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Techno-Economic Trade-Offs and Strategic Decision-Making in Maritime Decarbonisation: Evaluating Alternative Fuel Pathways under Uncertainty

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Abstract

Maritime transport is undergoing a complex transition toward lower greenhouse gas emissions under increasing regulatory and market pressure. This study develops an integrated techno-economic perspective on maritime decarbonisation by examining the interaction between regulatory frameworks, alternative fuel pathways, and strategic decision-making in shipping. The analysis combines insights from institutional theory and real options theory to explain how shipowners respond to uncertainty related to technology, fuel availability, infrastructure development, and future environmental regulation. The paper evaluates major alternative marine fuels, including liquefied natural gas, biofuels, hydrogen, ammonia, and methanol, in terms of emissions reduction potential, technological maturity, infrastructure readiness, and economic implications. Particular emphasis is placed on the evolving regulatory environment shaped by the International Maritime Organization and European Union policies such as the EU ETS and FuelEU Maritime. The Greek shipping industry is used as an illustrative case for understanding strategic adaptation under regulatory and technological uncertainty. The findings indicate that no single fuel pathway currently satisfies all operational and economic requirements, leading shipowners to adopt flexible and portfolio-based investment strategies. The study contributes to a broader understanding of strategic adaptation within the maritime energy transition. This study contributes by proposing an integrated decision-making framework that combines Institutional Theory and Real Options Theory for strategic fuel selection under regulatory uncertainty.

Keywords: Institutional theory, Real options theory, Fuel flexibility, Carbon intensity regulation, ESG finance, Fleet investment, Energy transition, Green maritime governance, Operational optimization, Sustainable shipping systems.

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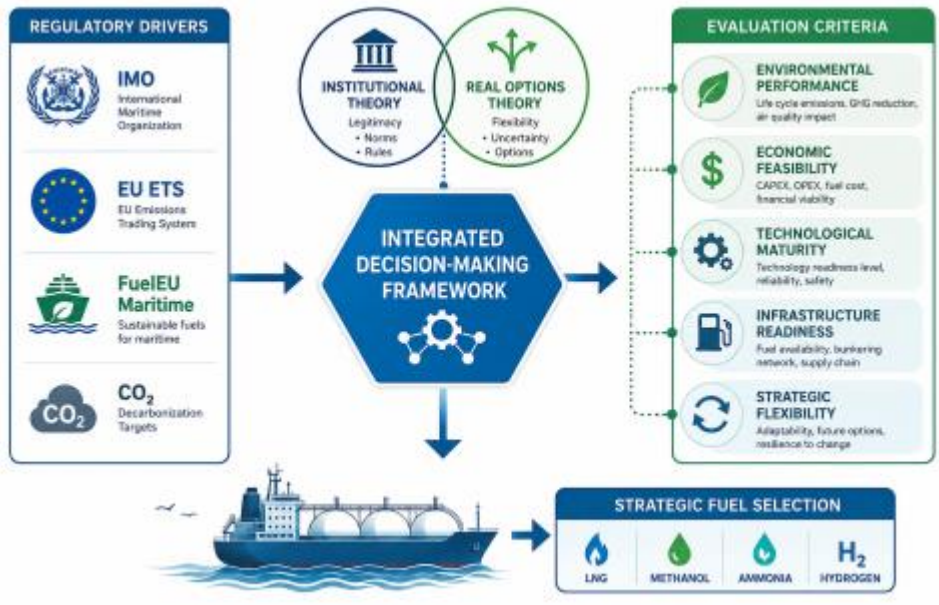
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Graphical abstract



1. Introduction

Maritime transport plays a fundamental role in the global economy, facilitating approximately 90% of international trade (IMO, 2020). Despite its relative energy efficiency compared to other transport modes, the sector remains a significant contributor to greenhouse gas (GHG) emissions, accounting for nearly 3% of global anthropogenic emissions (IMO, 2020). As international climate commitments intensify, the decarbonisation of shipping has evolved from a long-term aspiration into an immediate strategic and operational priority.

Unlike other sectors, maritime decarbonisation is characterised by a high degree of technological and economic uncertainty. The absence of a universally dominant low- or zero-carbon fuel, combined with long asset lifecycles and capital-intensive investment decisions, creates a complex decision-making environment for shipowners. At the same time, the regulatory landscape is becoming increasingly stringent (IMO, 2023; European Commission, 2021). The International Maritime Organization (IMO) has introduced progressively ambitious emissions reduction targets, while regional actors such as the European Union are implementing market-based mechanisms, including carbon pricing and fuel standards, that directly affect operational costs and investment strategies.

Within this evolving context, the transition toward low- and zero-carbon shipping cannot be understood solely as a technological shift. Instead, it represents a broader techno-economic transformation shaped by the interaction of regulatory frameworks, fuel pathways, market pressures, and financial constraints. Shipowners are required to navigate this transition by making strategic decisions under conditions of uncertainty, balancing short-term compliance requirements with long-term competitiveness and asset value preservation.

Although the literature has extensively examined regulatory developments, alternative fuels, and emissions reduction technologies, existing studies often address these dimensions in isolation. There remains a need for a more integrated perspective that captures how regulatory pressure, technological options, and economic considerations jointly influence strategic behaviour in the shipping industry.

This paper addresses this gap by developing a techno-economic analysis of maritime decarbonisation pathways. It synthesises current knowledge on regulatory frameworks, clean propulsion technologies, and economic implications, while placing particular emphasis on their interdependencies and combined effects on decision-making.

The Greek shipping industry is employed as an empirical reference point to ground the analysis in real-world practice. As the world's leading shipowning nation, Greece provides a critical lens through which to examine how globally active shipowners respond to regulatory complexity, fuel uncertainty, and evolving market expectations. The strategic behaviour of Greek shipowners characterised by flexibility, phased investment, and operational optimisation offers valuable insights into broader industry trends.

The contribution of this study is twofold. First, it advances the literature by providing an integrated techno-economic perspective on maritime decarbonisation, moving beyond descriptive reviews toward a more analytical interpretation of transition dynamics. Second, it lays the foundation for the development of a structured framework that explains

how shipowners make strategic decisions under conditions of regulatory and technological uncertainty.

The remainder of the paper is structured as follows. Section 2 introduces the theoretical and analytical framework underpinning the study. Sections 3 and 4 examine regulatory drivers and technological pathways, respectively, while Section 5 analyses the economic and operational implications for shipowners. Section 6 discusses the case of the Greek shipping industry, and Section 7 develops a conceptual synthesis of the findings. The final section presents the main conclusions and outlines directions for future research.

2. Methodological Approach

This study adopts a conceptual and literature-based methodological approach to examine the techno-economic dimensions of maritime decarbonisation and the strategic responses of shipowners under conditions of regulatory and technological uncertainty.

The analysis is based on a structured synthesis of academic literature, institutional reports, and policy documents related to maritime emissions regulation, alternative marine fuels, investment decision-making, and shipping economics. Key sources include publications from the International Maritime Organization (IMO), the European Commission, the International Energy Agency (IEA), the International Renewable Energy Agency (IRENA), and classification societies such as DNV, alongside peer-reviewed academic studies in maritime transport and energy transition research.

Rather than conducting primary empirical research or quantitative modelling, the study develops an interpretive analytical framework that integrates institutional theory and real options theory in order to explain how regulatory pressures, technological uncertainty, and techno-economic constraints jointly shape strategic decision-making in shipping.

