ENHANCING THE SUSTAINABILITY OF THE SHIPPING INDUSTRY THROUGH THE REDUCTION OF GREENHOUSE GAS EMISSIONS: LITERATURE REVIEW

DOI: 10.26341/issn.2241-4010-2026-3a-5-L02193

Kouroukl is Antonios
Phd Candidate, University of Western Macedonia, Department of Management Science and Technology, Kozani, Greece
dmst00036@uowm.gr

Chatzitheodoridis Fotios
Professor,University of Western Macedonia, Department of Management Science and Technology, Kozani, Greece
fxtheodoridis@uowm.gr

Loizou Efstratios
Professor,University of Western Macedonia, Department of Management Science and Technology, Kozani, Greece
eloizou@uowm.gr

Spinthiropoulos Kostas
Professor,University of Western Macedonia, Department of Management Science and Technology, Kozani, Greece
kspinthiropoulos@uowm.gr

Michailidis Anastasios
Professor,Aristotelio University Thessaloniki, Department of Quality Assurance Unit, Thessaloniki, Greece
tassosm@agro.auth.gr

Abstract

The decarbonisation of maritime transport has emerged as a central challenge for global sustainability, driven by escalating climate commitments, regulatory pressure, and market expectations. Although shipping has traditionally been regarded as an energy-efficient transport mode, its growing contribution to greenhouse gas (GHG) emissions necessitates a fundamental transformation of propulsion technologies, operational practices, and investment strategies.

This paper presents a comprehensive literature review of regulatory developments, clean propulsion technologies, and economic implications associated with the reduction of GHG emissions in maritime transport, with particular emphasis on the Greek shipping industry. The analysis examines the evolving regulatory framework at both global and European levels, including key instruments introduced by the International Maritime Organization and the European Union, and evaluates their impact on shipowners' strategic decision-making.

Furthermore, the study reviews a broad range of technological decarbonisation pathways, encompassing transitional fuels such as liquefied natural gas and biofuels, as well as emerging zero-carbon options including hydrogen, ammonia, and renewable methanol. Economic and operational considerations—such as capital expenditure, operating costs, access to finance, and charter market dynamics—are analysed to assess their role in shaping technology adoption.

The Greek shipping industry is examined as a case study, highlighting a pragmatic, flexibility-oriented approach to decarbonisation based on fuel-ready vessels, operational *optimisation, and participation in research and innovation initiatives. The findings indicate that no single technological solution currently dominates, underscoring the need for a portfolio-based strategy supported by regulatory alignment, infrastructure development, and coordinated action among stakeholders. The paper concludes that Greek shipping is well positioned to contribute to global maritime decarbonisation while maintaining long-term competitiveness under conditions of technological and regulatory uncertainty.*

Keywords: *Maritime decarbonisation; Greenhouse gas emissions; Clean propulsion technologies; Regulatory framework; Greek shipping; Sustainability; Alternative marine fuels*

1. INTRODUCTION

Maritime transport constitutes the backbone of global trade, facilitating nearly 90% of international cargo movements. Despite its historical reputation as an energy-efficient transport mode, the sector's continued expansion and persistent reliance on fossil fuels have led to a growing contribution to global greenhouse gas (GHG) emissions. According to recent international assessments, maritime transport currently accounts for approximately 3% of global anthropogenic emissions, a figure projected to increase substantially by mid-century in the absence of effective mitigation measures.

In response to mounting climate concerns, the shipping industry is undergoing its most profound transformation since the transition from sail to steam. Regulatory pressure, technological innovation, and market-driven environmental expectations collectively shape a new operational paradigm focused on decarbonisation. The International Maritime Organization (IMO), alongside regional actors such as the European Union, has introduced increasingly stringent frameworks aimed at reducing carbon intensity and accelerating the adoption of cleaner propulsion technologies.

Within this evolving landscape, the Greek shipping industry occupies a pivotal position. As the world's leading commercial fleet owner, Greek shipowners exert significant influence over global investment trends, technology diffusion, and compliance strategies. Their decisions are driven not only by regulatory obligations but also by competitiveness, access to finance, and long-term risk management in an uncertain fuel transition environment.

