685	1.7911	1.8329
0.9	1.7005	2.80	4.99676	15.68	7.0688	1.7914	1.8331
1	1.7007	2.81	4.99716	15.67	7.0691	1.7916	1.8333

(see SI S9–S12 for metric definitions and calculation steps)

D. Hedge Ratios Dynamics by Port and Fuel

This subsection examines the evolution of optimal hedge ratios across bunker ports and fuel types during the 2025–2044 horizon under the balanced risk-aversion setting (λ = 0.5). Figure 11 plots the rolling annual hedge ratios derived from the mean–variance optimisation, showing how swap coverage is dynamically adjusted in response to simulated price volatility and forecast uncertainty. Three main patterns emerge: consistently high hedge intensity across most fuel–port combinations, clear differentiation between fuels, and temporal variation in hedging behaviour as markets evolve.

Figure 11: Rolling Annual Optimal Hedge Ratios by Port and Fuel Type at λ = 0.5
Source: Author's simulation, (2025–2044)

The analysis demonstrates distinct patterns of hedge behaviour across fuels. MGO exhibits the highest hedge intensity throughout the planning horizon. In Rotterdam, Gibraltar, and Houston, hedge ratios for MGO remain above 0.95 and reach near-total coverage (0.98) by the early 2040s. This behaviour reflects its elevated volatility and thinner liquidity compared with other fuels, consistent with the large standard deviations reported in Appendix C (Table C1). VLSFO shows a more gradual rise in hedge ratios, especially in Fujairah, Gibraltar, and Houston, where coverage approaches 1.00 by 2044. This trend indicates either growing volatility in spot pricing or more favourable swap terms as forward-market efficiency improves. HSFO, by contrast, demonstrates flatter hedge profiles, with stable or even slightly declining ratios in Singapore and Rotterdam. Its relatively low variance (see SI Stage 1, S1.5) suggests that forward contracts deliver less incremental benefit compared with spot purchases in these hubs.

The results further demonstrate substantial heterogeneity across ports. In Port Louis, hedge ratios for both MGO and VLSFO rise steeply after 2035, reflecting deteriorating spot predictability or widening forward premiums in a constrained supply environment. In contrast, Singapore and Houston show declining hedge ratios for HSFO, implying improved price stability in high-volume hubs or reduced asymmetry between spot and swap pricing. Rotterdam's mixed profile—high hedging for MGO but stable or declining ratios for HSFO—illustrates how localised market structures shape hedging needs at the fuel-specific level.

These findings highlight the value of a dynamic optimisation framework that calibrates hedge intensity to port- and fuel-specific volatility conditions, rather than relying on static or uniform coverage rules. By targeting swap protection to fuels and locations with the highest risk exposure, the model directs hedging capital where it delivers the strongest buffer against cost shocks, while maintaining flexibility in more stable markets. For PIS, this approach enhances cost predictability and ensures that financial resources are deployed with maximum efficiency, reinforcing the robustness of the proposed procurement framework.

E. Cost Decomposition and Efficiency Gains

To evaluate the distributional efficiency of the hedging strategy, procurement cost and risk outcomes are disaggregated by port and fuel type under a moderate risk-aversion setting ($\lambda = 0.5$). Results are based on 500 scenario simulations across the 2025–2044 horizon, with performance assessed using mean cost, variance, standard deviation, and downside risk indicators.

At the port level (Table 6), hedging effectiveness varies substantially. Port Louis shows the strongest response, with variance reduced by 98.25% at only a marginal cost increase, reflecting both its small procurement share and highly volatile spot pricing. Houston also demonstrates strong benefits, with variance falling by 73.59%, consistent with its role as a large-volume yet volatile procurement hub. By contrast, Singapore—although accounting for more than USD 900 million in purchases—records only a 12.85% variance reduction, suggesting that stable spot conditions and narrower spot–swap spreads limit hedging responsiveness. Rotterdam, Gibraltar, and Fujairah show moderate reductions, between 5% and 10%, consistent with their intermediate volatility profiles.

Table 6: Summary of Risk Metrics and Hedging Performance per Port

Port	Mean Cost (USD x 10^6)	Cost Increase (%)	Variance (USD^2 in x 10^{13})	Std. Dev. (USD x 10^6)	VaR_{90} (USD x 10^6)	$CVaR_{90}$ (USD x 10^6)	Variance Reduction (%)
Fujairah	330.60	1.27	19.22	13.86	348.50	358.50	5.16
Gibraltar	61.72	1.89	1.38	3.72	66.50	68.60	8.66
Houston	212.70	8.32	17.44	13.21	230.10	236.60	73.59
Port Louis	167.90	1.94	0.08	0.89	168.90	169.80	98.25
Rotterdam	18.67	1.99	0.13	1.15	20.07	20.70	9.88
Singapore	907.30	2.20	323.80	56.90	984.30	1,015.00	12.85

(see Appendix C for full numerical values; simulated outputs generated in SI Stage 1)

At the fuel-type level (Table 7), MGO delivers the largest hedge gains, with variance reduced by 67.71% for only a 3.37% increase in mean cost. HSFO follows with a 56.67% variance reduction, while VLSFO—despite being PIS's largest procurement category—achieves only 6.18% variance reduction, indicating weak responsiveness to hedging. These results confirm that hedging efficiency depends more on fuel-specific volatility characteristics than procurement volume.

Table 7: Summary of Risk Metrics and Hedging Performance per Fuel Type

Fuel Type	Mean Cost (USD x 10^8)	Cost Increase (%)	Variance (USD^2 in x 10^{14})	Std. Dev. (USD x 10^7)	VaR_{90} (USD x 10^8)	$CVaR_{90}$ (USD x 10^8)	Variance Reduction (%)
HSFO	4.14	4.45	3.90	1.97	4.41	4.50	56.67
MGO	1.66	3.37	1.54	1.24	1.83	1.89	67.71
VLSFO	11.19	1.98	38.17	6.18	12.02	12.38	6.18

(see Appendix C for full numerical values; simulated outputs generated in SI Stage 1)

The decomposition highlights that MGO and HSFO are the most responsive to swap hedging and therefore should be prioritised in volatile or thinly traded ports such as Port Louis and Houston. By contrast, VLSFO and stable procurement hubs such as Singapore appear less sensitive, making aggressive hedging less cost-effective.

Finally, the results validate λ = 0.5 as a strategically sound hedge intensity. As shown in Section 4.2.2.C, this setting achieves nearly all attainable variance reduction (≈15.7%) with cost increases kept below 3%. VaR and CVaR metrics also stabilise at this level, confirming that extreme downside risks are already well contained. A time-phased assessment of hedge efficiency over sub-periods (2025–2030, 2030–2035, 2035–2040, and 2040–2044) is provided in Chapter 5, where robustness is tested against regulatory tightening and alternative market conditions.

F. CVaR Reduction as a Budget Buffer for Clean Fuel Transition

This section quantifies the downside protection generated by hedging against extreme fuel price volatility. Under a moderate hedge intensity (λ = 0.5), the model reduces the $CVaR_{90}$ by USD 17.89 million over the 2025–2044 horizon, compared with a spot-only strategy (λ = 0). $CVaR_{90}$ represents the average procurement cost in the worst 10% of simulated outcomes, making it a direct indicator of resilience against tail-risk events.

The port-level distribution of this effect is reported in Table 8, which aggregates $CVaR_{90}$ values under spot-only, balanced, and fully hedged strategies. Results show that hedging is particularly effective in Port Louis, where $CVaR_{90}$ falls from USD 161.8 million to USD 146.2 million, and in Houston, where $CVaR_{90}$ decreases by more than USD 5 million. By contrast, Singapore, despite being PIS's largest procurement hub, shows little responsiveness, with $CVaR_{90}$ remaining almost unchanged across hedge intensities. These differences highlight that hedging provides the greatest benefit in volatile or thinly supplied markets, while liquid hubs exhibit natural stability.

Table 8: Port-Level $CVaR_{90}$ under Alternative Hedge Intensities

Port	Sum of $CVaR_{90}$ (USD)		
	λ = 0	λ = 0.5	λ = 1
Fujairah	321,760,944.16	324,380,176.83	324,696,688.05
Gibraltar	61,391,526.95	61,830,172.67	61,866,285.78
Houston	219,376,694.73	214,296,201.66	214,573,763.92
Port Louis	161,811,067.60	146,160,200.55	146,170,191.66
Rotterdam	18,650,552.94	18,802,161.30	18,814,566.64
Singapore	916,967,080.29	916,600,247.76	917,188,265.48
Total	1,699,957,866.67	1,682,069,160.76	1,683,309,761.52

(500 scenario simulations, 2025–2044; see SI S13–S16 for formulation)

At the aggregate level, the impact of hedging is illustrated in Figure 12. Compared to the spot-only strategy, the λ = 0.5 policy consistently lowers $CVaR_{90}$ across the horizon, confirming that partial hedging compresses downside risk without materially inflating mean costs. While not directly reflected as year-on-year cost savings, this $CVaR_{90}$ reduction creates a meaningful cost buffer[1]—a portion of the budget that PIS no longer needs to reserve for covering extreme fuel price shocks.

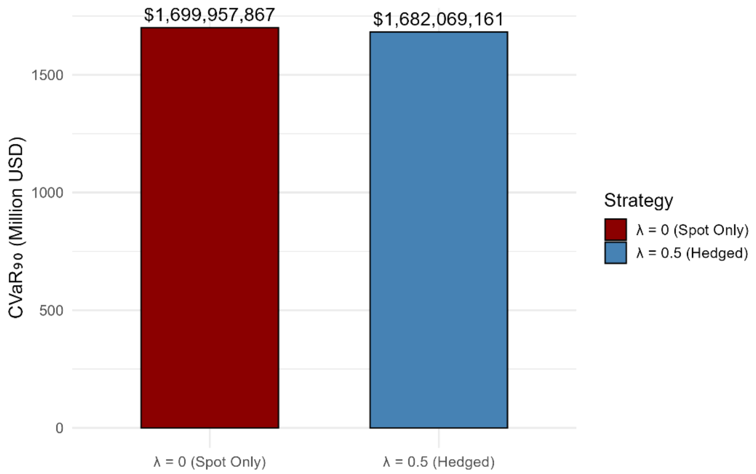


Figure 12: $CVaR_{90}$ Comparison Between Spot-Only and Hedged Strategies
Source: Author's Simulation, (2025–2044)

The realism of this buffer is confirmed by a comparison with operational data. As shown in Figure 13, the modelled annualised benefit of CVaR-based hedging (USD 894,435) closely aligns with the actual spot procurement loss that PIS experienced in 2024 (USD 921,013). This alignment validates the empirical plausibility of the model and its practical value as a planning instrument.

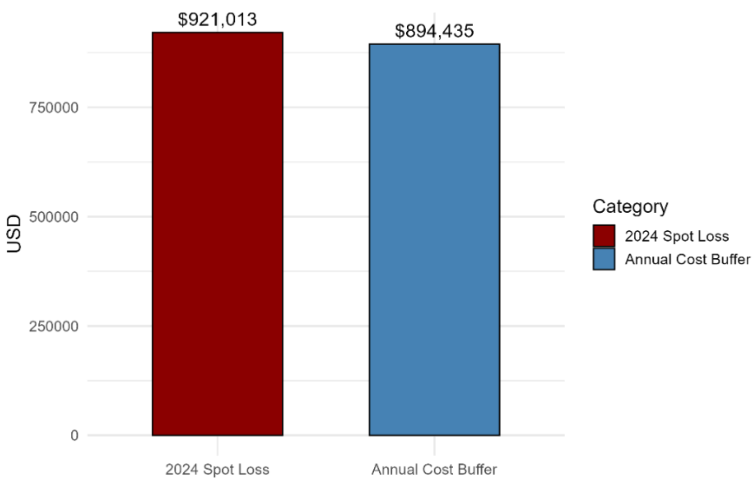


Figure 13: 2024 Spot Market Actual Loss Compared to Annualised Hedging Buffer
Source: Author's Simulation, (2025–2044)

[1] A protected portion of the fuel procurement budget resulting from reduced downside risk (e.g. lower $CVaR_{90}$). In this thesis, it refers to financial room made available through hedging, which can be reallocated toward cleaner fuel investments or FuelEU Maritime compliance.

In sum, the λ = 0.5 strategy not only reduces procurement cost variance by more than 15% (see Section 4.2.2.C) but also establishes a forward-looking financial buffer. This buffer strengthens budget stability and creates capacity to reallocate resources toward cleaner fuels, ensuring that PIS can simultaneously enhance resilience to market shocks and prepare for compliance with FuelEU Maritime requirements.

4.3. Fuel Mix Pathways

Building on the procurement optimisation in Section 4.2, this section presents the second stage of the model, which addresses compliance with the FuelEU Maritime Regulation's WtW GHG-intensity targets. Stage 1 identified λ = 0.5 as the most cost-efficient hedge configuration under price uncertainty, but it did not consider emissions constraints. Stage 2 therefore reallocates bunker fuel volumes across ports and fuel types to reduce fleet-average WtW GHG-intensity and ensure compliance with the 2025–2044 target trajectory.

The optimisation combines port-level demand forecasts, fuel-specific emission factors, and FuelEU thresholds. Non-compliance incurs a penalty of €58.54 per gigajoule. Based on an average emission factor of ~91 gCO_2eq/MJ for conventional fuels, this equals about €639/tCO_2eq, or USD 694/tCO_2eq at an exchange rate of 1.08 USD/EUR. For comparison, the EU ETS allowance price in 2025 is USD 83.56/tCO_2eq, illustrating the dual regulatory costs influencing procurement choices.

Results from Stage 1 showed that λ = 0.5 not only reduces variance by over 15% but also generates a cumulative CVaR cost buffer of USD 17.89 million relative to a spot-only strategy. In Stage 2, this buffer is treated as financial capacity to absorb the premium of alternative fuels required for compliance. Risk management and emissions reduction are thus linked: hedging provides the financial headroom that enables PIS to transition toward lower-emission fuels such as bio-MGO, e-methanol, and blue ammonia without breaching budgetary discipline.