The methodological approach follows a qualitative synthesis logic, whereby regulatory developments, fuel pathways, and economic implications are comparatively evaluated through existing literature and industry evidence. The Greek shipping industry is employed as an illustrative empirical reference point due to its leading position in global shipping and its exposure to both international and regional regulatory frameworks.

This approach enables the study to provide an integrated perspective on maritime decarbonisation while identifying the strategic trade-offs associated with alternative fuel adoption, fleet investment, and operational adaptation under uncertainty.

3. Theoretical Framework: Regulation, Uncertainty and Strategic Decision-Making in Maritime Decarbonisation

The transition toward low- and zero-carbon shipping can be conceptualised as a complex socio-technical and economic transformation shaped by regulatory intervention, technological uncertainty, and strategic adaptation. To capture these dynamics, this study adopts an integrated theoretical perspective combining insights from institutional theory and real options theory. This hybrid approach provides a structured lens through which to interpret how external pressures and internal strategic considerations jointly influence decision-making in the maritime sector.

3.1. *Institutional Pressures and Regulatory Drivers*

Institutional theory offers a well-established framework for understanding how organisations respond to external pressures arising from regulatory, normative, and market environments (DiMaggio & Powell, 1983). Within the context of maritime decarbonisation, regulatory frameworks introduced by the International Maritime Organization (IMO) and the European Union function as coercive mechanisms that shape firm behaviour by imposing binding constraints on emissions performance, fuel selection, and operational practices.

In parallel, normative pressures emerge from market actors, including charterers, cargo owners, and financial institutions, which increasingly incorporate environmental performance criteria into contracting and financing decisions. Initiatives such as ESG-based lending and sustainability-linked financing reinforce these expectations, contributing to the institutionalisation of decarbonisation as a core strategic objective. Recent evidence further indicates that stronger ESG disclosure and sustainability-oriented governance improve firms' long-term competitiveness, facilitate access to sustainable finance, and reinforce corporate environmental performance. These developments strengthen the role of institutional alignment as a strategic driver of maritime decarbonisation (Duan *et al.*, 2025).

Mimetic pressures further arise as firms imitate early adopters of alternative fuels and energy-efficient technologies in order to maintain competitiveness and legitimacy within the industry.

From this perspective, maritime decarbonisation is not solely driven by technological feasibility but is fundamentally shaped by institutional alignment. Shipowners are required to conform to evolving regulatory standards while simultaneously responding to market expectations, leading to convergence toward lower-emission practices across the industry.

3.2. *Technological Uncertainty and Real Options Logic*

While institutional theory explains the direction and intensity of external pressures, it does not fully capture how firms make investment decisions under conditions of uncertainty. Maritime decarbonisation is characterised by significant ambiguity regarding the future dominance of alternative fuels, the evolution of regulatory frameworks, and the long-term cost trajectories of competing technologies.

Real options theory provides a complementary analytical lens by conceptualising investment decisions as a series of staged commitments under uncertainty (Dixit & Pindyck, 1994, Trigeorgis, 1996). Rather than committing irreversibly to a single technological pathway, firms may adopt flexible strategies that preserve the option to switch

between fuels or technologies as new information becomes available.

In the shipping industry, this logic is reflected in the increasing adoption of fuel-ready and dual-fuel vessels, which allow shipowners to defer final investment decisions while maintaining compliance with current regulations. Such strategies can be interpreted as "option value" investments, enabling firms to hedge against the risk of technological lock-in and future regulatory misalignment.

The application of real options logic is particularly relevant in a capital-intensive sector characterised by long asset lifecycles and high sunk costs. By prioritising flexibility, shipowners can balance the trade-off between early adoption of emerging technologies and the risk of premature or suboptimal investment decisions.

3.3. *Integrating Institutional and Techno-Economic Perspectives*

The combination of institutional theory and real options theory enables a more comprehensive understanding of maritime decarbonisation as a techno-economic transition. Institutional pressures define the direction and urgency of change, while real options logic explains how firms strategically respond to uncertainty in technology and market conditions.

This integrated perspective highlights that decarbonisation pathways are not determined solely by emissions performance or cost efficiency, but by the interaction between regulatory compliance, technological feasibility, and strategic flexibility. Consequently, shipowners' decisions regarding fuel adoption, fleet renewal, and operational optimisation can be understood as adaptive responses to a dynamic and multi-layered environment.

Within this framework, techno-economic factors such as capital expenditure, operating costs, fuel availability, and lifecycle emissions interact with institutional constraints to shape feasible and desirable decarbonisation strategies. The resulting decision-making process is inherently iterative, involving continuous reassessment of regulatory developments, technological progress, and market signals.

3.4. *Implications for Analytical Approach*

Building on this theoretical foundation, the present study adopts a techno-economic analytical approach that explicitly links regulatory drivers, technological pathways, and economic considerations. The analysis that follows is therefore structured to reflect these interdependencies.

Regulatory frameworks are examined as institutional drivers of change, alternative fuels and propulsion technologies are evaluated in terms of techno-economic performance, and shipowners' strategies are interpreted through the lens of flexibility and risk management. The Greek shipping industry is used as an empirical reference point to illustrate how these theoretical dynamics manifest in practice within a globally competitive and highly regulated context.

By integrating theoretical and empirical insights, the study moves beyond descriptive analysis and contributes to a more systematic understanding of strategic decision-making in maritime decarbonisation.

4. Regulatory Framework as an Institutional Driver of Maritime Decarbonisation

The regulatory framework governing maritime decarbonisation has evolved into a central mechanism shaping strategic decision-making within the shipping industry. From an institutional perspective, regulatory instruments function as coercive pressures that not only impose compliance requirements but also redefine the economic and technological landscape in which shipowners operate. As a result, environmental regulation is no longer a peripheral constraint but a primary driver of investment, operational practices, and long-term fleet strategies.

5. The IMO Framework and the Institutionalisation of Decarbonisation

At the global level, the International Maritime Organization (IMO) constitutes the core institutional authority responsible for regulating greenhouse gas (GHG) emissions from international shipping. The adoption of the Initial IMO GHG Strategy in 2018 marked a critical turning point, establishing quantitative emissions reduction targets and signalling a transition toward a low-carbon maritime system (IMO, 2020). Subsequent policy developments have further strengthened this trajectory, culminating in the commitment to achieve net-zero emissions around mid-century (IMO, 2023).

From an institutional standpoint, these developments reflect the progressive formalisation of decarbonisation as a binding industry norm. The incorporation of lifecycle-based emissions assessment, particularly through the well-to-wake approach, expands the scope of regulatory accountability beyond onboard emissions to include upstream fuel production and distribution processes. This shift fundamentally alters the relative attractiveness of alternative fuels, as compliance is increasingly evaluated on a holistic emissions basis rather than solely at the point of use.

5.1. *From Design Standards to Operational Performance: MARPOL Annex VI*

The evolution of MARPOL Annex VI illustrates a broader transition from prescriptive regulation toward performance-based governance. Early measures, such as the Energy Efficiency Design Index (EEDI), focused primarily on technical specifications for new vessels, effectively embedding energy efficiency into ship design. However, more recent instruments, including the Ship Energy Efficiency Management Plan (SEEMP) and the Data Collection System (DCS), extend regulatory oversight to operational performance and emissions monitoring.