This paper provides a structured literature review of regulatory developments, clean propulsion technologies, and economic implications related to the reduction of GHG emissions in shipping, with a particular focus on the Greek fleet. By synthesizing existing research, the study highlights the drivers and barriers of maritime decarbonisation and assesses the strategic role of Greek shipping in the global transition toward sustainability.

2. REGULATORY FRAMEWORK GOVERNING MARITIME DECARBONISATION

The international regulatory framework for maritime decarbonisation has evolved rapidly, transforming environmental compliance into a central determinant of strategic and investment decisions within the shipping industry. What was once a primarily voluntary or technical consideration has now become a binding operational and financial constraint, shaping vessel design, fuel selection, and day-to-day operations.

At the global level, the International Maritime Organization (IMO) provides the core regulatory architecture for greenhouse gas (GHG) mitigation, while regional actors—most notably the European Union—have adopted more ambitious and economically binding mechanisms. The interaction between these regulatory layers creates both compliance challenges and strategic opportunities for shipowners.

2.1 Evolution of the IMO's GHG Strategy

The IMO's environmental governance framework is anchored in MARPOL Annex VI, which regulates air pollution from ships. A major milestone was the adoption of the Initial IMO GHG Strategy in 2018, which established quantitative targets for reducing the carbon intensity of international shipping by at least 40% by 2030 and total GHG emissions by at least 50% by 2050, relative to 2008 levels.

Subsequent revisions of the strategy have increased ambition, with the IMO moving toward a commitment to net-zero emissions "around 2050." A key conceptual shift within the revised strategy is the adoption of lifecycle-based emissions assessment, commonly referred to as the well-to-wake approach. This transition significantly affects the perceived sustainability of alternative fuels, placing greater emphasis on upstream production pathways rather than solely on onboard emissions.

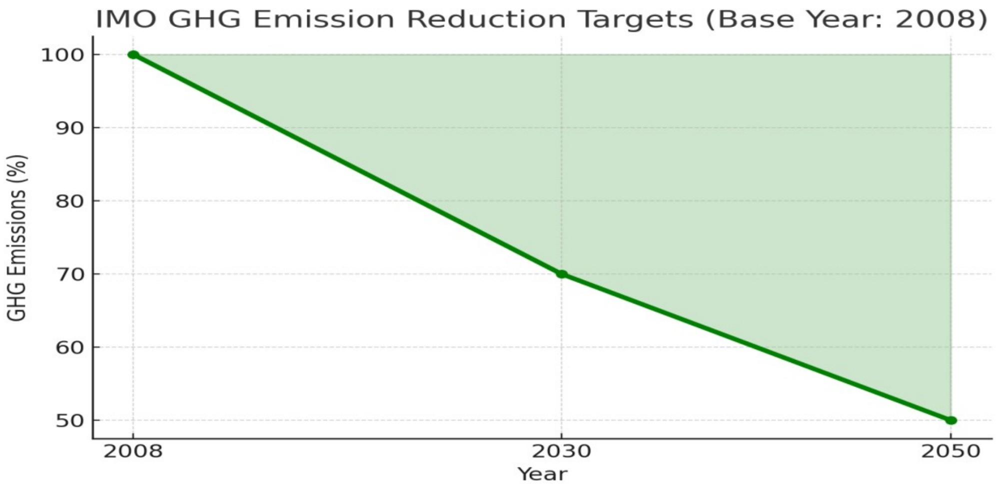

Figure 1: IMO greenhouse gas emission reduction targets relative to 2008 levels.
Source: IMO (2023).

2.2 MARPOL Annex VI: From Design to Operational Control

MARPOL Annex VI has progressively expanded beyond sulphur and nitrogen oxide control to encompass comprehensive energy efficiency and emissions monitoring mechanisms. Instruments such as the Energy Efficiency Design Index (EEDI) for newbuildings and the Ship Energy Efficiency Management Plan (SEEMP) have institutionalised energy efficiency as a regulatory requirement rather than a voluntary practice.