The remainder of this section is structured as follows. Section 4.3.1 outlines the FuelEU Maritime targets, emission benchmarks, and the compliance gap under a fossil-fuel baseline. Section 4.3.2 presents optimisation results for the baseline and LPG-based scenarios, comparing cost, GHG performance, and penalty exposure. Section 4.3.3 incorporates FuelEU flexibility mechanisms into the compliance strategy. Section 4.3.4 describes the fleet composition and demand profile that anchor the optimisation. All calculations follow SI Stage 2 (S17–S22), with output files listed in the replication checklist and figures assembled under Stage 4.

4.3.1. Compliance Benchmarks and Emission Factors

Stage 2 builds directly on the hedging framework of Stage 1 by incorporating FuelEU Maritime's WtW GHG-intensity thresholds as binding constraints. While Chapter 2 reviewed the regulatory background, this section translates those provisions into operational benchmarks for the optimisation model.

The regulation sets its baseline at 91.16 gCO_2eq/MJ (2020) and imposes stepwise reductions toward an 31% cut by 2044. Table 9 summarises the annual limits applied in this study. These values provide the target ladder against which PIS's simulated fleet fuel mix is assessed.

Table 9: Annual Maximum Well-to-Wake GHG Intensity Targets for Marine Fuels

Year	Max Allowable GHG Intensity (gCO_2eq/MJ)	Reduction vs. 2020 Baseline
2020 - 2025	91.16	0%
2025 – 2029	89.34	-2%
2030 – 2034	85.69	-6%
2035 – 2039	77.94	-14.5%
2040 – 2044	62.90	-31%

Source: Regulation (EU) 2023/1805, Annex I

To operationalise compliance testing, each fuel type in the model is assigned a lifecycle emission factor as shown in Table 10 combining upstream (well-to-tank) and downstream (tank-to-wake) components.

Table 10: Well-to-Wake GHG Emission Factors by Fuel Type for Optimisation Inputs

Fuel Molecule	WtW-GHG intensity (gCO_2eq/MJ)	LHV (MJ/tonne)
HSFO	94.00	40,500
VLSFO	92.60	41,000
MGO	90.60	42,700
LPG	74.10	46,000
Bio-LPG	20.00	46,000
Bio-MGO	34.02	42,700
e-Methanol	30.67	19,900
Blue Ammonia	30.84	18,600

Source: Author's compilation based on (CE Delft, 2022; European Parliament and Council, 2023; DNV, 2024a)

Applied to PIS's 2024 baseline fuel mix (60% VLSFO, 25% MGO, 15% HSFO), the weighted fleet intensity is around 91.8–92.1 gCO_2eq/MJ. This already exceeds the 2025 FuelEU limit (89.34), indicating that without fuel reallocation, PIS would be non-compliant from the first year of enforcement. At the prevailing penalty rate of €58.54/GJ (≈USD 694/tCO_2eq), exposure grows rapidly as thresholds tighten, further compounded by EU ETS pricing.

This section therefore establishes the compliance gap that Stage 2 seeks to address: reallocating bunker procurement across fuels and ports to achieve regulatory alignment while containing costs.

4.3.2. Results of Stage 2 Optimisation: Fuel Mix Pathways

A. Optimisation Setup and Model Constraints

This section outlines the configuration of the second-stage optimisation model, which evaluates PIS's long-term compliance with the FuelEU Maritime Regulation under alternative bunker procurement strategies. While Stage 1 established hedge intensity ($\lambda = 0.5$) as the most cost-efficient balance of cost and volatility, Stage 2 holds this setting constant and introduces GHG intensity thresholds as binding regulatory constraints for 2025–2044.

Two scenarios are simulated. The baseline case assumes no adjustment from the 2024 PIS's procurement structure and the LPG-MGO compliance scenario. Energy demand is projected to grow by 2% annually from a baseline of 174.57 million MJ in 2025. For each year, the model calculates fuel-specific consumption, weighted WtW GHG-intensity, and total procurement cost. Lower heating values (MJ/tonne) and WtW emissions factors (gCO_2eq/MJ) follow FuelEU Maritime Annex I and supplementary LCA benchmarks as documented in SI Stage 2 (S18–S19).

Fuel price inputs combine $\lambda = 0.5$ hedge-adjusted expectations from Stage 1 for VLSFO and MGO with an exogenous LPG benchmark of USD 15 per GJ, equivalent to USD 672.65 per tonne. Regulatory costs are incorporated through both FuelEU Maritime penalties and EU ETS liabilities, using the benchmark values and escalation rules defined in Section 4.3.1 and SI Stage 2 (S20–S21).

Finally, the compliance scenario applies a dynamic adjustment mechanism: a root-finding algorithm iteratively solves for the annual LPG share required to meet FuelEU thresholds exactly. Both scenarios preserve the same demand growth trajectory, ensuring comparability of costs, emissions, and compliance outcomes. Their outputs include annual fuel mix shares, cost components, GHG intensity trajectories, and regulatory exposures, which form the basis for the comparative analysis in Sections 4.3.2.B and 4.3.2.C.

B. Baseline Fuel Mix: Cost and Compliance Impact (2025-2044)

This section assesses the financial and regulatory implications of maintaining PIS's historical international operation across its EU-bound voyages. The baseline reflects 2024 operational data from 12 tankers—comprising both LPG carriers and product tankers, a mix of owned and time-chartered tonnage—that collectively completed 76 voyages into EU/EEA ports. Across these voyages, the fleet consumed 2,690.59 tonnes of VLSFO and 1,504.84 tonnes of MGO, corresponding to a weighted mix of 64.1% VLSFO and 35.9% MGO. This static composition is carried forward throughout the simulation horizon, representing a business-as-usual case with no decarbonisation effort. Vessel-level details are provided in Appendix C, Table C4.

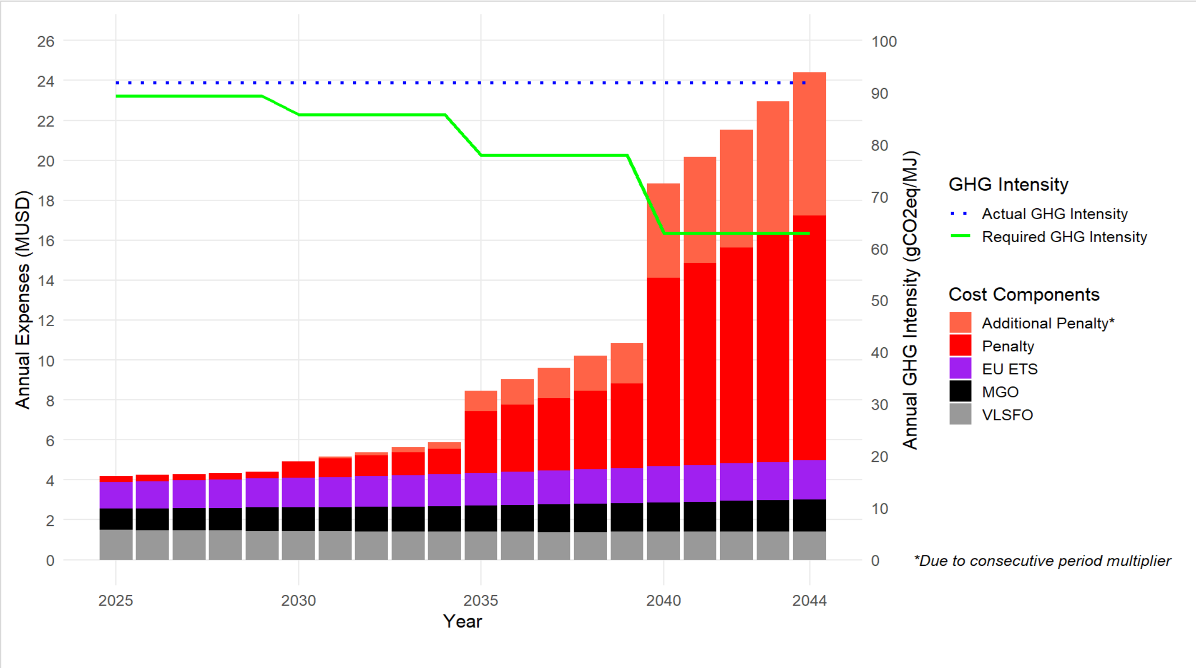
Annual energy demand is assumed to grow by 2% per year from a baseline of 174.57 million MJ in 2025. Procurement costs are based on $\lambda = 0.5$ hedge-adjusted expectations from Stage 1. Emissions are calculated using lower heating values and FuelEU Maritime WtW-GHG intensity factors (Annex I; see SI S18–S19).

Under this static mix, the fleet's average GHG intensity remains constant at 91.67 gCO_2eq/MJ, exceeding every regulatory threshold from 2025 onward: 89.34 gCO_2eq/MJ for 2025–2029, 85.69 for 2030–2034, 77.94 for 2035–2039, and 62.90 for 2040–2044. This gap generates escalating regulatory liabilities. EU ETS costs and FuelEU Maritime penalties are calculated for excess emissions above the threshold, compounding by 10% for consecutive years of non-compliance, in accordance with Regulation 2023/1805, Article 23 (DNV, 2024a).

Figure 14 depicts the resulting cost and compliance profile. In the early period, expenditures are dominated by fuel purchases and EU ETS charges. As thresholds tighten, however, FuelEU Maritime penalties (red bars) become the dominant cost driver, reaching USD 12.27 million in 2044 alone. The constant fleet intensity (blue dotted line) diverges steadily from the declining benchmark (green solid line), widening the compliance gap over time. Over the 20-year horizon, cumulative fuel expenditure amounts to USD 54.68 million, while regulatory liabilities escalate to USD 111.76 million—more than double bunker costs. The fleet accrues a compliance deficit of 59,349 tCO_2eq, confirming that business-as-usual procurement is unsustainable: regulatory costs overwhelm operating expenses, and compliance becomes infeasible without fuel switching.

This baseline establishes the critical reference point for evaluating mitigation. Section 4.3.2.C introduces a compliance-oriented optimisation mechanism, dynamically blending

MGO and LPG to close the emissions gap. The analysis assesses whether the cost buffer generated through Stage 1 hedging can be reallocated to finance this transition while preserving economic efficiency.



Fuel Cost (2025-2044): 54.68 MUSD	Regulatory Cost (2025-2044): 111.76 MUSD	Total Cost (2025-2044): 166.44 MUSD	Accumulated Compliance Balance (2025-2044): -59,349 tCO_2eq

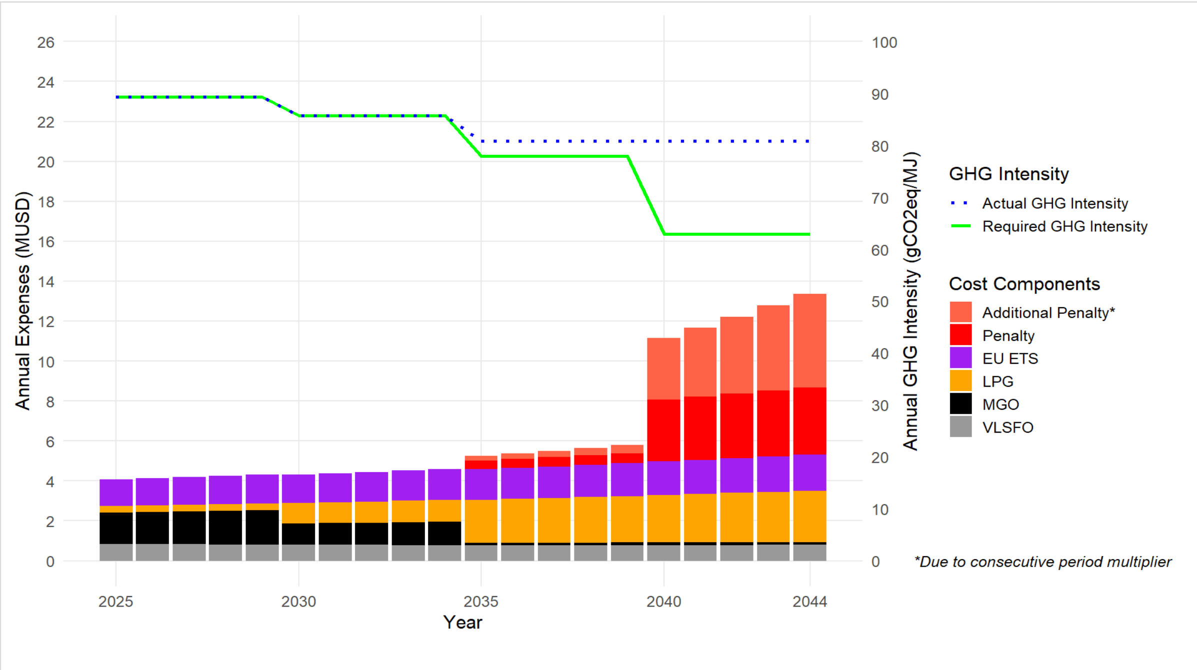
Figure 14: Annual Fuel Cost and GHG Intensity-Baseline Scenario
Source: Author's simulation, (2025-2044)

C. LPG-MGO Compliance Scenario: Cost and Emissions Performance

This section evaluates a transitional compliance pathway in which LPG is introduced as a partial substitute for MGO, while VLSFO consumption amounts to 1,504.84 tonnes in the base year. The model preserves total energy demand—174.57 million MJ in 2025 with 2% annual growth—consistent with projected fleet activity. A minimum 5% MGO share is imposed to reflect pilot ignition requirements for dual-fuel LPG engines, ensuring operational feasibility in line with the FuelEU Maritime framework.

Figure 15 illustrates the resulting GHG trajectory. Between 2025 and 2034, the LPG–MGO blend achieves full compliance, with actual WtW GHG-intensity closely aligned with FuelEU thresholds. From 2035 onwards, however, tightening caps (77.94 gCO_2eq/MJ by 2035 and 62.90 gCO_2eq/MJ by 2040) outpace the mitigation achievable through LPG substitution. Despite annual optimisation of ratios, the fleet accumulates a compliance shortfall of 25,010 tCO_2eq by 2044. As mandated under Article 23 of Regulation (EU) 2023/1805, consecutive years of non-compliance trigger escalating FuelEU penalties, compounded annually by 10%. No surplus credits are generated, preventing banking or pooling to offset these deficits.