This shift has important strategic implications. By linking compliance to actual fuel consumption and emissions data, regulators effectively integrate environmental performance into daily operational decision-making. Consequently, shipowners must adopt continuous optimisation practices such as speed management, route

planning, and digital monitoring to maintain regulatory compliance. In institutional terms, this represents a move toward outcome-based regulation, where performance metrics rather than design characteristics determine compliance status (IMO, 2023).

5.2. *EEXI and CII: Embedding Decarbonisation in Operational Strategy*

The introduction of the Energy Efficiency Existing Ship Index (EEXI) and the Carbon Intensity Indicator (CII) further reinforces the integration of regulatory requirements into both technical and operational dimensions of shipping. EEXI establishes minimum efficiency thresholds for existing vessels, often necessitating technical interventions such as engine power limitation or retrofitting energy-saving devices.

In contrast, CII directly evaluates operational performance by measuring emissions intensity relative to transport work and assigning annual ratings. This mechanism introduces a dynamic compliance regime in which shipowners must continuously manage vessel performance to avoid regulatory penalties or commercial disadvantages. From a theoretical perspective, CII transforms emissions performance into a competitive variable, aligning regulatory compliance with market positioning (IMO, 2023).

5.3. *European Union Policies and the Economic Internalization of Emissions*

While IMO regulations establish a global baseline, the European Union has adopted a more stringent approach that accelerates decarbonisation through market-based instruments. The inclusion of maritime transport in the EU Emissions Trading System (EU ETS) represents a significant shift toward the economic internalization of carbon emissions (European Commission, 2023). By assigning a monetary cost to emissions, the EU ETS directly affects operational expenditure and alters the relative competitiveness of alternative fuels.

In parallel, the FuelEU Maritime regulation imposes progressively stricter limits on the greenhouse gas intensity of marine fuels, effectively incentivizing the adoption of low- and zero-carbon energy sources. These measures are embedded within the broader “Fit for 55” policy framework, which aims to align the maritime sector with the European Union’s climate neutrality objectives (European Commission, 2021).

From an institutional perspective, EU policies intensify coercive pressures while simultaneously creating economic incentives for technological transition. For shipowners operating within European trade routes, compliance is no longer solely a regulatory obligation but also a financial consideration that directly influences investment and operational strategies.

5.4. *Multi-Level Regulatory Complexity and Strategic Implications*

The coexistence of global and regional regulatory regimes creates a multi-level institutional environment characterised by overlapping requirements and varying degrees of stringency. Shipowners must navigate this complexity by aligning their strategies with both IMO standards and more ambitious regional policies, particularly those of the European Union.

This multi-layered regulatory structure amplifies uncertainty while simultaneously reinforcing the direction of transition. On the one hand, differences in regulatory scope and timing complicate compliance planning and investment decisions. On the other hand, the convergence toward stricter emissions targets reduces the likelihood of regulatory reversal, thereby strengthening the long-term rationale for decarbonisation investments.

Within this context, regulatory frameworks act not only as constraints but also as signals that shape expectations regarding future technological and market developments. Shipowners interpret these signals when making strategic decisions, often favouring flexible investment approaches that allow adaptation to evolving regulatory conditions. This behaviour aligns with the real options perspective, in which uncertainty and irreversibility encourage staged and adaptable investment strategies.

Overall, the regulatory environment functions as a primary institutional driver of maritime decarbonisation, influencing both the direction and the pace of technological adoption. Understanding this role is essential for analysing how techno-economic pathways are formed and how strategic responses emerge within the shipping industry.

6. Techno-economic Evaluation of Clean Propulsion Pathways

The decarbonisation of maritime transport is fundamentally a techno-economic challenge shaped by the interaction between technological feasibility, economic viability, and regulatory alignment. Rather than converging toward a single dominant solution, the sector is characterised by a diversity of competing fuel pathways, each associated with distinct advantages, limitations, and uncertainty profiles. **Figure 1** presents a comparative overview of the emissions reduction potential across the main alternative fuel pathways (Bouman *et al.*, 2017; Gilbert *et al.*, 2018; IRENA, 2021).

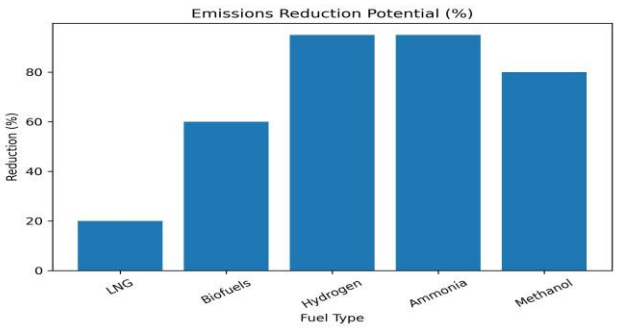


Figure 1. Emissions reduction potential across major alternative maritime fuels. Source: Adapted from Bouman *et al.* (2017); Gilbert *et al.* (2018); IRENA (2021).

Within this context, shipowners are required to evaluate alternative propulsion options not only in terms of emissions reduction potential but also with respect to cost

structures, infrastructure availability, and long-term strategic flexibility.

From a techno-economic perspective, the selection of marine fuels can be understood as a multi-criteria decision problem, in which lifecycle emissions performance, capital expenditure (CAPEX), operational expenditure (OPEX), and technological maturity jointly determine feasibility (Gilbert *et al.*, 2018; Bicer and Dincer, 2021). Importantly, these criteria are dynamically influenced by evolving regulatory frameworks and market conditions, reinforcing the need for adaptive and flexible investment strategies (Bouman *et al.*, 2017; Psaraftis, 2019).

6.1. *Transitional Fuels and Incremental Decarbonisation*

Liquefied natural gas (LNG) and advanced biofuels are widely recognised as transitional solutions that enable incremental emissions reductions while relying on relatively mature technologies. LNG offers significant reductions in sulphur oxides and nitrogen oxides, alongside moderate carbon dioxide emissions benefits. However, its lifecycle performance is increasingly scrutinised due to methane slip, which reduces its overall climate advantage under well-to-wake accounting frameworks (Bouman *et al.*, 2017).

Biofuels provide an alternative pathway with the advantage of compatibility with existing engine technologies, allowing for rapid deployment without major capital investment. Nevertheless, their long-term scalability remains uncertain due to constraints related to feedstock availability, sustainability certification, and cost volatility. From a techno-economic standpoint, both LNG and biofuels are primarily aligned with short- to medium-term compliance strategies rather than long-term decarbonisation objectives.

6.2. *Zero-Carbon Fuels and Long-Term Transition Pathways*

Hydrogen, ammonia, and renewable methanol represent key candidates for achieving deep decarbonisation in the maritime sector. These fuels offer significantly lower lifecycle emissions, particularly when produced from renewable energy sources. However, their adoption is constrained by substantial technological, economic, and infrastructural barriers (IRENA, 2021; IEA, 2023).

Hydrogen-based propulsion systems, particularly when combined with fuel cells, provide zero-emission operation at the point of use (Bicer and Dincer, 2021; IEA, 2020). Yet, challenges related to storage, low energy density, and high production costs limit their applicability, especially for long-distance shipping. Ammonia, by contrast, offers higher energy density and benefits from existing global production and distribution networks, making it a promising option for deep-sea transport. However, safety concerns and the need for advanced engine technologies introduce additional complexity.