The introduction of the Fuel Oil Data Collection System (DCS) further enhanced transparency by mandating systematic reporting of fuel consumption and emissions. Collectively, these measures have laid the groundwork for performance benchmarking and data-driven regulatory enforcement, enabling a gradual shift from prescriptive design standards toward outcome-based regulation.

2.3 EEXI and CII: A Dual Compliance Regime

A significant regulatory development was the introduction of the Energy Efficiency Existing Ship Index (EEXI) and the Carbon Intensity Indicator (CII), which together form a dual compliance regime applicable to the existing fleet. EEXI establishes a minimum technical efficiency threshold, often requiring interventions such as engine power limitation or the installation of energy-saving devices.

In contrast, CII evaluates actual operational performance, categorising vessels annually from A to E based on emissions per cargo mile. This operational focus directly links regulatory compliance to voyage planning, speed management, and fuel consumption strategies. For shipowners, maintaining favourable CII ratings has become essential not only for compliance but also for commercial attractiveness and asset valuation.

2.4 European Union Climate Policies Affecting Shipping

While IMO regulations apply globally, the European Union has adopted a more stringent and economically binding approach to maritime decarbonisation. The inclusion of shipping in the EU Emissions Trading System (ETS) from 2024 introduces explicit carbon pricing, requiring shipowners to purchase emission allowances for voyages involving EU ports.

In parallel, the FuelEU Maritime regulation—effective from 2025—sets progressively tightening limits on the greenhouse gas intensity of marine fuels. These measures are embedded within the broader “Fit for 55” policy package, which aims to achieve climate neutrality across the European economy. For shipowners operating extensively within European trades, EU regulations significantly accelerate the economic rationale for cleaner propulsion technologies.

2.5 National and Regional Dimensions: The Greek Context

At the national and regional level, Greece has initiated measures to support maritime decarbonisation through port electrification projects, alternative fuel bunkering initiatives, and participation in EU-funded research programmes. Strategic ports such as Piraeus and Igoumenitsa are gradually enhancing infrastructure readiness for LNG, shore power, and future alternative fuels.

For Greek shipowners, the regulatory landscape is particularly complex due to simultaneous exposure to global IMO rules and advanced EU climate policies. Compliance therefore necessitates a forward-looking approach that integrates regulatory forecasting, technological flexibility, and long-term investment planning. The literature consistently identifies regulatory alignment as a key driver of green investment decisions within the Greek fleet.

3. CLEAN PROPULSION TECHNOLOGIES: CURRENT STATUS AND FUTURE OUTLOOK

The decarbonisation of maritime transport is fundamentally a technological challenge, yet one characterised by high uncertainty and fragmentation. Given the diversity of vessel types, operational profiles, and trade routes, no single propulsion technology or fuel can currently serve as a universal solution. Instead, the literature increasingly converges on a portfolio-based approach, combining transitional fuels, zero-carbon alternatives, and energy efficiency measures to achieve both short-term compliance and long-term climate neutrality *as summarized in table 1.*

Technology	Estimated Cost (Million $)	GHG Reduction (%)	Commercial Availability
Scrubbers	2.5	10	High
LNG Retrofit	10.0	20	Medium
Biofuel Switch	1.0	60	Medium
Electric Propulsion	12.0	80	Low
Hydrogen Fuel Cell	15.0	100	Low
Ammonia Engine	14.0	100	Experimental

Table 1: Cost, effectiveness and maturity of selected clean propulsion technologies.
Source: OECD/ITF (2022); DNV (2023).

Regulatory developments at both IMO and EU levels have accelerated technological experimentation, while market pressures from charterers and financial institutions further incentivise early adoption. However, technological maturity, infrastructure readiness, fuel availability, and lifecycle emissions performance remain decisive factors shaping investment decisions.