Economically, the scenario performs markedly better than the baseline. Total fuel procurement costs amount to USD 61.45 million, while cumulative regulatory liabilities (EU ETS plus FuelEU penalties) are limited to USD 70.42 million. The combined cost of USD 131.87 million is USD 34.57 million lower than the baseline, where penalties escalated sharply after 2030. These gains are concentrated in the early years of compliance and are further supported by the USD 17.89 million cost buffer secured under Stage 1 hedging (Section 4.2). This confirms the model's central proposition: hedging-based buffers can be reallocated to finance cleaner fuels, reducing both volatility and regulatory burden.



Fuel Cost (2025-2044): 61.45 MUSD	Regulatory Cost (2025-2044): 70.42 MUSD	Total Cost (2025-2044): 131.87 MUSD	Accumulated Compliance Balance (2025-2044): -25,010 tCO_2eq

Figure 15: Annual Fuel Cost and GHG Intensity-LPG-MGO Scenario
Source: Author's simulation, (2025-2044)

The bunker fuel mix shifts significantly under this pathway. Across 2025–2044, LPG represents on average 45.1% of the total mass, VLSFO 35.9%, and MGO 19.1%. Compared with the 2024 profile (64.1% VLSFO, 35.9% MGO), this represents a substantial structural adjustment. Yet the persistent MGO floor—needed for ignition—constrains further decarbonisation. Once regulatory thresholds fall below 80 gCO_2eq/MJ, the LPG–MGO pathway is no longer sufficient. This outcome echoes FuelEU Maritime's own technical assessments: fossil-based alternatives such as LPG can delay but not eliminate compliance gaps, and achieving long-run alignment requires fuels with lifecycle intensities below 60 gCO_2eq/MJ (e.g. advanced biofuels, e-methanol, renewable ammonia).

In summary, the LPG–MGO scenario offers PIS a cost-effective compliance bridge through the mid-2030s, combining early regulatory alignment with significant cost savings. However, its eventual shortfall highlights the limitations of fossil-based alternatives. The pathway therefore provides temporary relief but must be paired with longer-term adoption of advanced fuels. Section 4.3.3 examines whether FuelEU flexibility mechanisms can extend this compliance window and mitigate residual liabilities in the 2035–2044 period.

4.3.3. Credit Mechanism and Compliance Flexibility

While the LPG–MGO pathway achieves compliance in the first decade, it generates a growing GHG intensity shortfall from 2035 onwards. This section evaluates the potential of FuelEU Maritime's flexibility instruments—banking, borrowing, and pooling—to mitigate this deficit. These mechanisms, established under Articles 20 and 21 of Regulation (EU) 2023/1805, are intended to provide transitional compliance options when fuel market or infrastructure constraints prevent strict adherence to annual targets.

Banking permits surplus compliance credits—earned when actual intensity falls below the annual cap—to be carried forward. In the LPG–MGO case, however, no surpluses are generated: the fleet tracks the threshold closely between 2025 and 2034 but never outperforms it. With no credits accumulated, banking cannot be applied.

Borrowing allows temporary exceedance of the GHG limit by up to 2% of intensity, provided the excess is compensated in the following year. It cannot be used in consecutive years and carries a 10% compliance cost uplift. Given the scale of the LPG–MGO deficit—25,010 tCO_2eq accumulated by 2044—borrowing is inadequate. Its restrictions limit it to short-term tactical use, not as a structural solution for persistent non-compliance.

Pooling provides a more strategic option by allowing operators to aggregate vessels into compliance groups, with performance assessed on an average basis. In principle, PIS could offset its fossil-fuelled fleet by partnering with operators of RFNBO-fuelled ships (e.g. e-methanol). Illustrative case studies in the FuelEU Maritime report suggest that one e-methanol vessel could offset as many as 54 fossil-fuel vessels in 2025–2029, 22 ships in 2030–2034, but only three or fewer beyond 2035 due to the steeply tightening intensity caps (DNV, 2024a). For PIS, this implies that pooling could offer temporary relief if established early, ideally before 2033 when double crediting of RFNBOs still applies. Yet practical uncertainties remain significant: governance frameworks, contractual terms, availability of surplus-compliant partners, and verification procedures are still under development, limiting pooling's near-term reliability.

In sum, the analysis shows that reliance on FuelEU Maritime's credit mechanisms cannot close the compliance gap left by the LPG–MGO strategy. Banking is unavailable, borrowing is insufficient, and pooling is uncertain. These findings confirm the need for a third-stage transition strategy that incorporates advanced fuels directly—such as bio-MGO, e-methanol, blue ammonia—or secured participation in verified high-compliance pools. Section 4.3.4 therefore examines PIS's fleet composition and propulsion readiness to assess its capacity to integrate such fuels within the final decade of the regulatory horizon.

4.3.4. Fleet Composition and Technical Readiness

PIS's capacity to meet FuelEU Maritime requirements must be assessed in light of the technical readiness of its EU-serving fleet. In 2024, twelve tankers—including LPG carriers and product tankers—completed 76 EU-linked voyages, consuming 4,195 tonnes of fuel split between VLSFO (64.1%) and MGO (35.9%). This operational profile underpinned the LPG–MGO baseline scenario (Section 4.3.2), which achieves compliance until 2034 through fuel mix optimisation alone.

From 2035, however, the regulatory caps tighten sharply, surpassing what the LPG–MGO blend can deliver. At this point, compliance depends not only on procurement strategy but also on the technical ability of vessels to operate on lower-intensity fuels. PIS is positioned to respond through its modern dual-fuel fleet. Three VLGCs—Pertamina Gas Dahlia, Pertamina Gas Caspia, and Pertamina Gas Amaryllis—delivered between 2021 and 2024, already operate on LPG and are equipped with electronic energy-efficient engines, with Gas Dahlia and Gas Caspia also being ammonia-ready. These ships form the technical anchor for deeper decarbonisation beyond 2035. In addition, PIS's orderbook and chartering arrangements provide scope to introduce vessels capable of running on fuels such as e-methanol, bio-MGO, and blue ammonia, all of which are evaluated in Chapter 5 sensitivity scenarios.

This approach avoids costly retrofits by leveraging assets already designed for dual-fuel operation. From 2035 onwards, the optimisation model therefore considers fuel procurement pathways that align with the technical capabilities of these vessels. By synchronising procurement strategy with fleet readiness, PIS establishes a pragmatic compliance pathway that balances operational feasibility, regulatory targets, and cost exposure in the tightening phase of the FuelEU Maritime trajectory.

Chapter 5. Sensitivity Analysis

5.1. Introduction

This chapter conducts a sensitivity analysis to test the robustness of the Stage 2 fuel-mix optimisation framework under alternative regulatory, operational, and fleet assumptions. While Chapter 4 demonstrated that PIS can achieve cost-effective compliance through hedging and reallocation strategies, long-term resilience requires evaluating how these strategies perform when exposed to deviations in fuel prices, technology adoption, policy enforcement, and fleet readiness. Sensitivity analysis therefore functions as a stress-test, validating whether the optimised pathways remain viable when conditions diverge from the baseline.

The analysis proceeds in a structured sequence. Section 5.2 introduces five alternative fuel-blend pathways which reflecting different assumptions about technology maturity, infrastructure development, and cost exposure. Section 5.3 evaluates the potential of compliance flexibility mechanisms such as banking, borrowing, and pooling to extend regulatory alignment when fuel-switching strategies alone are insufficient. Section 5.4 integrates external validation to assess the operational credibility of the model outputs.

Through this structure, the sensitivity analysis moves from scenario-specific results to integrated strategic insights. It not only quantifies the resilience of alternative compliance pathways but also provides actionable guidance on how PIS can allocate its cost buffer most effectively, combining financial risk management with regulatory strategy. Sensitivity mechanics, including VLSFO-cut tests, optimisation procedures, and accumulated compliance calculations, follow SI Stage 3 (S25–S26). Inputs, intermediate files, and outputs are listed in the replication checklist.

5.2. Alternative Fuel Blend Scenarios

This section evaluates a set of alternative fuel-blend scenarios that extend beyond the baseline optimisation in Chapter 4, with the aim of exploring multiple compliance pathways under the FuelEU Maritime framework. Each scenario represents a distinct strategic orientation, from incremental adoption of transitional fuels to accelerated integration of emerging alternatives and is tested across the 2025–2044 horizon to capture both near-term feasibility and long-term regulatory performance.

The scenarios vary in terms of technological maturity, price behaviour, supply chain readiness, and alignment with PIS's current and projected fleet. Some pathways prioritise fuels with established infrastructure but limited GHG-reduction potential, while others test emerging fuels that offer deeper emissions cuts but face uncertainty over cost, scalability, and regulatory acceptance. By systematically modelling these trade-offs, the analysis identifies which strategies best balance compliance certainty, cost control, and operational feasibility.

Each scenario is presented in a consistent format to support comparability: (a) optimisation structure and compliance rationale – outlines the regulatory logic behind the chosen blend and how annual GHG-intensity targets are achieved, (b) fleet mix and emissions performance – details how the fuel portfolio evolves over time, its compatibility with PIS's vessel capabilities, and the trajectory of actual versus required GHG intensities, and (c) economic viability and strategic fit – assesses total procurement and regulatory costs, alongside compliance credit balances, positioning the scenario within PIS's broader strategic roadmap.

This structured approach enables detailed evaluation of individual pathways while facilitating cross-scenario comparison in later sections. All results are generated from Stage 1 cost simulations and risk metrics (SI S9–S12), re-optimised under Stage 2 emissions constraints, and assembled via Stage 4. Replication files and intermediate outputs are listed in the SI checklist.

5.2.1. Alternative Fuel Blend Scenario: LPG-MGO-e-Methanol

A. Optimisation Structure and Regulatory Rationale

The LPG–MGO–e-Methanol scenario builds on the Stage 1 cost-hedging baseline (λ = 0.5) by introducing a phased fuel transition aligned with tightening FuelEU Maritime GHG-intensity thresholds. VLSFO consumption amounts to 1,504.84 tonnes in the base year to preserve limited operational flexibility, while MGO is maintained at a minimum 10% share as a mandatory pilot fuel. e-Methanol is priced at USD 80.40 per GJ, equivalent to USD 1,600 per tonne, in line with conservative market assumptions.

Between 2025 and 2034, compliance is achieved primarily by substituting MGO for LPG, lowering the fleet's weighted GHG intensity below the regulatory benchmark. From 2035 onwards, the optimisation solver progressively substitutes e-methanol for LPG to match the sharper reduction in allowable intensity. The annual blending ratios are adjusted dynamically to close the compliance gap exactly, ensuring penalty-free operation across the entire horizon.

B. Fleet Mix and Emission Performance

The feasibility of this pathway is supported by PIS's existing dual-fuel LPG fleet, together with chartered and orderbook vessels designed to operate on e-methanol, these assets allow implementation without retrofitting or speculative newbuilds.

On a mass basis, the optimised fuel mixes over 2025–2044 averages 30.60% LPG, 25.96% VLSFO, 23.60% MGO, and 19.84% e-methanol. Converted to an energy basis, LPG accounts for 36.05%, followed by VLSFO (27.10%), MGO (26.46%), and e-methanol (10.39%). Figure 16 shows the resulting intensity trajectory: LPG dominates prior to 2035, reducing emissions relative to MGO and VLSFO, while e-methanol is phased in thereafter to deliver deeper cuts. The optimised pathway tracks the FuelEU targets precisely, avoiding both shortfalls and unnecessary over-compliance, thus preserving operational flexibility and cost efficiency.

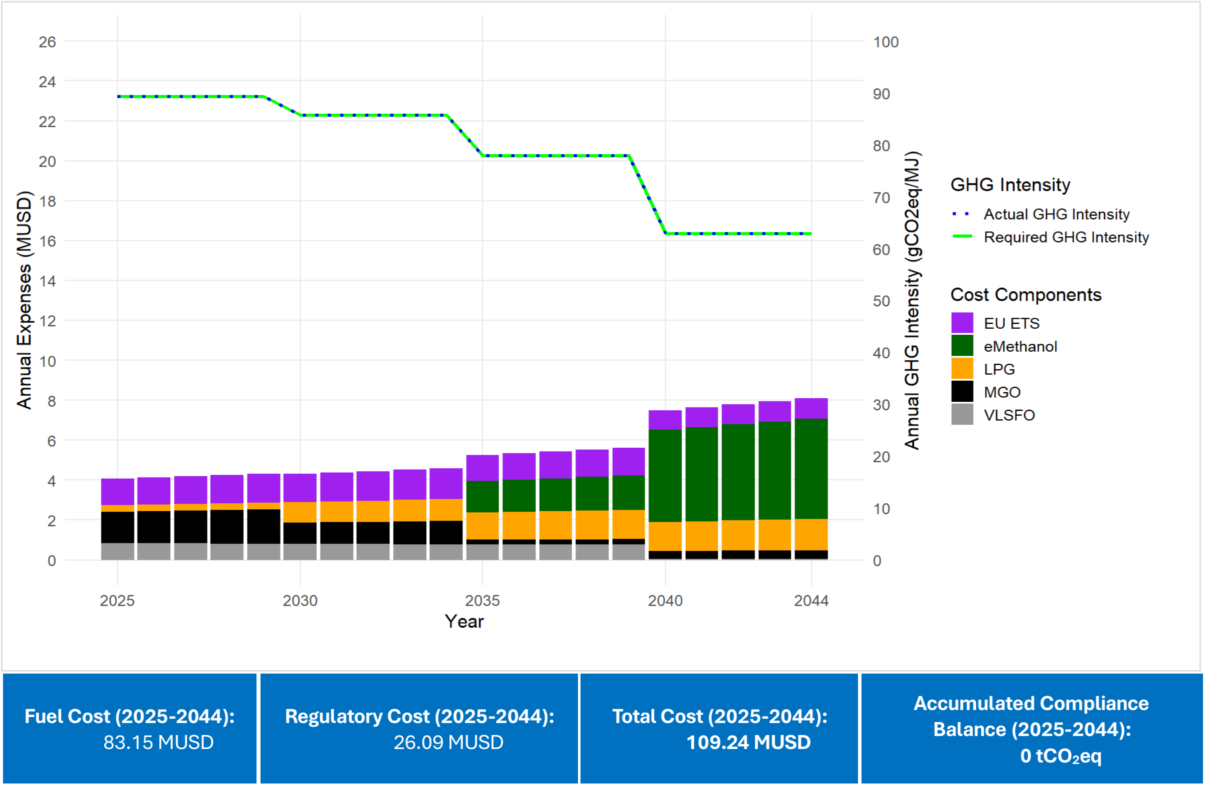


Figure 16: Annual Cost and GHG Intensity-LPG-MGO-e-Methanol Scenario
Source: Author's simulation, (2025-2044)

C. Economic Viability and Strategic Fit

Over the full horizon, fuel procurement costs amount to USD 83.15 million—USD 21.70 million higher than the LPG–MGO scenario. However, the hedge-generated cost buffer of USD 17.89 million from Stage 1 absorbs about 82.4% of this incremental burden. At the same time, regulatory compliance costs fall sharply to USD 26.09 million, compared with USD 70.42 million in the LPG–MGO pathway and USD 111.76 million in the fossil-fuel baseline. The cost profile reflects full elimination of FuelEU penalties, avoidance of borrowing provisions, and stabilisation of EU ETS exposure.