Methanol has emerged as a pragmatic intermediate solution, combining relatively low storage complexity with increasing availability of renewable production pathways. Its growing adoption in the container shipping segment reflects a balance between technological feasibility and emissions reduction potential, although its lower energy density implies higher fuel consumption (IRENA, 2022).

6.3. *Electrification and Hybrid Solutions*

Electrification represents the most energy-efficient decarbonisation pathway for short-sea shipping and inland waterways. Battery-electric systems offer zero operational emissions and reduced maintenance requirements, making them particularly suitable for ferries and coastal vessels operating over short distances. Hybrid propulsion systems, combining batteries with conventional or alternative fuels, further enhance operational flexibility and emissions performance.

Despite these advantages, current battery technology limitations restrict large-scale application in deep-sea shipping. As a result, electrification is best understood as a segment-specific solution rather than a universal pathway.

6.4. *Carbon Capture as a Complementary Strategy*

Onboard carbon capture and storage (CCS) technologies provide a potential retrofit solution for reducing emissions from existing vessels. By capturing carbon dioxide prior to atmospheric release, CCS can extend the operational viability of conventional fuels under increasingly stringent regulatory constraints. However, energy penalties, space requirements, and unresolved logistical challenges related to CO_2 storage and offloading limit its widespread adoption. Consequently, CCS is generally considered a complementary rather than primary decarbonisation pathway.

6.5. *Comparative Techno-economic Assessment*

The diversity of fuel options highlights the absence of a universally optimal solution. Instead, each pathway involves trade-offs between emissions performance, cost, technological maturity, and infrastructure readiness.

The analysis indicates that transitional fuels offer lower investment risk and immediate compliance benefits but are unlikely to achieve long-term decarbonisation targets. In contrast, zero-carbon fuels provide stronger alignment with future regulatory trajectories but involve higher uncertainty and capital intensity. This trade-off reinforces the relevance of flexible investment strategies, as shipowners seek to balance short-term operational requirements with long-term strategic positioning (DNV, 2023).

6.6. *Strategic Implications Under Uncertainty*

From a real options perspective, the coexistence of multiple fuel pathways and uncertain technological trajectories increases the value of flexibility in investment decisions. Shipowners increasingly adopt strategies that preserve optionality, such as investing in dual-fuel engines or fuel-ready vessel designs. These approaches enable incremental adaptation as regulatory frameworks evolve and technological solutions mature.

The techno-economic evaluation of propulsion pathways therefore extends beyond static cost comparisons to encompass dynamic decision-making under uncertainty. The optimal strategy is not necessarily the immediate adoption of the lowest-emission technology, but rather the selection of pathways that maintain adaptability while ensuring regulatory compliance and economic viability.

Overall, the transition toward low- and zero-carbon shipping is best understood as a portfolio problem, in which multiple technologies coexist and evolve over time. This perspective underscores the importance of integrating techno-economic analysis with strategic considerations in order to fully capture the complexity of maritime decarbonisation. **Table 1** summarises Techno-economic comparison of alternative maritime decarbonisation pathways (DNV, 2023; IRENA, 2022; IEA, 2020; Bicer and Dincer, 2021).

Table 1. Techno-economic characteristics of alternative maritime decarbonisation pathways.

Fuel / Technology	Emissions	CAPEX	OPEX	Maturity	Infrastructure	Key Uncertainty
LNG	Medium (15–25% GHG reduction)	Medium	Medium	High	High	Methane slip
Biofuels	Medium-High	Low	High	Medium	Medium	Feedstock
Hydrogen	Very High	Very High	Very High	Low	Low	Storage & cost
Ammonia	Very High	High	High	Medium	Medium	Safety
Methanol	High	Medium	Medium-High	Medium-High	Medium	Availability
Electrification	Zero	High	Low	High	Medium	Range
CCS	Medium-High	High	High	Low-Medium	Low	Storage

Note: The qualitative ratings (Low, Medium, High, Very High) represent relative comparative assessments derived from the literature rather than fixed quantitative thresholds. CAPEX refers to the relative investment required for vessel construction or retrofit, OPEX reflects expected operational costs, technological maturity indicates commercial readiness, while infrastructure readiness reflects the current availability of bunkering and supply networks (DNV, 2023; IEA, 2020; IRENA, 2022).

Source: Compiled and adapted from DNV (2023); IRENA (2022); IEA (2020); Bicer and Dincer (2021).

6.7. *Comparative synthesis of the pathways*

The comparison in **Table 1** highlights a clear strategic trade-off pathways with higher technological maturity and infrastructure readiness generally offer lower implementation risk, but they do not necessarily provide the strongest long-term emissions reduction. LNG, for example, combines relatively high maturity and infrastructure readiness with only moderate lifecycle emissions benefits and continued exposure to methane-slip risk. Biofuels can reduce retrofit requirements and therefore lower initial investment barriers, yet their scalability and feedstock sustainability remain important constraints. By contrast, hydrogen and ammonia offer very high emissions-reduction potential but currently involve higher CAPEX, lower infrastructure readiness, and greater technological or operational uncertainty. Renewable methanol occupies an intermediate position, combining comparatively manageable handling requirements with a growing supply base, although its lower energy density and fuel availability remain relevant considerations. Electrification is particularly attractive where vessel range and charging infrastructure permit its use, while onboard CCS is better interpreted as a complementary retrofit option. Overall, the comparison indicates that fuel selection should be treated as a multi-criteria decision in which emissions performance, investment requirements, infrastructure readiness, technological maturity, and strategic flexibility are evaluated jointly rather than optimised independently. This supports the portfolio-based and staged investment logic developed in the present study.

7. Economic and Operational Implications: A Strategic Perspective

The transition toward low- and zero-carbon shipping entails profound economic and operational implications that extend beyond technological adoption. From a techno-economic and strategic perspective, decarbonisation affects capital allocation, cost structures, market positioning, and access to finance. These dimensions are closely interrelated and collectively shape the decision-making environment in which shipowners operate (Dixit & Pindyck, 1994; Trigeorgis, 1996).

7.1. *Capital Investment and Fleet Strategy Under Uncertainty*

Decarbonisation requires substantial capital investment, particularly in newbuilding vessels incorporating alternative fuel technologies or fuel-ready designs. Compared to conventional vessels, these investments involve significant cost premiums, reflecting both technological complexity and uncertainty regarding future fuel pathways.

From a strategic standpoint, shipowners face a trade-off between early adoption of emerging technologies and the risk of technological obsolescence (Psaraftis, 2019). **Figure 2** provides a comparative representation of CAPEX and OPEX trade-offs across alternative fuel pathways (DNV, 2023; IEA, 2020; Balcombe *et al.*, 2019).

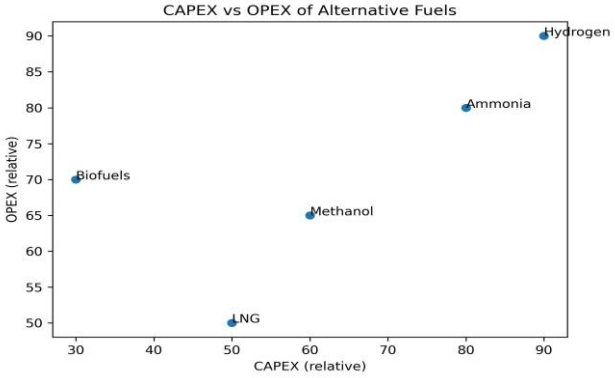


Figure 2. CAPEX and OPEX profiles of alternative maritime fuel options. Source: Adapted from DNV (2023); IEA (2020); Balcombe *et al.* (2019).