3.1 Liquefied Natural Gas (LNG) as a Transitional Solution

Liquefied Natural Gas (LNG) is widely recognised as a transitional marine fuel, offering substantial reductions in sulphur oxides (SO_x) and nitrogen oxides (NO_x), alongside moderate carbon dioxide (CO_2) reductions of approximately 15–20% compared to heavy fuel oil (HFO). These characteristics have positioned LNG as a compliance-driven solution, particularly in the context of MARPOL Annex VI and Emission Control Areas.

Greek shipowners have been among the early adopters of LNG, especially in LNG carriers, dual-fuel tankers, and ferries. The attractiveness of LNG lies not only in emissions reductions but also in its technological maturity and expanding global bunkering infrastructure. Nevertheless, the literature highlights growing concerns regarding methane slip—unburned methane released during combustion and fuel handling—which significantly undermines LNG's lifecycle greenhouse gas performance. As regulatory focus shifts toward well-to-wake emissions accounting, LNG's long-term compatibility with net-zero targets remains uncertain.

3.2 Biofuels: Drop-in Flexibility and Lifecycle Challenges

Advanced biofuels, particularly second- and third-generation variants derived from waste biomass or algae, offer a flexible decarbonisation pathway due to their compatibility with existing marine engines. This "drop-in" characteristic enables rapid deployment without significant capital expenditure, making biofuels especially attractive as a short- to medium-term solution.

Lifecycle assessments indicate that biofuels can achieve substantial GHG reductions when sustainably sourced. However, scalability, feedstock availability, cost volatility, and certification frameworks remain critical challenges. The literature emphasises that without robust sustainability criteria, biofuels risk indirect land-use change effects that may offset climate benefits. Despite these limitations, pilot applications in European short-sea shipping suggest that biofuels can play a complementary role in transitional decarbonisation strategies.

3.3 Hydrogen and Fuel Cell Technologies

Hydrogen propulsion represents one of the most promising zero-emission pathways, provided that hydrogen is produced from renewable energy sources (green hydrogen). When utilised in fuel cells, hydrogen produces no CO_2 emissions at the point of use, making it particularly attractive for climate-neutral shipping.

However, significant technical and economic barriers persist. Hydrogen's low volumetric energy density necessitates cryogenic or high-pressure storage systems, increasing space requirements and vessel design complexity. Fuel cell technologies, including proton exchange membrane fuel cells (PEMFC) and solid oxide fuel cells (SOFC), are advancing but remain costly and limited in scale. Consequently, current applications are largely confined to pilot projects involving ferries, inland vessels, and short-sea shipping, predominantly in Northern Europe.

3.4 Ammonia as a Long-Term Deep-Sea Fuel

Ammonia has emerged in the literature as a leading candidate for deep-sea, long-distance shipping decarbonisation. As a carbon-free fuel at the point of combustion, ammonia aligns closely with long-term IMO decarbonisation objectives. Additionally, its existing global production and transport infrastructure offer strategic advantages over hydrogen.

Despite these benefits, ammonia poses significant safety and environmental challenges. Its high toxicity necessitates stringent handling protocols, while combustion can generate nitrogen oxides (NO_x), requiring advanced after-treatment systems. Engine manufacturers are actively developing ammonia-capable engines, with commercial availability anticipated in the mid-2020s. For Greek shipowners, ammonia represents a long-term strategic option rather than an immediate solution, dependent on regulatory clarity and fuel supply chains.

3.5 Methanol: A Rapidly Emerging Alternative

Methanol has gained increasing attention as a pragmatic alternative fuel due to its relatively simple storage requirements, lower toxicity compared to ammonia, and compatibility with dual-fuel engines. Importantly, methanol can be produced from renewable sources, offering the potential for significant lifecycle GHG reductions.

The growing orderbook of methanol-fuelled vessels—particularly in the container segment—signals strong industry momentum. For shipowners, methanol offers a balance between technological feasibility and decarbonisation potential, although its lower energy density increases fuel consumption volumes. Infrastructure development remains uneven, but rapid investment by major ports suggests improving availability in the near term.