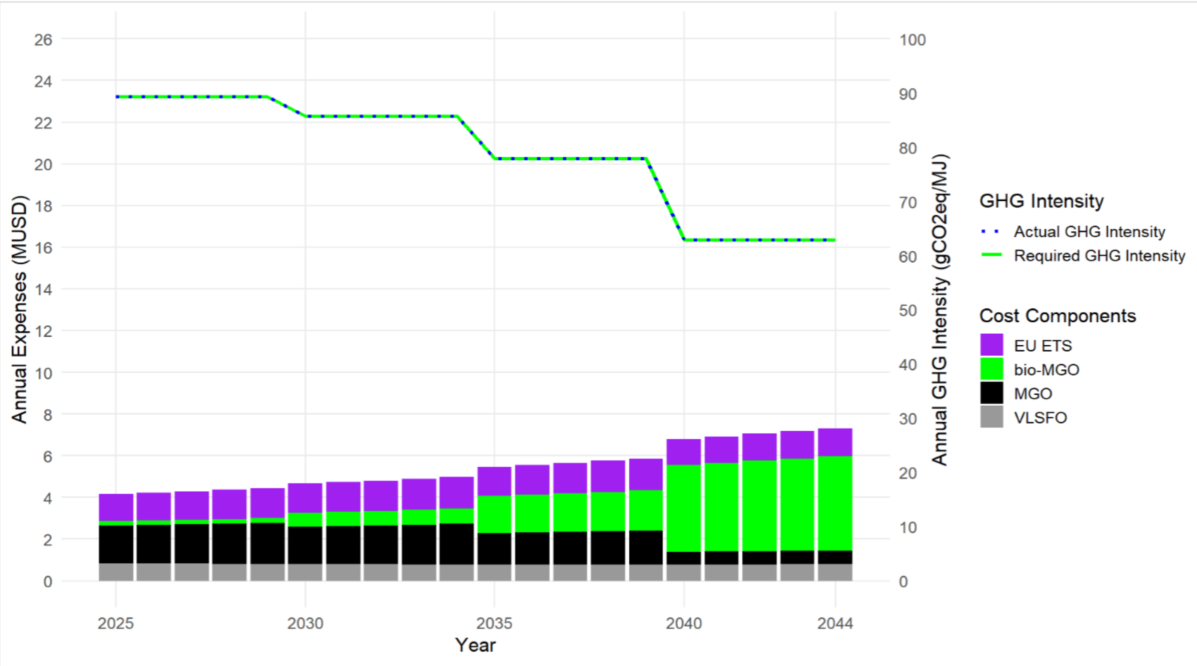
Strategically, this scenario leverages PIS's fleet readiness while minimising additional capital expenses. It offers a technically feasible and financially balanced pathway that closes the compliance gap in the 2035–2044 window, ensures predictable cost exposure, and integrates seamlessly with the Stage 1 risk-hedging framework. By aligning procurement optimisation with regulatory compliance, LPG–MGO–e-Methanol emerges as a robust bridge scenario, combining operational feasibility with long-term resilience.

5.2.2. Alternative Fuel Blend Scenario: MGO-bio-MGO

A. Optimisation Structure and Regulatory Rationale

This scenario evaluates a compliance strategy in which fossil MGO is progressively blended with bio-MGO to meet the FuelEU Maritime WtW GHG-intensity thresholds for 2025–2044. Annual energy demand is anchored to the 2024 operational baseline of 174.57 million MJ, growing at 2% per year. VLSFO consumption amounts to 1,504.84 tonnes in the base year, reflecting continuity with current practices, while the remaining requirement is allocated between fossil MGO and bio-MGO. Bio-MGO is priced at USD 35 per GJ, equivalent to USD 1,494.50 per tonne, and is assigned a WtW GHG-intensity of 34.02 gCO_2eq/MJ, compared to 90.6 gCO_2eq/MJ for conventional MGO. A dynamic blending function determines the minimum annual share of bio-MGO needed to exactly meet the regulatory thresholds, preserving both feasibility and cost efficiency.

B. Fleet Mix and Emission Performance



Fuel Cost (2025-2044): 81.20 MUSD	Regulatory Cost (2025-2044): 27.92 MUSD	Total Cost (2025-2044): 109.12 MUSD	Accumulated Compliance Balance (2025-2044): 0 tCO_2eq

Figure 17: Annual Cost and GHG Intensity-MGO-bio-MGO Scenario
Source: Author's simulation, (2025-2044)

As shown in Figure 17, the optimised MGO–bio-MGO blend achieves precise alignment with the FuelEU Maritime intensity targets across the entire horizon. The actual GHG-intensity trajectory (blue dotted line) tracks the regulatory benchmarks (green solid line) without overshoot or shortfall, ensuring full compliance and eliminating penalty exposure. The cumulative compliance balance closes at zero, confirming regulatory neutrality over the 20-year simulation period.

The optimised bunker mix averages 40.75% fossil MGO, 35.87% VLSFO, and 23.38% bio-MGO, expressed on a mass basis. The role of bio-MGO intensifies after 2035, when the cap declines to 77.94 gCO_2eq/MJ, and becomes indispensable by 2040 when the allowable level falls to 62.90 gCO_2eq/MJ—thresholds unachievable with fossil MGO alone. Importantly, this strategy requires no change in bunkering infrastructure or vessel propulsion, making it technically straightforward relative to other low-carbon options.

C. Economic Viability and Strategic Fit

Total fuel expenditure in this scenario amounts to USD 81.20 million, an increase of USD 26.52 million over the fossil baseline (USD 54.68 million). However, regulatory costs fall sharply to USD 27.92 million—down from USD 111.76 million in the baseline—due to complete avoidance of FuelEU Maritime penalties and reduced EU ETS exposure. The resulting total lifecycle cost is USD 109.12 million, substantially lower than business-as-usual and competitive with infrastructure-intensive alternatives.

The additional fuel expense is partially absorbed by the USD 17.89 million cost buffer generated in Stage 1, covering 67.5% of the incremental burden. This reinforces the strategic link between financial hedging and compliance investment: risk management in Stage 1 creates fiscal space to finance bio-MGO adoption in Stage 2. Operationally, the scenario avoids retrofitting or new fuel systems, aligning well with PIS's existing fleet and bunkering logistics.

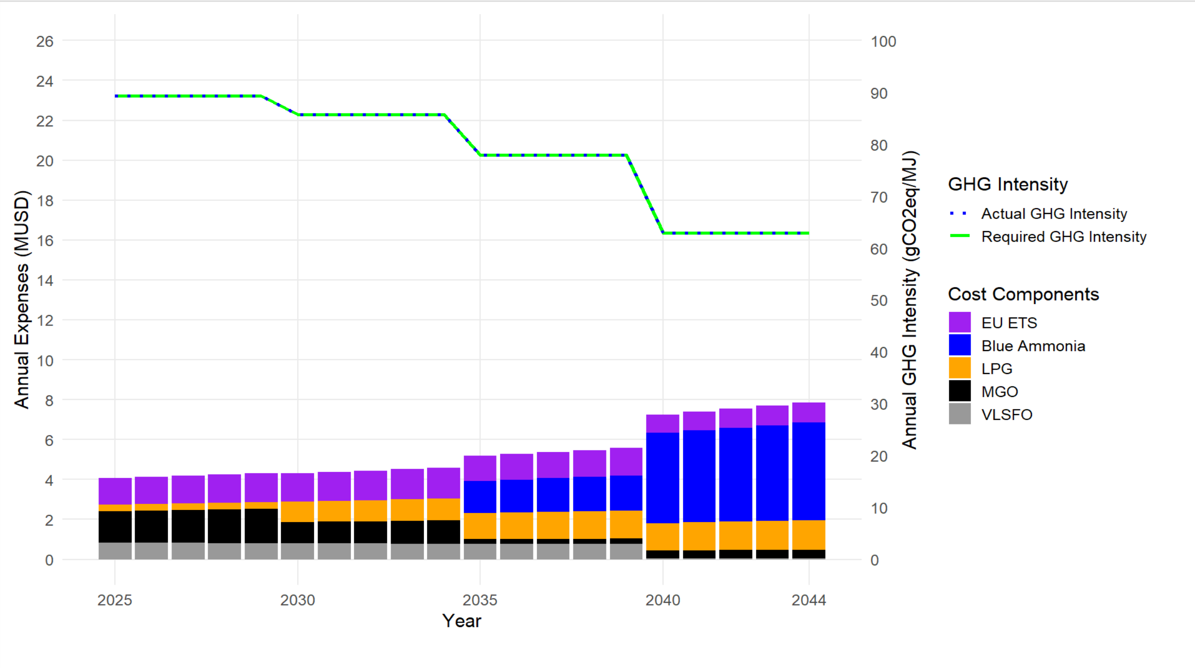
5.2.3. Alternative Fuel Blend Scenario: LPG-MGO-Blue Ammonia

A. Optimisation Structure and Regulatory Rationale

This scenario examines a compliance pathway in which blue ammonia is introduced from 2035 to close the final FuelEU Maritime compliance gap. The framework builds on the assumptions used in earlier scenarios: energy demand is anchored to 174.57 million MJ in 2025, growing at 2% annually until 2044. VLSFO consumption amounts to 1,504.84 tonnes in the base year, reflecting a managed reduction of fossil dependency while ensuring operational continuity. Blue ammonia is priced at USD 80.65 per GJ, equivalent to USD 1,500 per tonne, consistent with conservative market assumptions.

During 2025–2034, the model applies the LPG–MGO blend established in Section 4.3.2 as sufficient to meet interim thresholds. From 2035, blue ammonia is phased in alongside LPG and MGO to satisfy the tightening target of 62.90 gCO_2eq/MJ by 2044. The optimisation maintains a minimum 10% MGO share for ignition stability, consistent with dual-fuel operational requirements. Lifecycle emission factors are set at 74.1 gCO_2eq/MJ for LPG, 90.6 for MGO, and 30.84 for blue ammonia.

B. Fleet Mix and Emission Performance



Fuel Cost (2025-2044): 82.01 MUSD	Regulatory Cost (2025-2044): 25.77 MUSD	Total Cost (2025-2044): 107.78 MUSD	Accumulated Compliance Balance (2025-2044): 0 tCO_2eq

Figure 18: Annual Cost and GHG Intensity-LPG-MGO-Blue Ammonia Scenario
Source: Author's simulation, (2025-2044)

The scenario capitalises on PIS's technical readiness. Three dual-fuel LPG carriers—Pertamina Gas Dahlia, Pertamina Gas Caspia, and Pertamina Gas Amaryllis—delivered in 2024 with Gas Dahlia and Gas Caspia also being ammonia-ready, provide immediate operational feasibility. These vessels, together with modern charter options, allow the staged introduction of blue ammonia without retrofitting or speculative capital expenses.

As shown in Figure 18, the actual GHG intensity (blue dotted line) tracks the regulatory benchmark (green solid line) throughout the horizon. The optimised bunker mix averages 29.53% LPG, 25.96% VLSFO, 23.60% MGO, and 20.90% blue ammonia, expressed on a mass basis. Compliance is maintained under LPG–MGO blending until 2034, after which the inclusion of blue ammonia ensures full alignment with the 2035–2044 thresholds. The cumulative compliance balance closes at zero by 2044, avoiding penalties and credit borrowing. This outcome underscores the importance of introducing hydrogen-derived fuels once regulatory thresholds fall below the range achievable by fossil or transitional blends.

C. Economic Viability and Strategic Fit

The total fuel procurement cost over 2025–2044 is USD 82.01 million, with regulatory costs contained at USD 25.77 million. The resulting total lifecycle cost of USD 107.78 million represents a saving of USD 58.66 million compared with the baseline fossil strategy. Although fuel costs exceed the LPG–MGO scenario (USD 61.45 million), the increase is partially offset by the USD 17.89 million cost buffer generated in Stage 1 (Section 4.2), which absorbs around 87.01% of the additional expenditure.

Strategically, this pathway offers compliance security without requiring new capital investment. PIS leverages its dual-fuel, ammonia-ready fleet and selective chartering to enable flexible fuel sourcing, maintaining alignment with its low capital expenses procurement strategy. The adoption of blue ammonia not only secures FuelEU compliance in the final decade but also positions PIS within the broader transition toward hydrogen-derived fuels anticipated in EU and IMO policy frameworks.

5.2.4. Alternative Fuel Blend Scenario: LPG-MGO-bio-MGO

A. Optimisation Structure and Regulatory Rationale

This scenario extends the dual-fuel blending framework by introducing bio-MGO from 2035 onwards, enabling compliance with the stricter FuelEU Maritime thresholds in the later decades. The operational baseline mirrors previous scenarios: VLSFO amounts to 1,504.84 tonnes in the base year, while total energy demand starts at 174.57 million MJ in 2025 and grows at 2% annually through 2044. Bio-MGO is priced at USD 35 per GJ, equivalent to USD 1,494.50 per tonne, consistent with conservative market assumptions.