In this context, investment decisions increasingly reflect real options logic, whereby flexibility and reversibility are prioritised over immediate optimisation. Fuel-ready and dual-fuel vessels exemplify this approach, enabling shipowners to defer definitive fuel choices while maintaining compliance with existing regulations (Dixit & Pindyck, 1994, Trigeorgis, 1996).

Fleet renewal strategies are therefore shaped not only by cost considerations but also by expectations regarding regulatory developments and technological evolution. This forward-looking orientation reinforces the importance of adaptability in capital allocation decisions.

7.2. *Operational Costs and Carbon Pricing Mechanisms*

Operational expenditure (OPEX) is significantly affected by decarbonisation policies, particularly through the introduction of market-based instruments such as carbon pricing (EMSA and EEA, 2021). The inclusion of maritime transport in emissions trading systems, most notably within the European Union, effectively internalises the cost of carbon emissions, transforming environmental performance into a direct economic variable (European Commission, 2023, Faber *et al.*, 2021).

This shift alters the relative competitiveness of fuels and operational practices. Energy-efficient vessels and low-emission fuels gain a cost advantage, while carbon-intensive operations become progressively less viable. As a result, shipowners increasingly adopt operational optimisation measures including speed reduction, route optimisation, and digital performance monitoring to minimise fuel consumption and emissions exposure.

Operational decision-making is thus directly linked to both regulatory compliance and cost efficiency, reinforcing the integration of environmental considerations into day-to-day vessel management.

7.3. *Market Dynamics and Competitive Positioning*

Decarbonisation is also reshaping competitive dynamics within shipping markets. Charterers and cargo owners are increasingly incorporating environmental performance criteria into vessel selection processes, particularly in long-term charter agreements. Transparency in emissions reporting and compliance with carbon intensity standards are becoming critical determinants of commercial attractiveness.

Vessels with superior environmental performance are more likely to secure favourable charter rates and long-term contracts, while those with poor emissions profiles risk reduced utilisation or market exclusion. This dynamic effectively transforms decarbonisation from a regulatory obligation into a source of competitive differentiation.

From a strategic perspective, environmental performance becomes an intangible asset that enhances market positioning, particularly in segments where sustainability considerations are prioritised.

7.4. *Financing Constraints and ESG Integration*

Access to finance plays a pivotal role in enabling the transition toward low-carbon shipping. Financial institutions are increasingly aligning their lending practices with environmental, social, and governance (ESG) criteria, as reflected in initiatives such as sustainability-linked loans and climate-aligned shipping portfolios.

Recent evidence also suggests that ESG disclosure and governance capabilities can strengthen corporate sustainability and improve the credibility of environmental commitments, while environmentally oriented leadership may increase investment in green technologies and environmental governance (Duan *et al.*, 2025; Lei *et al.*, 2026). For shipping firms, this implies that decarbonisation strategy should be integrated with governance and disclosure systems rather than treated solely as a fleet-technology decision.

Frameworks such as the Poseidon Principles link financing conditions to emissions performance, creating direct incentives for shipowners to invest in low-carbon technologies (Poseidon Principles, 2022). Companies with credible decarbonisation strategies benefit from improved access to capital and more favourable financing terms, while those with carbon-intensive fleets may face higher borrowing costs or restricted access to funding. Recent research also indicates that stronger ESG disclosure practices are positively associated with corporate sustainability and may improve firms' credibility among investors and financial institutions. These findings further support the argument that transparent environmental governance is becoming an increasingly important determinant of financing conditions and long-term strategic resilience (Duan *et al.*, 2025).

This financial dimension reinforces the alignment between regulatory compliance, environmental performance, and economic viability, further embedding decarbonisation within strategic decision-making processes.

7.5. *Operational Complexity and Human Capital*

The adoption of alternative fuels and advanced technologies introduces additional operational complexity, particularly in relation to safety, maintenance, and crew training. Fuels such as ammonia and hydrogen require specialised handling procedures and enhanced safety protocols, while digital monitoring systems demand new technical competencies.

Consequently, human capital emerges as a critical enabler of successful decarbonisation. Investments in crew training and organisational capabilities are necessary to support the effective implementation of new technologies and operational practices. Failure to address these requirements may limit the practical feasibility of otherwise viable technological solutions.

7.6. *Strategic Trade-offs and Decision-Making Framework*

The economic and operational implications of decarbonisation ultimately converge in a set of strategic trade-offs. Shipowners must balance short-term cost increases against long-term regulatory compliance, technological uncertainty against competitive positioning, and capital investment against financial constraints.

These trade-offs can be conceptualised within an integrated decision-making framework in which regulatory

drivers, techno-economic factors, and market conditions interact to shape strategic outcomes. Under conditions of uncertainty, flexibility emerges as a central strategic principle, enabling shipowners to adapt to evolving regulatory and technological landscapes.

In this context, decarbonisation strategies are best understood not as fixed pathways but as dynamic processes involving continuous reassessment and adjustment. The ability to manage this complexity effectively constitutes a key determinant of long-term competitiveness in the maritime sector.

8. The Greek Shipping Industry as an Empirical Application of Decarbonisation Strategies

The Greek shipping industry provides a particularly relevant empirical context for examining maritime decarbonisation, due to its dominant position in global shipping and its extensive exposure to diverse regulatory regimes. Operating across multiple market segments and geographical regions, Greek shipowners are required to simultaneously respond to global regulatory frameworks and more stringent regional policies, while maintaining competitiveness in highly volatile markets (Smith *et al.*, 2021).

Within the theoretical and techno-economic framework developed in this study, the Greek shipping sector can be interpreted as an illustrative case of strategic adaptation under conditions of regulatory pressure and technological uncertainty. Rather than representing an exceptional case, the behaviour of Greek shipowners reflects broader industry dynamics, offering insights that are generalisable to the global shipping system.

8.1. *Fleet Strategy and Investment Behaviour*

A defining characteristic of Greek shipping is its strong orientation toward fleet renewal and asset flexibility. Investment decisions increasingly incorporate environmental performance considerations alongside traditional commercial criteria. However, rather than committing to a single decarbonisation pathway, Greek shipowners tend to adopt flexible investment strategies, such as fuel-ready and dual-fuel vessel designs.

This approach is consistent with real options logic, as it allows firms to preserve strategic flexibility while deferring irreversible investment decisions under uncertainty. By maintaining the option to transition between fuels as technologies mature and regulatory conditions evolve, shipowners effectively hedge against the risk of technological lock-in.

The following propositions are derived from the integrated theoretical and techno-economic framework developed in this study and are supported by evidence from existing maritime decarbonisation literature, industry practices, and observed strategic responses within the Greek shipping sector. Rather than representing empirically tested hypotheses, the propositions function as analytical statements that synthesise recurring patterns identified across regulatory developments, investment behaviour, operational adaptation, and fuel transition strategies in the shipping industry.

Proposition 1: Existing literature and observed industry practices suggest that shipowners operating under high technological and regulatory uncertainty tend to prioritise flexible investment strategies over early commitment to specific fuel pathways.

Theoretical foundation. This proposition is derived from **Real Options Theory**, which argues that under conditions of irreversible investment and high uncertainty, preserving managerial flexibility generates option value and reduces the risk of technological lock-in (Dixit & Pindyck, 1994; Trigeorgis, 1996).