3.6 Electrification and Hybrid Propulsion Systems

Battery-electric propulsion systems represent the most energy-efficient decarbonisation solution for short-sea shipping and inland waterways. Zero operational emissions, high energy efficiency, and reduced maintenance requirements make electrification particularly attractive for ferries and coastal vessels.

Hybrid configurations combining batteries with conventional or alternative fuel engines further enhance operational flexibility. While battery technology limitations currently restrict application to short distances, advancements in energy density and charging infrastructure are gradually expanding feasibility. The Norwegian electric ferry network is frequently cited in the literature as a benchmark for scalable implementation.

3.7 Carbon Capture and Storage (CCS) Onboard Ships

Onboard carbon capture and storage (CCS) technologies aim to capture CO_2 emissions before release into the atmosphere, offering a potential retrofit solution for existing fleets. Pilot studies report capture rates exceeding 80%, suggesting technical viability.

However, CCS systems impose significant energy penalties, space requirements, and operational complexity. Regulatory frameworks for CO_2 storage and offloading remain underdeveloped, limiting large-scale adoption. As such, CCS is generally viewed as a supplementary or transitional option rather than a primary decarbonisation pathway.

3.8 Comparative Fuel Impact and Strategic Implications

Fuel choice plays a decisive role in determining emissions performance. Conventional fuels such as HFO and marine diesel oil (MDO) exhibit the highest lifecycle GHG emissions, while alternative fuels demonstrate varying degrees of reduction depending on production pathways. The literature increasingly stresses the importance of lifecycle-based assessment frameworks to avoid shifting emissions upstream.

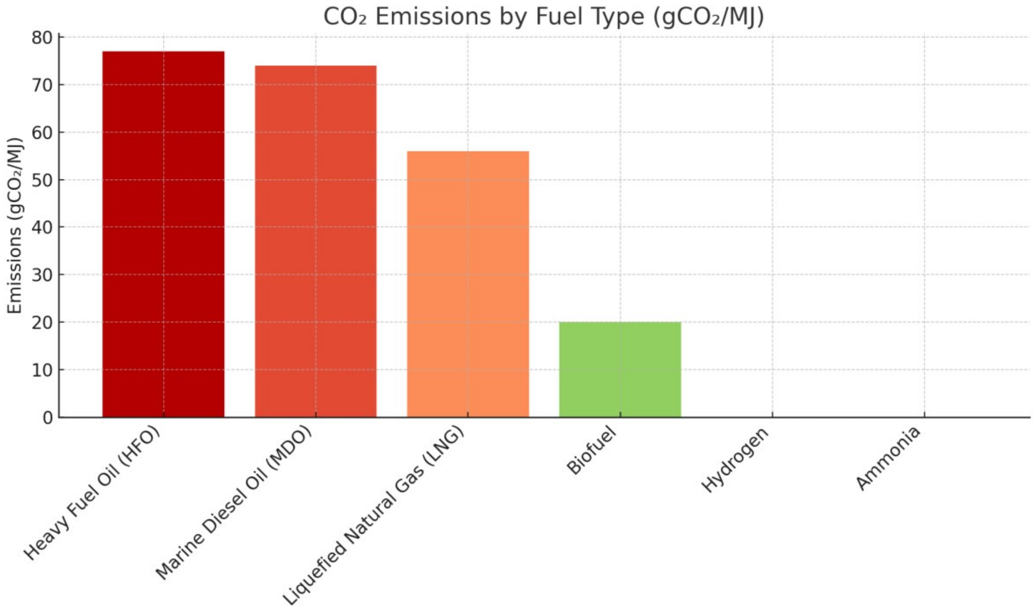

Figure 2: Lifecycle greenhouse gas emissions (gCO_2/MJ) by marine fuel type.
Source: World Bank (2021); DNV (2023).

For Greek shipping, the technological landscape suggests a phased approach: transitional solutions such as LNG and biofuels in the short term, combined with investment in fuel-ready vessels to preserve flexibility for future adoption of zero-carbon fuels such as ammonia, hydrogen, or methanol.