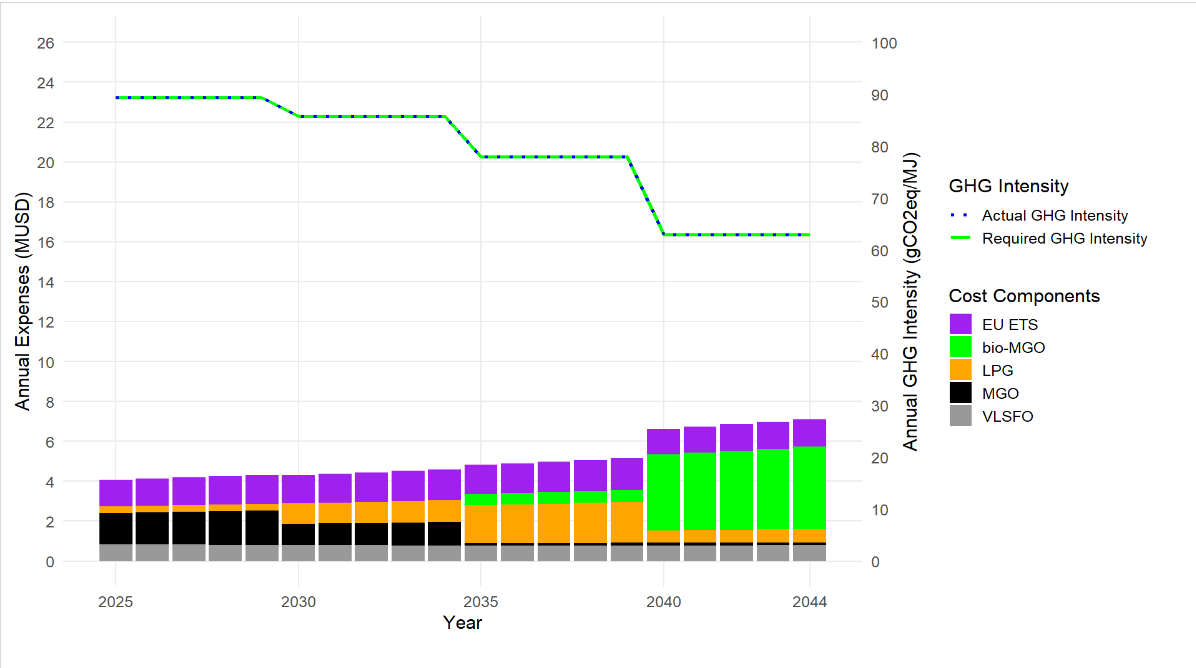
Between 2025 and 2034, compliance is secured through dynamic optimisation of the LPG–MGO ratio, keeping actual intensity below the 89.34–85.69 gCO_2eq/MJ limits. Once the cap tightens to 77.94 gCO_2eq/MJ in 2035 and to 62.90 gCO_2eq/MJ by 2040, the optimiser introduces bio-MGO as a substitute for fossil MGO. A technical constraint ensures that fossil MGO never falls below 5% of the mix, preserving ignition stability for dual-fuel engines. The solver optimises annual shares of LPG, MGO, and bio-MGO to achieve exact compliance without overperformance.

B. Fleet Mix and Emission Performance

The scenario achieves uninterrupted compliance from 2025 to 2044. As shown in Figure 19, the fleet's actual GHG intensity (blue dotted line) aligns precisely with the declining

FuelEU Maritime thresholds (green solid line), closing the horizon with a cumulative compliance balance of 0 tCO_2eq. On average, the composition of the energy mix is 34.19% VLSFO, 29.74% LPG, 22.97% MGO, and 13.09% bio-MGO. This configuration balances the continued use of higher-intensity fuels early in the period with targeted bio-MGO adoption in later years, ensuring that regulatory compliance is met without excessive reliance on any single fuel.

Operational feasibility is underpinned by PIS's existing LPG dual-fuel carriers and the technical compatibility of product tankers with bio-MGO, which can be adopted without retrofitting or major infrastructure changes. The scenario therefore achieves compliance through progressive reallocation of bunker shares, not structural fleet modifications, making it operationally realistic.



Fuel Cost (2025-2044):	Regulatory Cost (2025-2044):	Total Cost (2025-2044):	Accumulated Compliance Balance (2025-2044):
73.70 MUSD	28.55 MUSD	102.25 MUSD	0 tCO_2eq

Figure 19: Annual Cost and GHG Intensity-LPG-MGO-bio-MGO Scenario
Source: Author's simulation. (2025-2044)

C. Economic Viability and Strategic Fit

Over the 2025–2044 horizon, total fuel expenditure amounts to USD 73.70 million, with regulatory costs (EU ETS only) of USD 28.55 million, producing a total lifecycle cost of USD 102.25 million. This represents a saving of USD 64.19 million compared with the baseline fossil-fuel strategy (USD 166.44 million). Crucially, the scenario avoids all FuelEU Maritime penalties by maintaining exact compliance and limits ETS liabilities through the reduced GHG intensity achieved post-2035.

Relative to the baseline, the scenario increases fuel procurement costs by USD 19.02 million (USD 73.70 million vs. USD 54.68 million). However, 94.06% of this incremental burden is offset by the USD 17.89 million hedge-derived cost buffer established in Stage 1 (Section 4.2), leaving only minimal net exposure. Strategically, this pathway provides a credible bridge to deeper decarbonisation technologies, ensuring continuity of operations with currently available dual-fuel-ready assets and supply chains. Its reliance on biomass-derived fuels also diversifies compliance risk, offering resilience in the event of delays to RFNBO or ammonia deployment.

5.2.5. Alternative Fuel Blend Scenario: LPG-MGO-bio-LPG

A. Optimisation Structure and Regulatory Rationale

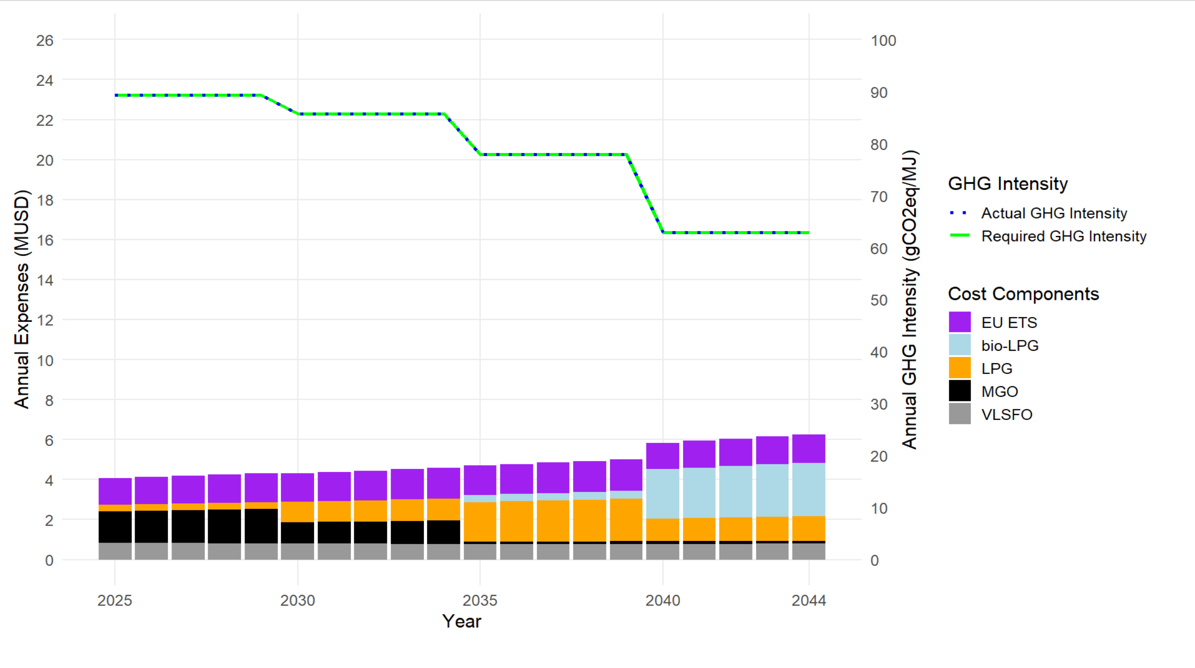
This scenario evaluates a compliance pathway in which bio-LPG is phased into PIS's bunker mix after 2035 to meet tightening FuelEU Maritime thresholds. The operational baseline is aligned with earlier scenarios, with VLSFO consumption amounts at 1,504.84 tonnes in the base year. Total energy demand begins at 174.57 million MJ in 2025 and increases at an annual growth rate of 2% through 2044, while the remaining demand is dynamically allocated between fossil LPG, MGO, and bio-LPG through yearly optimisation. Bio-LPG is priced at USD 30 per GJ, equivalent to USD 1,380 per tonne, in line with conservative market assumptions, and is assigned a WtW intensity of 20 gCO_2eq/MJ, compared to 74.1 gCO_2eq/MJ for fossil LPG and 90.6 gCO_2eq/MJ for MGO.

Between 2025 and 2034, compliance is achieved through LPG–MGO blending. From 2035 onward, the optimiser gradually substitutes fossil LPG with bio-LPG, ensuring that the fleet's well-to-wake intensity remains within the regulatory caps while maintaining at least 5% MGO as pilot fuel for dual-fuel engines. Figure 20 shows that the optimised blend maintains exact compliance across all years, with the actual intensity curve closely tracking the regulatory benchmark. The cumulative compliance balance closes at 0 tCO_2eq, confirming that no penalties or surplus credits are generated.

B. Fleet Mix and Emission Performance

The strategy aligns with PIS's technical capacity, given the presence of LPG-ready and dual-fuel LPG carriers (e.g. Pertamina Gas Dahlia, Pertamina Gas Caspia, and Pertamina Gas Amaryllis), which can operate on fossil LPG and bio-LPG interchangeably without modification. Because bio-LPG is chemically identical to fossil LPG, no capital expenses is required for infrastructure or engine retrofits. The model enforces a 5% minimum MGO share for ignition stability, ensuring operational feasibility.

By 2044, bio-LPG attains its highest contribution to the energy mix, displacing a substantial share of fossil LPG and materially reducing lifecycle GHG intensity. Across 2025–2044, the average fuel mix is 35.87% VLSFO, 32.87% fossil LPG, 20.81% MGO, and 10.45% bio-LPG on a mass basis. This configuration fulfils the dual objective of sustaining high energy density while ensuring compliance with regulatory caps throughout the planning horizon.



Fuel Cost (2025-2044): 68.80 MUSD	Regulatory Cost (2025-2044): 28.82 MUSD	Total Cost (2025-2044): 97.62 MUSD	Accumulated Compliance Balance (2025-2044): 0 tCO_2eq

Figure 20: Annual Cost and GHG Intensity-LPG-MGO-bio-LPG Scenario
Source: Author's simulation, (2025-2044)

C. Economic Viability and Strategic Fit

Financially, the LPG–MGO–bio-LPG pathway is the most cost-efficient compliance scenario modelled. Over the 2025–2044 horizon, fuel procurement totals USD 68.80 million, while regulatory costs (EU ETS only) amount to USD 28.82 million, yielding a total lifecycle cost of USD 97.62 million. This represents a 74% reduction in regulatory burden compared to the baseline scenario (USD 111.76 million).

Relative to the baseline, the scenario raises fuel procurement costs by USD 14.12 million (USD 68.80 million compared with USD 54.68 million). This additional burden is fully absorbed by the USD 17.89 million hedge-derived cost buffer established in Stage 1 (Section 4.2), leaving a surplus available to cover other exposures.

The absence of FuelEU Maritime penalties and the stable progression of bio-LPG adoption provide budgetary predictability and strengthen long-term cost control. Strategically, this pathway capitalises on PIS's existing LPG-capable fleet, requires no retrofitting, and leverages a fuel with both high energy content and low lifecycle emissions. It therefore emerges as a frontrunner among the tested pathways—offering a zero-penalty, low capital expenses solution that aligns compliance with cost efficiency and operational readiness.

5.2.6. Sensitivity of Alternative Fuel Blend Scenario

This section examines the effect of reducing VLSFO volumes between 2035 and 2044 across four alternative fuel pathways —LPG–MGO–bio-LPG, LPG–MGO–bio-MGO, LPG–MGO–Blue Ammonia, and LPG–MGO–e-Methanol. The test evaluates phased reductions of 25%, 50%, 75%, and 100% relative to the baseline VLSFO allocation, with displaced volumes reallocated dynamically to the cleanest available fuels in each scenario. This approach simulates either regulatory tightening under FuelEU Maritime or proactive corporate decarbonisation strategies to accelerate the phase-out of high-intensity fossil fuels.

A. Optimisation Structure and Regulatory Rationale

At 0% reduction, all scenarios maintain exact compliance without generating surplus credits. Progressive VLSFO removal, however, produces increasingly large compliance buffers, the scale of which depends on the substitution fuels. The bio-MGO and bio-LPG pathways exhibit the strongest response due to the comparatively high emissions of VLSFO, whereas the blue ammonia and e-methanol cases show more modest gains since their baseline configurations are already low in carbon intensity.

Figure 21 illustrates the 50% reduction case, which consistently emerges as the most cost-effective midpoint. In the biofuel scenarios, it doubles the surplus credit balance (+14,480 tCO_2eq) relative to the 25% case, while keeping incremental fuel costs moderate. In the blue ammonia and e-methanol pathways, the same cut produces smaller surpluses (+4,746 tCO_2eq) because baseline emissions are already low.

Figure 22 shows the 100% reduction case, which maximises the compliance surplus in all scenarios. Surpluses reach +28,960 tCO_2eq in the biofuel cases, but only +9,492 tCO_2eq in the blue ammonia and e-methanol blends. Although a complete phase-out effectively insulates the fleet against tighter future targets, it results in proportionally higher cost penalties and delivers diminishing marginal gains compared with the 50% case.