8.2. *Adoption of Technologies and Operational Practices*

The adoption of clean propulsion technologies within the Greek fleet reflects a pragmatic and incremental approach to decarbonisation. While there is significant investment in LNG-fuelled and dual-fuel vessels, particularly in segments where regulatory compliance is critical, there is no uniform shift toward a single alternative fuel.

At the same time, operational measures such as speed optimisation, digital performance monitoring, and fuel efficiency improvements play a central role in achieving emissions reductions. These practices demonstrate that decarbonisation is not solely technology-driven but is embedded in day-to-day operational decision-making.

Proposition 2: Current industry evidence indicates that, in the absence of a dominant technological solution, operational optimisation emerges as a primary mechanism for achieving short-term emissions reductions.

Theoretical foundation. This proposition also draws upon **Real Options Theory**, extending its logic from capital investment to operational decision-making. When long-term technological trajectories remain uncertain, operational optimisation measures—including speed management, voyage optimisation, and digital performance monitoring—allow shipowners to achieve immediate emissions reductions while preserving flexibility regarding future technological investments (Dixit & Pindyck, 1994; Trigeorgis, 1996).

8.3. *Market Positioning and Competitive Strategy*

Greek shipping companies operate in highly competitive international markets, where commercial success depends on cost efficiency, reliability, and increasingly, environmental performance. As charterers and cargo owners place greater emphasis on emissions transparency and sustainability, environmental performance becomes an important determinant of market positioning.

Greek shipowners respond to these pressures by integrating decarbonisation into their competitive strategies, seeking to balance compliance with profitability. This involves not only technological investment but also strategic engagement with charterers and financial institutions.

Proposition 3: Regulatory developments and market trends increasingly position environmental performance as

a source of competitive differentiation in global shipping markets.Financing and Institutional Alignment

Access to finance is closely linked to environmental performance, particularly as financial institutions align lending practices with ESG criteria. Greek shipping companies that demonstrate credible decarbonisation strategies are better positioned to secure sustainability-linked financing and favourable lending terms.

At the same time, the need to comply with both IMO and EU regulatory frameworks creates a complex institutional environment that reinforces the importance of forward-looking strategic planning. Shipowners must anticipate regulatory developments and align investment decisions accordingly.

Theoretical foundation. This proposition is primarily supported by **Institutional Theory**, particularly the concept of **normative institutional pressures**. As environmental performance increasingly influences the expectations of charterers, cargo owners, financial institutions, and other stakeholders, shipping companies strengthen their competitive position by adopting decarbonisation strategies that enhance organisational legitimacy and market reputation (DiMaggio & Powell, 1983).

Proposition 4: Alignment with institutional and financial frameworks appears to enhance access to capital and support the implementation of decarbonisation strategies.Infrastructure Constraints and Systemic Challenges

Despite proactive strategies at the firm level, the transition toward low- and zero-carbon shipping is constrained by broader systemic factors, particularly infrastructure availability. The limited development of alternative fuel bunkering and port infrastructure in certain regions, including parts of the Mediterranean, restricts the feasibility of large-scale adoption of emerging fuels.

This highlights the interdependence between private investment decisions and public infrastructure development, underscoring the need for coordinated action among stakeholders.

Theoretical foundation. This proposition is derived from **Institutional Theory**, emphasising the combined influence of **coercive** and **normative pressures**. Regulatory requirements imposed by the IMO and the European Union, together with ESG-oriented financing initiatives such as the Poseidon Principles, create institutional incentives that encourage firms to align their investment decisions with sustainability objectives in order to secure long-term access to capital and maintain regulatory legitimacy (DiMaggio & Powell, 1983; Poseidon Principles, 2022).

Proposition 5: The pace and effectiveness of maritime decarbonisation are strongly influenced by the alignment between firm-level strategies and infrastructure development at the system level.

Theoretical foundation. This proposition integrates **Institutional Theory** and **Real Options Theory**. While institutional theory explains how external regulatory frameworks and infrastructure development shape the broader transition environment, real options theory highlights the importance of maintaining strategic flexibility when critical infrastructure remains uncertain or unevenly developed. Consequently, successful maritime decarbonisation depends on the dynamic alignment between firm-level investment decisions and the evolution of supporting energy and port infrastructure (DiMaggio & Powell, 1983; Dixit & Pindyck, 1994).

8.4. *Synthesis: Strategic Adaptation in Practice*

Overall, the Greek shipping industry illustrates how shipowners navigate the complex interplay between regulatory pressure, techno-economic constraints, and market dynamics. The observed strategies characterised by flexibility, incremental adoption, and operational optimisation are consistent with the integrated theoretical framework developed in this study.

Rather than pursuing a single optimal pathway, Greek shipowners adopt a portfolio-based approach that balances short-term compliance with long-term adaptability. This behaviour reinforces the argument that maritime decarbonisation is best understood as a dynamic and iterative process shaped by uncertainty and strategic choice.

The insights derived from the Greek case support the broader applicability of the proposed techno-economic framework and provide a foundation for understanding decarbonisation strategies across the global shipping industry (DNV, 2023).

9. Discussion: Towards an Integrated Techno-economic Understanding of Maritime Decarbonisation

The analysis presented in this study highlights that maritime decarbonisation cannot be adequately understood through isolated examination of regulatory, technological, or economic dimensions. Instead, the transition toward low- and zero-carbon shipping emerges as a systemic process shaped by the interaction of institutional pressures, techno-economic constraints, and strategic responses.

By integrating insights from institutional theory and real options theory, this paper advances a more comprehensive interpretation of decarbonisation pathways. Regulatory frameworks particularly those developed by the International Maritime Organization and the European Union function as primary drivers that define both the direction and urgency of change. At the same time, technological uncertainty and the absence of a dominant fuel pathway create a decision-making environment in which flexibility becomes a critical strategic asset.

The techno-economic evaluation of alternative fuels demonstrates that no single solution currently satisfies all criteria related to emissions reduction, cost efficiency, technological maturity, and infrastructure readiness (Balcombe *et al.*, 2019; IRENA, 2021). This fragmentation reinforces the importance of portfolio-based strategies, in which multiple technologies coexist and evolve over time. Within such a landscape, shipowners are not selecting a

single optimal pathway but are instead managing a set of strategic options under uncertainty (IEA, 2020; Smith *et al.*, 2021).

The empirical insights derived from the Greek shipping industry further support this interpretation. The observed emphasis on fuel flexibility, incremental adoption, and operational optimisation reflects a broader industry pattern consistent with real options logic. Shipowners respond to regulatory and market pressures not by committing to irreversible investments, but by preserving adaptability in the face of evolving conditions.

From a theoretical perspective, the findings suggest that maritime decarbonisation should be conceptualised as a dynamic and iterative process rather than a linear transition. Institutional pressures create convergence toward emissions reduction, but the pathways through which this convergence occurs remain heterogeneous and path-dependent. This highlights the importance of considering both structural drivers and firm-level strategies in understanding transition dynamics.