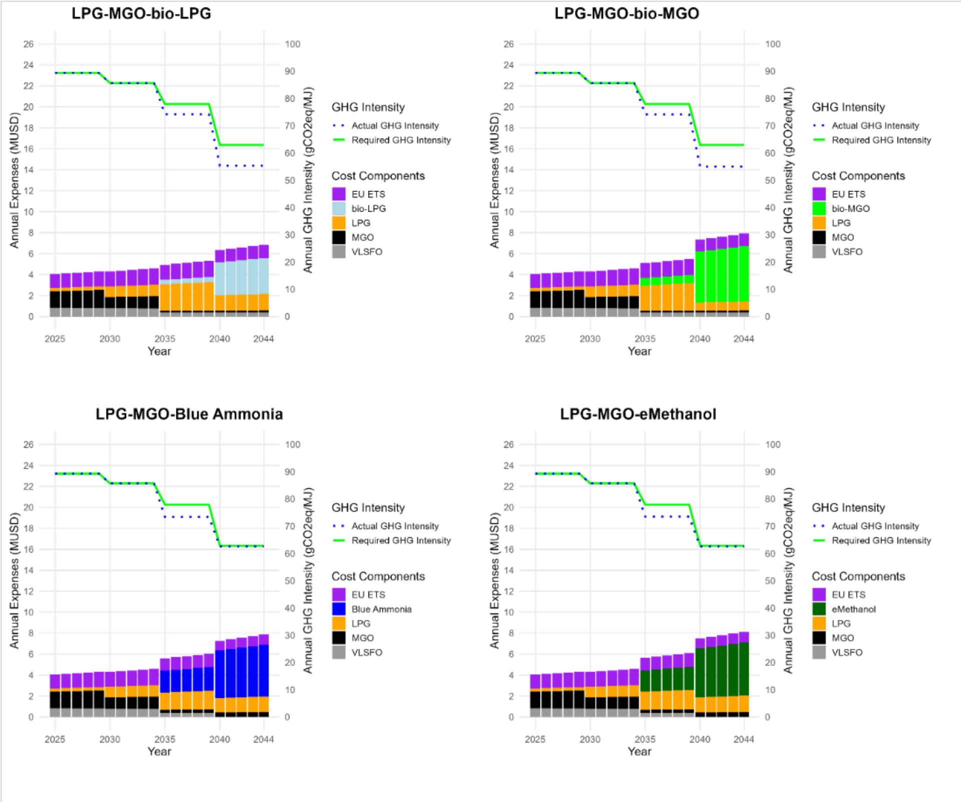


Figure 21: Sensitivity to 50% VLSFO Volume Reduction from 2035-2044
Source: Author's simulation, Annual Cost and GHG Intensity-Alternative Fuel Blend Scenario

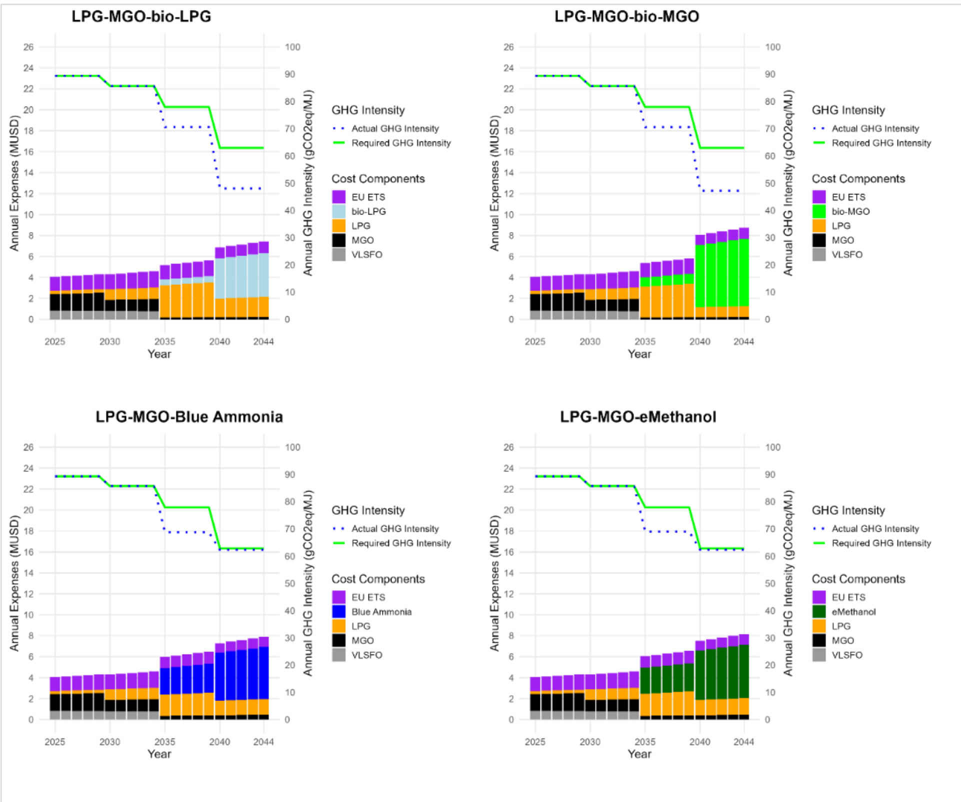


Figure 22: Sensitivity to 100% VLSFO Volume Reduction from 2035-2044
Source: Author's simulation, Annual Cost and GHG Intensity-Alternative Fuel Blend Scenario

B. Fleet Mix and Emission Performance

The displacement of VLSFO reshapes the fleet's operational mix in distinct ways. In LPG–MGO–bio-LPG, renewable LPG becomes the dominant substitute, enabled by existing LPG-ready carriers, while MGO is retained only as pilot fuel. In LPG–MGO–bio-MGO, bio-MGO volumes expand significantly, reflecting compatibility with current engines but at a higher unit cost. For blue ammonia and e-methanol, substitution accelerates the uptake of already low-intensity fuels, but the marginal emissions benefit declines as the baseline mix is already compliant.

At 50% VLSFO reduction, all scenarios record meaningful intensity declines without over-compliance. At 100%, fossil VLSFO is eliminated entirely, producing the lowest possible intensity profiles and maximising surplus credit balances.

C. Economic Viability and Strategic Fit

The cost implications of VLSFO phase-out are summarised in Table 11.

Table 11: Sensitivity Summary of Alternative Fuel Blend Scenario

% VLSFO Volume Reduction 2035-2044	Fuel Cost 2025-2044 (MUSD)	Regulatory Cost 2025-2044 (MUSD)	Total Cost 2025-2044 (MUSD)	Accumulated Compliance Balance 2025-2044 (tCO_2eq)
Alternative Fuel Blend Scenario: LPG-MGO-bio-LPG				
0%	68.80	28.82	97.62	0
25%	71.35	28.36	99.71	+7,240
50%	73.89	27.89	101.78	+14,480
75%	76.43	27.43	103.86	+21,720
100%	78.98	26.97	105.95	+28,960
Alternative Fuel Blend Scenario: LPG-MGO-bio-MGO				
0%	73.70	28.55	102.25	0
25%	76.92	28.05	104.97	+7,240
50%	80.15	27.55	107.70	+14,480
75%	83.38	27.05	110.43	+21,720
100%	86.60	26.54	113.14	+28,960
Alternative Fuel Blend Scenario: LPG-MGO-Blue Ammonia				
0%	82.01	25.77	107.78	0
25%	83.41	25.50	108.91	+2,373
50%	84.81	25.22	110.03	+4,746
75%	86.22	24.95	111.17	+7,119
100%	87.62	24.68	112.30	+9,492
Alternative Fuel Blend Scenario: LPG-MGO-e-Methanol				
0%	83.15	26.09	109.24	0
25%	84.57	25.84	110.41	+2,373
50%	86.00	25.58	111.58	+4,746
75%	87.42	25.33	112.75	+7,119
100%	88.85	25.07	113.92	+9,492

Source: Author's simulation, Annual Cost and GHG Intensity-Alternative Fuel Blend Scenario

In the biofuel scenarios (LPG–MGO–bio-LPG and LPG–MGO–bio-MGO), a 50% reduction delivers a compliance surplus of +14,480 tCO_2eq with only a +4.16 to +5.45 MUSD increase in total costs. Moving to a full 100% reduction maximises the surplus at +28,960 tCO_2eq, but the associated cost rises to +8.33 to +10.89 MUSD, illustrating diminishing marginal returns.

In the low-carbon fuel scenarios (LPG–MGO–Blue Ammonia and LPG–MGO–e-Methanol), the impact is more modest: a 50% VLSFO cut results in cost escalations of just +2.25 to +2.34 MUSD and a surplus of +4,746 tCO_2eq, while complete elimination increases costs by +4.52 to +4.68 MUSD and yields a maximum surplus of +9,492 tCO_2eq. These results confirm that while biofuel-based pathways gain the most from VLSFO reductions, the low-carbon blends already achieve near-compliance in their baseline form, leaving less scope for additional gains.

From a strategic perspective, the 50% VLSFO reduction case represents the most balanced option, combining moderate cost increases with meaningful compliance surpluses, particularly in biofuel pathways. By contrast, the 100% case ensures maximum regulatory security but incurs significantly higher costs and diminishing marginal returns. For PIS, this suggests a pragmatic strategy of adopting mid-range VLSFO reductions in the near term, while preserving the option of full displacement if regulatory tightening accelerates.

5.3. Compliance Strategy: Banking, Borrowing, and Pooling

FuelEU Maritime provides three flexibility mechanisms—banking, borrowing, and pooling—that can be used to smooth compliance under tightening GHG intensity targets. Their value for PIS varies significantly across scenarios.

Banking offers the greatest strategic benefit, but only in high-surplus cases. With 50–100% VLSFO reduction, the bio-MGO and bio-LPG pathways generate surpluses of +14,480 to +28,960 tCO_2eq. Banking these credits could offset the steep thresholds after 2040, avoiding costly late-stage fuel switching and reinforcing the Stage 1 cost buffer.

Borrowing is far less useful, as its annual allowance is restricted to an estimated ~3,500–4,000 tCO_2eq (approximately 2% of the compliance obligation), cannot be exercised in consecutive years, and incurs a 10% surcharge. Given that deficits in fossil-dominated pathways exceed 25,000 tCO_2eq by 2044, borrowing cannot address structural non-compliance and functions only as a tactical stopgap.

Pooling offers potential if mature markets emerge. By partnering with operators of RFNBO-powered vessels, PIS could offset fossil-intensive profiles within a compliance pool. However, the effectiveness declines as thresholds tighten, and uncertainties around governance and contracting limit its near-term reliability.

In sum, banking is the only mechanism with substantive long-term value for PIS, pooling may serve as a complementary tool if institutional frameworks mature, while borrowing remains of negligible relevance. Flexibility instruments therefore act as supplements, not substitutes, for structural fuel switching.

5.4. External Validation

External validation was carried out through consultations with PIS managers across supply chain, procurement, and commercial functions. Feedback from supply chain functions confirmed that both the LPG–MGO–bio-LPG and LPG–MGO–bio-MGO scenarios are technically feasible with the existing fleet. PIS's LPG-ready carriers (Pertamina Gas Dahlia, Pertamina Gas Caspia, and Pertamina Gas Amaryllis) can operate on bio-LPG without retrofits, while the remainder of the fleet is fully compatible with bio-MGO. The projected compliance surplus in the 50% VLSFO-reduction case (+14,480 tCO_2eq; Table 11) was highlighted as a valuable buffer against tightening FuelEU intensity limits or operational volatility.

Feedback from procurement indicates that PIS currently relies exclusively on spot purchases and has not yet adopted derivative hedging. Stage 1 optimisation results indicate that a risk-managed buffer of USD 17.89 million could have absorbed up to 94.06% of incremental clean-fuel costs in the LPG–MGO–bio-MGO pathway and fully covered those costs in the LPG–MGO–bio-LPG pathway, while still leaving a surplus for other exposures. This provides a clear benchmark for evaluating the potential role of swaps in PIS's future procurement strategies.

Market feedback further supports the feasibility of both pathways, with bio-MGO already available at major bunkering hubs and bio-LPG supply projected to expand across Europe and Asia by the mid-2030s, making both scenarios commercially attainable within the planning horizon (DNV, 2024b).

In sum, the validation confirmed that the two recommended scenarios are technically executable, commercially realistic, and financially resilient. This supports the thesis argument that linking risk-adjusted procurement with compliance-oriented fuel strategies provides PIS with a pragmatic and cost-effective path to FuelEU alignment over the 2025–2044 horizon.

Chapter 6. Conclusions and Recommendations

This chapter brings together the results of the integrated optimisation framework, which combined swap-based price hedging (Stage 1), fuel-mix optimisation (Stage 2), and sensitivity testing (Chapter 5). The objective was to design a procurement strategy for PIS that reduces exposure to bunker price volatility while ensuring compliance with FuelEU Maritime well-to-wake GHG intensity limits.

The findings show that financial risk management and regulatory compliance reinforce each other. Stage 1 establishes a risk-adjusted baseline through hedging, generating a USD 17.89 million buffer. Stage 2 applies this buffer to low-carbon fuels, with optimised blending ensuring compliance across 2025–2044. Two pathways stand out—LPG–MGO–bio-LPG and LPG–MGO–bio-MGO—balancing cost efficiency, operational feasibility, and regulatory resilience.

The following sections answer each sub-research question directly and integrate the insights into strategic recommendations for PIS.

6.1. Answer to Sub-research Questions

As sub-research question 1 addressed how Pertamina International Shipping (PIS) can apply financial instruments and quantitative models to manage bunker price volatility, the thesis developed a quantitative procurement framework that integrates multivariate (DCC) GARCH price simulation with mean–variance portfolio optimisation. By generating monthly spot and swap price paths for the 2025–2044 horizon and optimising hedge ratios on a rolling basis, the framework enables dynamic adaptation to volatility clustering and cross-fuel price correlations. The procurement frontier demonstrates that a partial hedging strategy ($\lambda \approx 0.5$) reduces variance by 15.7% while increasing mean cost by only 2.7%, creating a USD 17.89 million cost buffer. This buffer stabilises annual budgets and reframes swaps from a purely defensive hedge into a proactive financial instrument that supports compliance investment.

As sub-research question 2 examined how procurement strategies influence well-to-wake GHG emissions across the fleet, the analysis shows that procurement choices directly shape the emissions trajectory. The optimisation model incorporates fuel-specific well-to-wake emission factors, demonstrating that continued reliance on VLSFO and MGO leads to persistent non-compliance beyond 2025. In contrast, blends incorporating LPG, bio-MGO, bio-LPG, blue ammonia, and e-methanol, reduce fleet-wide GHG intensity to within FuelEU Maritime thresholds. Fully compliant pathways illustrate how procurement can align cost control with regulatory performance, sequencing the transition to cleaner fuels to avoid abrupt compliance gaps.

As sub-research question 3 explored how the cost buffer generated through optimised hedging can be reallocated to finance clean-fuel adoption, the results confirm that Stage 1 risk management provides a direct financing bridge for decarbonisation. Relative to the baseline, the cost buffer offsets 62.84% of the additional USD 28.47 million fuel expenditure in the LPG–MGO–e-Methanol scenario, 65.46% of the additional USD 27.33 million in the blue ammonia scenario, 94.06% of the additional USD 19.02 million in the bio-MGO scenario, and fully covers the additional USD 14.12 million in the bio-LPG scenario, leaving a surplus to address other cost exposures. This demonstrates that financial risk management not only reduces exposure to volatility but also frees resources to underwrite compliance investments, thereby reducing reliance on external subsidies or new capital injections.

As sub-research question 4 considered how procurement strategies can reduce fleet GHG intensity in line with FuelEU Maritime targets, the optimisation confirms that carefully structured blending ensures actual GHG intensity tracks or falls below regulatory thresholds throughout the planning horizon. The LPG–MGO–bio-LPG and LPG–MGO–bio-MGO scenarios deliver full compliance from 2025 to 2044, while generating surpluses of up to +14,480 tCO_2eq under the 50% VLSFO reduction sensitivity. These surpluses act as a compliance buffer, insulating the fleet against future tightening of targets or operational shocks. The findings confirm that procurement optimisation—without reliance on fleet retrofits or speculative newbuildings—can serve as a primary compliance strategy.

As sub-research question 5 investigated how trade-offs between cost minimisation and GHG compliance can be evaluated, the frontier analysis and scenario comparisons reveal that cost-optimal and compliance-optimal strategies diverge. LPG–MGO delivers the lowest fuel cost but fails to meet regulatory thresholds after 2034, while e-methanol and blue ammonia achieve compliance surpluses but impose disproportionately high costs. The optimal balance is achieved in the LPG–MGO–bio-LPG and LPG–MGO–bio-MGO pathways, which deliver uninterrupted compliance, avoid penalty payments, and maintain total costs at USD 97.62 million and USD 102.25 million respectively over 20 years. These strategies strike the most effective balance between regulatory certainty, manageable incremental costs, and compatibility with PIS's existing fleet, offering resilience without capital-intensive interventions.

6.2. Answering the Main Research Question

The main research question of this thesis asked how Pertamina International Shipping (PIS) can optimise its international bunker procurement strategy to manage fuel price volatility, reduce GHG emissions, and comply with FuelEU Maritime requirements. The integrated modelling framework developed in this study demonstrates that this objective can be achieved through a dual-track strategy that combines financial hedging with optimised fuel blending.

On the financial side, multivariate (DCC) GARCH-based price simulations coupled with mean–variance optimisation reduce procurement cost volatility while generating a USD 17.89 million hedge surplus over the 2025–2044 horizon. This surplus acts as a cost buffer, directly financing the higher expenditure associated with low-carbon fuels and preventing compliance from becoming an unsustainable financial burden.

On the environmental side, the procurement strategy embeds FuelEU Maritime's well-to-wake GHG intensity thresholds into optimisation. The most balanced solutions—LPG–MGO–bio-LPG and LPG–MGO–bio-MGO—leverage PIS's existing LPG-ready and dual-fuel vessels to integrate renewable fuels after 2035, maintaining full compliance without penalties or borrowing provisions. Sensitivity testing confirms that additional measures, such as a 50% reduction in VLSFO use, generate compliance surpluses of up to +14,480 tCO_2eq at only moderate additional cost.

Taken together, these results show that cost stability and regulatory compliance are not competing priorities but mutually reinforcing outcomes of an integrated optimisation process. Hedging provides the financial headroom for clean-fuel adoption, while fuel blending ensures that environmental performance is achieved within the same procurement framework. The resulting strategy is financially resilient, operationally feasible, and environmentally robust—positioning PIS to meet decarbonisation mandates while safeguarding its competitiveness in the international tanker market.

6.3. Managerial Implications

The findings of this thesis highlight several strategic priorities for PIS in implementing an integrated bunker procurement strategy that balances cost stability with regulatory compliance:

1. Financial hedging as a compliance enabler
   The application of multivariate (DCC) GARCH–based mean–variance optimisation shows that hedging is not only a defensive tool against fuel price volatility but also a proactive mechanism for compliance. By stabilising costs and generating a USD 17.89

million buffer, hedging creates budgetary space to absorb the premium of low-carbon fuels. This reframes regulatory compliance from a financial burden into a transition that can be strategically financed through risk management.

2. Leveraging fleet readiness

   PIS's existing LPG-ready carriers and dual-fuel vessels provide a structural advantage. The operational feasibility of the LPG–MGO–bio-LPG and LPG–MGO–bio-MGO pathways, both of which achieve full FuelEU Maritime compliance without retrofit or newbuilding investments, derives directly from this readiness. This capability enables immediate and flexible adoption of alternative fuels in line with regulatory tightening, reducing transition risk relative to less adaptable competitors.

3. Embedding scenario-based triggers

   Sensitivity analysis confirms the importance of institutionalising trigger points within procurement policy. A 50% VLSFO reduction post-2035 generates compliance surpluses of +14,480 tCO_2eq at moderate cost, effectively creating an emissions buffer against accelerated GHG targets. Formalising such triggers within governance structures would ensure resilience under multiple regulatory and market trajectories.

4. Integrating procurement governance

   Operationalising the optimisation framework requires a unified governance model that links financial risk management, fleet operations, and compliance oversight. Coordinated decision-making, supported by shared performance metrics and continuous data exchange, is essential to fully realise the benefits of the integrated procurement strategy.

Adopting this portfolio-based approach—where cost efficiency, emissions performance, and operational feasibility are optimised concurrently—positions PIS to navigate volatile fuel markets, meet tightening FuelEU Maritime standards, and sustain competitiveness in the international tanker sector.

6.4. Limitations

While the optimisation framework developed in this thesis provides a robust basis for aligning PIS's bunker procurement with cost control and FuelEU Maritime compliance, several limitations must be acknowledged:

1. Market and regulatory uncertainty

   The modelling framework assumes a degree of stability in fuel prices, availability, and regulatory parameters that may not hold in practice. Volatility in alternative fuel markets—particularly bio-LPG, bio-MGO, blue ammonia, and e-methanol—along with uncertainties in supply chain readiness and infrastructure deployment, could significantly affect both cost projections and optimal blending ratios. In addition, policy evolution beyond currently legislated FuelEU and IMO measures introduces further uncertainty.

2. Hedging execution risks

   The multivariate (DCC) GARCH and mean–variance optimisation approach captures price co-movement and portfolio risk but does not model liquidity constraints or counterparty credit risk. In practice, these factors may limit the feasibility, pricing, and timing of swap transactions, especially for alternative fuels where forward markets remain shallow or underdeveloped.

3. Fleet deployment constraints

   Fleet compatibility assumptions are based on current technical specifications and declared dual-fuel readiness of PIS's owned and chartered tonnage. Delays in vessel deliveries, unforeseen retrofitting requirements, or deviations in charter agreements could restrict the operational feasibility of the identified fuel pathways. Time-chartered vessels may not always provide the flexibility assumed in the model.

4. Emissions performance variability

   The optimisation relies on standardised well-to-wake emission factors from FuelEU Maritime as a regulatory benchmark. Actual emissions may vary due to engine efficiency, fuel quality, or operational conditions. These deviations could affect compliance outcomes, surplus credit generation, and the robustness of long-term decarbonisation planning.

Recognising these limitations highlights the importance of adaptive management. The optimisation outputs should serve as decision-support tools rather than fixed prescriptions, with procurement, blending, and hedging strategies recalibrated as market, regulatory, and technical conditions evolve.

6.5. Recommendations for Future Research

Building on the findings of this research and acknowledging its limitations, several future research directions can be identified that would strengthen the theoretical foundation of integrated bunker procurement and compliance optimisation and enhance its practical relevance for shipping companies facing fuel price volatility and tightening regulatory constraints:

1. Incorporating stochastic fuel availability and disruptions

   Future models should embed uncertainty in fuel availability, supply chain bottlenecks, and port-specific bunkering capacity. Scenario generation that accounts for geopolitical risks, seasonal variations, and infrastructure development would improve the robustness of optimisation outcomes.

2. Integrating market liquidity and transaction costs in hedging

   The current framework models swap as frictionless instruments. Future work should include bid–ask spreads, margin requirements, and counterparty credit limits, particularly for emerging low-carbon fuels where forward market depth is thin. This would yield a more realistic risk–return profile for financial hedging.

3. Expanding regulatory scope

   While this thesis centred on FuelEU Maritime compliance, future research should address cross-regulatory interactions, including the forthcoming IMO Net Zero Framework—scheduled for adoption in October 2025 and entry into force around 2027–2028—and regional schemes beyond the EU ETS, to ensure procurement strategies remain resilient across divergent policy regimes.

4. Coupling procurement with technical efficiency measures

   Procurement optimisation could be enhanced by integrating the techno-economic impact of efficiency measures such as air lubrication systems, voyage optimisation tools, and hybrid energy storage. Joint modelling of technical upgrades and fuel strategies would provide a more holistic view of compliance pathways.

5. Applying adaptive optimisation and learning techniques

   Dynamic optimisation methods, such as reinforcement learning or adaptive programming, could enable real-time adjustment of procurement and blending strategies as new market and regulatory data emerge. This would allow models to evolve continuously rather than relying on static long-range projections.

By pursuing these research directions, future studies can develop the current framework into a fully adaptive, multi-fuel, and multi-regulatory procurement model, capable of ensuring long-term cost stability, compliance assurance, and operational flexibility for international shipping fleets.

References

Acciaro, M., Hoffmann, P. N., & Eide, M. S. (2013). The energy efficiency gap in maritime transport. *Journal of Shipping and Ocean Engineering, 3(1-2)*, 1-10. Retrieved from https://www.researchgate.net/profile/Shigalla-Mahongo/publication/259865499_Investigating_the_effect_of_winds_and_storms_on_shoreline_erosion_along_the_coast_of_Tanzania/links/5c5bfdc045851582c3d4647f/Investigating-the-effect-of-winds-and-storms-on-shorel

Alizadeh, A. H., & Nomikos, N. K. (2004). The efficiency of the forward bunker market. *International Journal of Logistics Research and Applications, 7(3)*, 281-296. doi:https://doi.org/10.1080/13675560412331298527

Alizadeh, A. H., & Nomikos, N. K. (2009). *Shipping derivatives and risk management.* Palgrave Macmillan.

Bai, X., & Kavussanos, M. G. (2022). Hedging IMO2020 compliant fuel price exposure using futures contracts. *Energy Economics, 110*, 106029. doi:https://doi.org/10.1016/j.eneco.2022.106029

Birge, J. R., & Louveaux, F. (2011). *Introduction to Stochastic Programming (2nd ed.).* Springer. doi:https://doi.org/10.1007/978-1-4614-0237-4

Bollerslev, T. (1986). Generalized autoregressive conditional heteroskedasticity. *Journal of Econometrics, 31(3)*, 307–327. doi:https://doi.org/10.1016/0304-4076(86)90063-1

Bouman, E. A.; Lindstad, E.; Rialland, A.; Strømman, A H. (2017). State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping – A review. *Transportation Research Part D: Transport and Environment, 52(A)*, 408–421. doi:https://doi.org/10.1016/j.trd.2017.03.022

CE Delft. (2022). *Technical and economic analysis of the EU FuelEU Maritime and EU ETS proposals.* CE Delft.

Clarksons Research. (2025). *Shipping Intelligence Network (SIN) Time Series.* Clarksons Research. Retrieved from https://www.clarksons.net/n/#/sin/timeseries

Creswell, J. W., & Creswell, D. J. (2018). *Research design: Qualitative, quantitative, and mixed methods approaches (5th ed.).* SAGE Publications.

DNV. (2024a). *FuelEU Maritime: Requirements, compliance strategies, and commercial impacts.* DNV. Retrieved from https://www.dnv.com/maritime/publications/fueleu-maritime.html

DNV. (2024b). *Maritime Forecast to 2050: Energy Transition Outlook 2024.* DNV. Retrieved from https://www.isesassociation.com/wp-content/uploads/2024/08/DNV_Maritime_Forecast_2050_2024-final-3.pdf

DNV. (2025). *Fuel Prices - Basic Data set.* Alternative Fuels Insight. Retrieved from https://afi.dnv.com/statistics/2ae7811e-af73-4b93-bc9a-19c440816b2a/Fuel_Prices-Basic

Eisenhardt, K. M. (1989). Building theories from case study research. *Academy of Management Review, 14(4)*, 532–550. doi:https://doi.org/10.5465/amr.1989.4308385

Engle, R. F. (2002). Dynamic conditional correlation: A simple class of multivariate GARCH models. *Journal of Business & Economic Statistics, 20(3)*, 339–350. doi:https://doi.org/10.1198/073500102288618487

European Parliament and Council. (2023). Regulation (EU) 2023/1805 on the use of renewable and low-carbon fuels in maritime transport. *Official Journal of the European Union*. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32023R1805

Forza, C. (2002). Survey research in operations management: A process-based perspective. *International Journal of Operations & Production Management, 22(2)*, 152–194. doi:https://doi.org/10.1108/01443570210414310

Ghosh, S., Lee, L. H., & Ng, S. H. (2015). Bunkering decisions for a shipping liner in an uncertain environment with service contract. *European Journal of Operational Research, 244(3)*, 792–802. doi:https://doi.org/10.1016/j.ejor.2015.02.012

Gibbert, M., Ruigrok, W., & Wicki, B. (2008). What passes as a rigorous case study? *Strategic Management Journal, 29(13)*, 1465–1474. doi:https://doi.org/10.1002/smj.722

Heitsch, H., & Römisch, W. (2003). Scenario reduction algorithms in stochastic programming. *Computational Optimization and Applications, 24(2–3)*, 187–206. doi: https://doi.org/10.1023/A:1021805924152

Heitsch, H., & Römisch, W. (2009). Scenario tree modeling for multistage stochastic programs. *Mathematical Programming, 118(2)*, 371-406. doi:https://doi.org/10.1007/s10107-007-0197-2

IMO. (2023). *2023 IMO Strategy on Reduction of GHG Emissions from Ships.* International Maritime Organization. Retrieved from https://wwwcdn.imo.org/localresources/en/MediaCentre/PressBriefings/Documents/2023%20Strategy%20%20on%20Reduction%20of%20GHG%20emissions%20from%20ships%20as%20adopted%20subject%20to%20any%20final%20editorials_.pdf

Markowitz, H. (1952). Portfolio Selection. *The Journal of Finance, 7(1)*, 77-91. doi:https://doi-org.eur.idm.oclc.org/10.2307/2975974

Notteboom, T., & Vernimmen, B. (2009). The effect of high fuel costs on liner service configuration in container shipping. *Journal of Transport Geography, 17(5)*, 325–337. doi:https://doi.org/10.1016/j.jtrangeo.2008.05.003

Pavlenko, N., Comer, B., Zhou, Y., Clark, N., & Rutherford, D. (2020). *The climate implications of using LNG as a marine fuel.* International Council on Clean Transportation. Retrieved from https://theicct.org/sites/default/files/publications/Climate_implications_LNG_marinefuel_01282020.pdf

Pedrielli, G., Lee, L. H., & Ng, S. H. (2015). Optimal bunkering contract in a buyer–seller supply chain under price and consumption uncertainty. *Transportation Research Part E: Logistics and Transportation Review, 77*, 77-94. doi:https://doi.org/10.1016/j.tre.2015.02.010

Pigou, A. C. (1920). *The Economics of Welfare.* London: Macmillan.