Recent studies further strengthen this interpretation by showing that governance quality, digital transformation and information-based market mechanisms can shape environmental performance and green investment. De Sisto *et al.* (2025) highlight the role of digital adaptation and governance in supporting environmental sustainability, while Jin *et al.* (2026) provide empirical evidence that ICT investment can improve carbon-emission efficiency in regional port systems. Complementing these findings, Lei *et al.* (2026) show that information networks can support green innovation through improved transparency, resource allocation and financing access, while Lei *et al.* (2026) also demonstrate that environmentally oriented executive backgrounds can strengthen corporate ESG performance through greater green-technology and environmental-governance investment. Taken together, these studies support the argument that maritime decarbonisation depends not only on fuel technologies and regulation, but also on organisational governance, digital capabilities, information quality and strategic leadership. These dimensions can therefore be incorporated into future empirical applications of the integrated framework proposed in this study (De Sisto *et al.*, 2025; Jin *et al.*, 2026; Lei *et al.*, 2026).

Overall, this study contributes to the literature by offering a structured and integrative perspective that bridges the gap between descriptive reviews and theory-driven analysis. It demonstrates that meaningful decarbonisation outcomes depend not only on technological innovation but also on the alignment of regulatory frameworks, economic incentives, and strategic decision-making processes.

10. Integrated Decision-Making Framework for Maritime Decarbonisation

The preceding analysis demonstrates that strategic fuel selection in maritime decarbonisation cannot be based solely on technological performance or regulatory compliance. Instead, investment decisions emerge from the interaction of multiple dimensions, including regulatory developments, technological maturity, economic feasibility, infrastructure availability and institutional pressures. Building upon the theoretical foundations presented in Section 2 and the strategic propositions developed in the previous section, this study proposes an integrated decision-making framework that synthesises these interacting dimensions into a coherent analytical model.

The framework recognises that regulatory uncertainty constitutes the primary external driver influencing investment decisions. International and regional regulations, together with market-based mechanisms and ESG-oriented financing initiatives, create institutional pressures that encourage shipowners to accelerate decarbonisation while simultaneously increasing uncertainty regarding the long-term viability of alternative fuel pathways.

At the firm level, these external pressures are evaluated through a techno-economic assessment that considers capital expenditure (CAPEX), operational expenditure (OPEX), greenhouse gas reduction potential, technological maturity and the availability of bunkering infrastructure. Rather than seeking an immediate optimal technological solution, shipowners are required to balance environmental performance with financial viability and operational flexibility.

From a strategic perspective, Real Options Theory suggests that maintaining investment flexibility represents a rational response under conditions of technological and regulatory uncertainty. Consequently, investment strategies such as dual-fuel vessels, fuel-ready designs and phased implementation reduce the risk of technological lock-in while preserving future adaptation opportunities as regulations, fuel markets and infrastructure evolve.

Ultimately, the proposed framework illustrates that competitive advantage in maritime decarbonisation depends on the successful alignment of institutional requirements, techno-economic performance and strategic flexibility. Instead of viewing regulatory compliance as an isolated objective, the framework conceptualises decarbonisation as a dynamic strategic decision-making process in which firms continuously adapt their investment choices to changing market conditions, policy developments and technological innovation. This integrated perspective represents the principal theoretical contribution of the present study and provides a foundation for future empirical validation across different shipping segments and geographical contexts.

The relationships among the principal factors influencing strategic fuel selection are synthesised in the conceptual framework presented in **Figure 3**. The framework integrates the theoretical perspectives of Institutional Theory and Real Options Theory into a unified decision-making model for maritime decarbonisation (DiMaggio & Powell, 1983; Dixit & Pindyck, 1994; Trigeorgis, 1996).

10.1. *Illustrative Application of the Proposed Framework*

To demonstrate the practical applicability of the proposed decision-making framework, it can be considered in the

context of the ongoing transition of the Greek shipping industry. Greek shipowners currently operate under increasing regulatory pressure arising from the IMO GHG Strategy, the inclusion of maritime transport in the EU Emissions Trading System (EU ETS), and the implementation of FuelEU Maritime. At the same time, significant uncertainty remains regarding the long-term availability, infrastructure development, and commercial maturity of alternative fuels such as green methanol, ammonia and hydrogen.

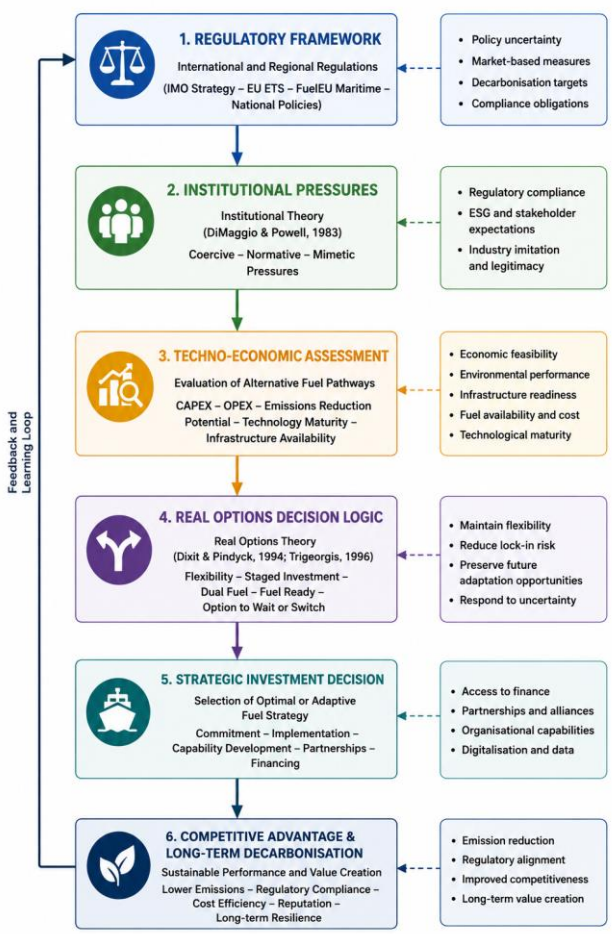


Figure 3. Integrated decision-making framework for strategic fuel selection under regulatory uncertainty (developed by the authors).

The framework can also be applied as a scenario-based decision process. For a shipowner whose vessels regularly call at EU ports, the first screening step would assess exposure to EU ETS and FuelEU Maritime requirements, followed by a comparison of candidate fuels against lifecycle emissions, CAPEX, OPEX, fuel availability and vessel compatibility. Where regulatory pressure is high but fuel-supply infrastructure is still uncertain, a dual-fuel or fuel-ready investment may preserve option value while meeting near-term requirements. Conversely, where reliable green-methanol or ammonia bunkering is available and the regulatory trajectory strongly favours low-carbon fuels, a more direct investment may become economically and strategically preferable. For policymakers, the same framework can be used in reverse: by identifying the infrastructure, financing and regulatory conditions that prevent otherwise attractive fuels from becoming feasible, authorities can target port bunkering investment, transitional incentives and regulatory coordination. The framework therefore functions not as a fixed fuel-ranking tool, but as a structured sequence of screening, comparison, risk assessment and staged commitment under alternative market and regulatory scenarios.

Under these conditions, the framework suggests that investment decisions should not be driven exclusively by environmental performance, but rather by a balanced assessment of regulatory requirements, technological maturity, infrastructure readiness, and financial feasibility. Consequently, transitional solutions such as LNG dual-fuel vessels and fuel-ready ship designs may represent rational intermediate strategies that preserve flexibility while reducing the risk of premature technological lock-in.

This illustrative application demonstrates how the integration of Institutional Theory and Real Options Theory provides a structured decision-making approach capable of supporting strategic investment decisions under conditions of uncertainty. Although the framework remains conceptual, it offers a practical analytical tool that may support shipowners, investors and policymakers in evaluating alternative decarbonisation pathways. Future research may further validate the proposed framework using empirical evidence from different shipping sectors and geographical regions.