PIS. (2024a). *Annual Report.* Pertamina International Shipping. Retrieved from https://www.pispertamina.com

PIS. (2024b). *Financial Report.* Pertamina International Shipping. Retrieved from https://www.pispertamina.com

Psaraftis, H. N. (2012). Market-based measures for greenhouse gas emissions from ships: A review. *WMU Journal of Maritime Affairs, 11*, 211–232. doi:https://doi.org/10.1007/s13437-012-0030-5

R Core Team. (2024). *R: A language and environment for statistical computing.* R Foundation for Statistical Computing. Retrieved from https://www.R-project.org/

Rockafellar, R. T., & Uryasev, S. (2000). Optimization of Conditional Value-at-Risk. *Journal of Risk, 2(3)*, 21-41. Retrieved from https://www.risknet.de/fileadmin/eLibrary/Rockafellar-Conditional-Value-at-Risk.pdf

Roux, M., Lodato, C., Laurent , A., & Astrup, T. F. (2024). A review of life cycle assessment studies of maritime fuels: Critical insights, gaps, and recommendations. *Sustainable Production and Consumption, 50*, 69-86. doi:https://doi.org/10.1016/j.spc.2024.07.016

SEA-LNG, & thinkstep. (2019). *Lifecycle GHG Emission Study on the Use of LNG as a Marine Fuel.* SEA-LNG & thinkstep. Retrieved from https://sea-lng.org/wp-content/uploads/2020/06/19-04-10_ts-SEA-LNG-and-SGMF-GHG-Analysis-of-LNG_Full_Report_v1.0.pdf

Snyder, H. (2019). Literature reviews as a research methodology: An overview and guidelines. *Journal of Business Research, 104*, 333–339. doi:https://doi.org/10.1016/j.jbusres.2019.07.039

Stefanakos, C. N., & Schinas, O. (2014). Forecasting bunker prices; A nonstationary, multivariate methodology. *Transportation Research Part C: Emerging Technologies, 38*, 177-194. doi:https://doi.org/10.1016/j.trc.2013.11.017

Stopford, M. (2009). *Maritime Economics (3rd ed.).* Routledge.

Tietenberg, T., & Lewis, L. (2018). *Environmental and natural resource economics (11th ed.).* Routledge.

UNCTAD. (2023). *Review of Maritime Transport 2023, Towards a Green and Just Transition.* United Nations.

Wang, Y., Meng, Q., & Tan, Z. (2018). Short-term liner shipping bunker procurement with swap contracts. *Maritime Policy & Management, 45(2)*, 211–238. doi:https://doi.org/10.1080/03088839.2017.1375165

Yin, R. K. (2014). Case Study Research: Design and Methods (5th ed.). *The Canadian Journal of Program Evaluation, 30*, 282. doi:https://doi.org/10.3138/cjpe.30.1.108

Appendix A: Supplementary Information (separate file)

The Supplementary Information (SI) is provided as a stand-alone document accompanying this thesis. It expands upon the main text by presenting extended methodological details, complete mathematical derivations, annotated R code, and replication outputs referenced in Chapters 3 until 5.

Each section and equation within the SI are numbered sequentially (e.g. S1–S26) and cross-referenced in the thesis for clarity. Figures and tables in Chapters 4 and 5 are assembled directly from SI outputs, while the replication checklist specifies the precise file order, scripts, and outputs required to reproduce all reported results.

Certain company-specific data has been excluded for confidentiality; however, the documented methodology remains fully reproducible with substitute or dummy data. The SI is designed as a transparent, reproducible, and academically rigorous appendix, ensuring that the research process can be replicated while the main thesis remains focused on research design, analysis, and contributions. The SI is intended exclusively for academic purposes and not for commercial use.

Appendix B: Input Assumptions

Table B1: Input Assumptions for Each Fuel-type Considered

Fuel Molecule	WtW-GHG intensity (gCO_2eq/MJ)	LHV (MJ/tonne)	Share of Pilot Fuel Oil (by energy)	Fuel Price (USD/GJ)	Fuel Price (USD/tonne)
HSFO	94.00	40,500	-	simulation	simulation
VLSFO	92.60	41,000	-	simulation	simulation
MGO	90.60	42,700	-	Simulation	Simulation
LPG	74.10	46,000	5%	15.00	672.65
Bio-LPG	20.00	46,000	5%	30.00	1,380.00
Bio-MGO	34.02	42,700	-	35.00	1,494.50
e-Methanol	30.67	19,900	10%	80.40	1,600.00
Blue Ammonia	30.84	18,600	10%	80.65	1,500.00

Source: Author's Compilation based on (Clarksons Research, 2025; DNV, 2025; CE Delft, 2022; European Parliament and Council, 2023; DNV, 2024a)

Table B2: EU ETS and FuelEU Penalty Assumptions

Description	Value	Unit
EU ETS	83.56	USD/tCO_2eq
Fuel EU Penalties	694.00	USD/tCO_2eq at an exchange rate of 1.08 USD/EUR

Source: Author's Compilation based on (Clarksons Research, 2025; CE Delft, 2022; European Parliament and Council, 2023; DNV, 2024a)

Appendix C: Company-Specific Data (confidential)

This appendix presents detailed numerical data obtained from Pertamina International Shipping. The tables report confidential information on historical procurement transactions, including volumes, prices, and port-level distributions for the years 2023 and 2024. These data are provided solely for assessment purposes in the defence of this thesis. They are not intended for publication, distribution, or circulation beyond the examination process. Aggregated insights derived from these figures are discussed in the main text (see Section 4.2.1 and 4.3.2), while the full numerical values are included here only to allow examiners to verify the accuracy of the analysis.

Table C1: Descriptive Statistics of PIS's Bunker Procurement by Year and Fuel Type

Year	Fuel Type	Total Transactions	Total Volume (MT)	Total Costs (USD Million)	Avg. Tender Price (USD/MT)	Price SD (USD/MT)	Min Price (USD/MT)	Max Price (USD/MT)
2023	VLSFO	165	161,335	99.32	617.51	45.94	534.00	721.00
2023	MGO	96	11,462	9.87	815.66	112.42	628.00	1,180.00
2023	HSFO	16	31,850	18.02	553.50	106.27	446.00	767.00
	TOTAL	**280**	**204,647**	**127.21**	**681.10**	**126.50**	**446.00**	**1,180.00**
2024	VLSFO	133	91,752	56.40	610.77	32.76	542.00	726.50
2024	MGO	101	11,238	8.50	748.05	85.22	601.00	1,160.00
2024	HSFO	33	52,012	25.52	494.86	38.44	425.00	628.75
	TOTAL	**267**	**155,002**	**90.42**	**648.38**	**104.14**	**425.00**	**1,160.00**

Note: SD = Standard deviation; USD = United State Dollars; MT = Metric Tonnes.

Table C2: Descriptive Statistics of PIS's Bunker Procurement by Port, 2023

Bunker Ports	Bunker Type	Total Transactions	Total Volume (MT)	Total Costs (USD Million)	Avg. Tender Price (USD/MT)	Price SD (USD/MT
Singapore	VLSFO	131	80,635	49.44	617.47	45.42
	MGO	75	7,652	6.07	781.93	86.05
	HSFO	8	12,600	6.33	494.06	43.56
	TOTAL	**214**	**100,887**	**61.85**	**670.5**	**105.66**
Fujairah	VLSFO	19	51,610	30.99	595.38	44.32
	MGO	4	1,490	1.49	993	56.11
	HSFO	1	1,600	0.71	446	-
	TOTAL	**24**	**54,700**	**33.2**	**655.43**	**163.25**
Houston	VLSFO	11	17,990	11.74	650.55	40.56
	MGO	8	760	0.7	904	64.16
	HSFO	4	5,200	2.77	529	41.49
	TOTAL	**23**	**23,950**	**15.22**	**717.57**	**153.76**

Gibraltar	VLSFO	-	-	-	-	-
	MGO	3	280	0.27	792	3.46
	HSFO	-	-	-	-	-
	TOTAL	**3**	**280**	**0.27**	**792**	**3.46**
Port Louis	VLSFO	1	4,200	2.88	685	-
	MGO	3	1,050	1.11	1,065.00	139.37
	HSFO	5	11,400	7.68	701.6	85.72
	TOTAL	**9**	**16,650**	**11.67**	**820.89**	**205.13**
Rotterdam	VLSFO	3	6,900	4.27	615.67	9.02
	MGO	1	50	0.04	778	-
	HSFO	1	1050	0.52	494	-
	TOTAL	**5**	**8,000**	**4.83**	**623.8**	**101.23**
Other Ports	VLSFO	-	-	-	-	-
	MGO	2	180	0.17	1052,50	17.68
	HSFO	-	-	-	-	-
	TOTAL	**2**	**180**	**0.17**	**1052,50**	**17.68**

Note: SD = Standard deviation; USD = United State Dollars; MT = Metric Tonnes.

Table C3: Descriptive Statistics of PIS's Bunker Procurement by Port, 2024

Bunker Ports	Bunker Type	Total Transactions	Total Volume (MT)	Total Costs (USD Million)	Avg. Tender Price (USD/MT)	Price SD (USD/MT
Singapore	VLSFO	112	59,322	36.42	610.40	28.74
	MGO	71	7,339	5.26	714.46	55.22
	HSFO	17	22,812	11.15	490.22	24.48
	TOTAL	**200**	**89,473**	**52.83**	**637.12**	**77.21**
Fujairah	VLSFO	7	19,500	11.72	603.03	33.75
	MGO	6	1,420	1.17	797.40	56.92
	HSFO	2	6,600	2.89	436.00	15.56
	TOTAL	**15**	**27,520**	**15.78**	**658.51**	**136.17**
Houston	VLSFO	7	7,720	4.80	624.71	60.24
	MGO	8	528	0.46	866.37	62.89
	HSFO	9	14,600	7.18	492.42	27.82
	TOTAL	**24**	**22,848**	**12.44**	**655.65**	**169.06**
Gibraltar	VLSFO	3	660	0.38	597.74	39.62
	MGO	8	910	0.73	797.38	58.66
	HSFO	3	4,800	2.40	501.33	28.57
	TOTAL	**14**	**6,370**	**3.51**	**691.16**	**139.61**

Port Louis	VLSFO	1	3,000	2.18	725.00	-
	MGO	2	326	0.33	1030.00	183.85
	HSFO	1	1,600	1.01	628.75	-
	TOTAL	**4**	**4,926**	**3.52**	**853.44**	**233.19**
Rotterdam	VLSFO	2	1050	0.61	584.00	29.70
	MGO	4	445	0.36	802.50	66.23
	HSFO	1	1,600	0.89	560.00	-
	TOTAL	**7**	**3,095**	**1.86**	**705.43**	**130.62**
Other Ports	VLSFO	1	500	0.29	588.00	-
	MGO	2	270	0.19	731.33	17.43
	HSFO	-	-	-	-	-
	TOTAL	**3**	**770**	**0.48**	**683.55**	**83.66**

Note: SD = Standard deviation; USD = United State Dollars; MT = Metric Tonnes.

Table C4: PIS Fleet Composition and Fuel Consumption in EU Voyages During 2024

Vessel Name	Ownership	Tanker Type	Year Built	Ship Age	DWT	Total Voyage	Total Fuel Consume in 2024		
							HSFO	VLSFO	MGO
Gas Ambalat	Owned	LPG	2014	11	3,769.00	32	-	200.26	742.74
Gas Antasena	Owned	LPG	2011	14	3,796.00	3	-		332.39
Gas Arjuna	Owned	LPG	2012	13	3,200.00	5	-		197.20
Marianna Golden	TC	LPG	1998	27	20,613.00	2	-	205.38	
Commodore One	TC	Products	2003	22	37,343.00	2	-	62.68	11.33
Emmanuel	TC	Products	2002	23	37,113.00	2	-	176.44	1.01
Panderman	Owned	Products	2017	8	17,500.00	3	-	340.52	7.12
Pangalengan	Owned	Products	2019	6	17,803.00	4	-	168.54	0.47
Papandayan	Owned	Products	2019	6	17,713.00	4	-	99.23	15.10
PIS Mahakam	Owned	Products	2008	17	8,981.00	5	-	119.06	97.20
Supreme Star	TC	Products	2004	21	34,806.00	10	-	803.32	54.61
Union Trust	TC	Products	2004	21	34,999.00	4	-	515.17	45.68
				Total	**237,636.00**	**76.00**	-	**2,690.59**	**1,504.84**