The practical implications of the proposed framework are summarised in **Table 2**, which translates the theoretical insights of this study into a structured decision-support matrix for strategic fuel selection under conditions of technological and regulatory uncertainty.

11. Conclusions and Implications

The decarbonisation of maritime transport represents a complex and multidimensional challenge that extends beyond technological innovation to encompass regulatory, economic, and strategic considerations. This study has developed an integrated techno-economic perspective on maritime decarbonisation, highlighting the interplay between institutional drivers, fuel pathways, and shipowners' strategic responses.

The findings confirm that regulatory frameworks constitute the primary catalyst for change. The evolving policies of the International Maritime Organization and the European Union have transformed emissions reduction from a voluntary objective into a binding constraint that directly influences investment decisions, operational practices, and market dynamics. At the same time, the absence of a dominant low- or zero-carbon fuel creates significant uncertainty, complicating long-term planning and increasing the risk associated with irreversible investments.

From a techno-economic standpoint, the analysis demonstrates that alternative fuel pathways involve substantial trade-offs between emissions performance, cost, technological maturity, and infrastructure availability (Balcombe *et al.*, 2019; Bicer and Dincer, 2021). Transitional fuels such as liquefied natural gas and biofuels

offer short-term compliance benefits, while zero-carbon options including hydrogen, ammonia, and renewable methanol provide stronger alignment with long-term decarbonisation targets but remain constrained by economic and technical barriers.

Table 2. Decision Support Matrix for Strategic Fuel Selection under Regulatory Uncertainty.

Decision Criterion	Strategic Consideration	Implication for Fuel Selection
Regulatory Pressure	Compliance with IMO GHG Strategy, EU ETS and FuelEU Maritime	Encourages early adoption of low- and zero-carbon fuel pathways while increasing the need for regulatory adaptability.
Technological Maturity	Commercial readiness and operational reliability of alternative fuels	Mature technologies reduce operational risk, whereas emerging fuels require cautious and phased investment strategies.
Infrastructure Availability	Availability of bunkering facilities and fuel supply chains	Limited infrastructure favours flexible solutions such as dual-fuel or fuel-ready vessels until wider deployment is achieved
Emissions Performance	Lifecycle GHG reduction and exposure to well-to-wake emissions requirements	Higher lifecycle performance strengthens long-term regulatory alignment and reduces carbon-cost exposure.
Financial Feasibility	CAPEX, OPEX, fuel-price exposure and access to ESG-linked finance	High upfront costs favour phased investment, financing diversification and option-preserving designs.
Strategic Flexibility	Ability to switch fuels, retrofit, or defer irreversible commitments	Fuel-ready, dual-fuel and phased solutions preserve option value when technology or market conditions remain uncertain.
Market and ESG Alignment	Charterer expectations, environmental disclosure and financing requirements	Stronger ESG performance can support commercial positioning, stakeholder legitimacy and access to capital.

Note: *The proposed decision support matrix synthesises the theoretical arguments developed in this study by integrating Institutional Theory and Real Options Theory into a practical analytical tool for strategic investment decision-making. The matrix is conceptual in nature and is intended to support managerial evaluation rather than provide prescriptive investment recommendations.*

The study further shows that shipowners respond to these conditions through strategies that prioritise flexibility, incremental adoption, and operational optimisation. These strategies are consistent with real options logic, enabling firms to manage uncertainty while maintaining competitiveness. The case of the Greek shipping industry illustrates how such approaches are implemented in practice within a globally competitive and highly regulated environment (Bouman *et al.*, 2017; DNV, 2023).

11.1. *Theoretical Contributions*

This paper contributes to the literature by integrating institutional theory and real options theory into a unified framework for analysing maritime decarbonisation. By linking regulatory pressures with strategic decision-making under uncertainty, the study moves beyond descriptive analysis and provides a more systematic understanding of transition dynamics in the shipping sector.

11.2. *Policy Implications*

The findings have important implications for policymakers. Effective decarbonisation requires not only ambitious regulatory targets but also coherent and stable policy frameworks that reduce uncertainty and support long-term investment. In particular, the alignment of global and regional regulations, the development of alternative fuel infrastructure, and the design of market-based mechanisms such as carbon pricing are critical for accelerating the transition.

11.3. *Managerial Implications*

For shipowners and industry stakeholders, the results emphasise the importance of strategic flexibility and adaptive decision-making. Investments in fuel-ready technologies, digital optimisation, and emissions monitoring systems can enhance resilience in a rapidly evolving regulatory and technological environment. Moreover, engagement with financial institutions and alignment with ESG frameworks are increasingly essential for securing access to capital.

11.4. *Limitations and Future Research*

Despite its contributions, this study has several limitations that should be recognised when interpreting its findings. First, the analysis is conceptual and literature-based and therefore does not provide primary empirical validation of the proposed relationships or propositions. The Greek shipping industry is used as an illustrative empirical reference rather than as a statistically tested case study, and the framework should not be interpreted as evidence of causal relationships. Second, the qualitative techno-economic ratings in Table 1 synthesise evidence from the literature but do not substitute for vessel-level cost data, fuel-price scenarios, lifecycle assessment or quantitative optimisation. Third, regulatory conditions, fuel availability, infrastructure readiness and technology costs evolve rapidly, which means that the relative attractiveness of pathways may change over time and across geographical regions. Future research should therefore empirically validate the framework through comparative case studies of shipping companies, surveys of shipowners and

managers, and quantitative models such as multi-criteria decision analysis, real-options valuation, lifecycle assessment and scenario-based cost modelling. Such studies could test the proposed propositions across different shipping segments (e.g., container, tanker, bulk and short-sea shipping), vessel ages and geographical contexts, including regions with different regulatory exposure and levels of alternative-fuel infrastructure. Further work should also examine how digital transformation, ESG governance, financing conditions and market-information networks interact with regulatory and technological uncertainty in shaping investment decisions. This research agenda would provide stronger evidence regarding the external validity and managerial usefulness of the proposed framework.

Further investigation is also needed into the scalability of alternative fuels, the evolution of global fuel supply chains, and the interaction between policy instruments and market behaviour. Such research would provide valuable insights into the long-term feasibility and effectiveness of maritime decarbonisation strategies.

11.5. *Final Remarks*

In conclusion, maritime decarbonisation should be understood as a dynamic techno-economic transition shaped by regulatory pressure, technological uncertainty, and strategic adaptation. Achieving meaningful progress will require coordinated action among policymakers, industry stakeholders, and financial institutions, as well as continued innovation in both technology and governance. The framework developed in this study provides a foundation for understanding this transition and for supporting more informed decision-making in the pursuit of sustainable shipping.

The framework should consequently be viewed as a decision-support architecture rather than a prescriptive fuel-selection rule; its value lies in structuring the reassessment of strategic options as regulatory, market, technological and infrastructure conditions change.

Beyond synthesising the existing literature on maritime decarbonisation, this study contributes by developing an integrated conceptual framework and a decision-support matrix that combine Institutional Theory and Real Options Theory into a unified approach for strategic fuel selection under regulatory uncertainty. By linking regulatory pressures, techno-economic considerations, and strategic flexibility, the proposed framework provides a structured basis for managerial decision-making and offers a foundation for future empirical validation across different shipping sectors and geographical contexts.

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