4. ECONOMIC AND OPERATIONAL IMPLICATIONS FOR SHIPOWNERS

The transition toward low- and zero-carbon shipping is not only a technological shift but also a fundamental economic and operational transformation. Decarbonisation strategies directly affect capital allocation, operating costs, commercial competitiveness, and access to finance. For shipowners, particularly those managing diversified fleets such as Greek shipping companies, investment decisions must balance regulatory compliance with market uncertainty and long-term asset value preservation.

4.1 Capital Expenditure and Fleet Renewal Strategies

The adoption of alternative propulsion technologies entails significant capital expenditure (CAPEX) premiums compared to conventional vessel designs. Empirical evidence from shipbuilding contracts indicates that LNG-ready vessels typically involve CAPEX increases of approximately 10–20%, while methanol- or ammonia-ready designs may raise initial investment costs by up to 25–30%. These premiums reflect not only fuel systems but also structural modifications, safety systems, and space allocation requirements.

Greek shipowners have traditionally demonstrated cautious investment behaviour, prioritising flexibility and optionality. As a result, many newbuilding orders incorporate “fuel-ready” or dual-fuel configurations rather than committing to a single long-term fuel pathway. This strategy mitigates the risk of technological lock-in and potential asset stranding in an evolving regulatory environment.

4.2 Operational Expenditure and Compliance Costs

Beyond capital costs, decarbonisation significantly influences operational expenditure (OPEX). The inclusion of maritime transport in the European Union Emissions Trading System (EU ETS) introduces recurring carbon costs for vessels calling at EU ports, effectively internalising the cost of emissions. FuelEU Maritime further amplifies these pressures by imposing progressive greenhouse gas intensity limits on marine fuels.

In response, shipowners increasingly deploy operational optimisation measures such as slow steaming, weather routing, hull and propeller optimisation, and digital performance monitoring. These strategies not only reduce fuel consumption and emissions but also support compliance with the Carbon Intensity Indicator (CII), linking daily operational decisions directly to regulatory performance ratings.

4.3 Market Competitiveness and Chartering Dynamics

Decarbonisation has become a critical determinant of commercial competitiveness in charter markets. Major charterers—particularly in the energy, manufacturing, and consumer goods sectors—now prioritise vessels with superior environmental performance and transparent emissions reporting. This shift is especially pronounced in long-term charter agreements, where charterers seek to minimise regulatory and reputational risks.

For Greek shipowners, the ability to offer CII-compliant and fuel-efficient vessels increasingly translates into improved chartering prospects and revenue stability. Conversely, vessels with poor emissions performance face growing risks of reduced utilisation, discounted charter rates, or exclusion from certain trades.

4.4 Financing, ESG Criteria, and Access to Capital

The financial dimension of maritime decarbonisation is closely linked to environmental, social, and governance (ESG) frameworks. Banks adhering to the Poseidon Principles assess shipping portfolios against IMO decarbonisation trajectories, directly influencing lending conditions. Similarly, institutional investors increasingly incorporate carbon performance metrics into investment decisions.

Greek shipping companies demonstrating credible decarbonisation strategies benefit from enhanced access to sustainability-linked loans, green bonds, and preferential financing terms. Conversely, vessels misaligned with future regulatory pathways risk higher financing costs or reduced capital availability. The literature highlights that alignment with ESG criteria is transitioning from a reputational consideration to a core financial requirement.

4.5 Operational Complexity and Human Capital Requirements

The adoption of alternative fuels introduces new operational complexities related to safety, maintenance, and crew competence. Fuels such as ammonia, hydrogen, and methanol require specialised handling procedures, revised safety management systems, and advanced monitoring technologies. Consequently, crew training and upskilling emerge as critical components of successful decarbonisation strategies.

Studies emphasise that human capital readiness can act as either an enabler or a bottleneck in technology adoption. Greek shipowners, supported by maritime education institutions and classification societies, increasingly invest in training programmes to ensure operational safety and regulatory compliance in the transition to cleaner propulsion systems.

4.6 Strategic Trade-Offs and Risk Management

Ultimately, decarbonisation decisions involve strategic trade-offs between short-term costs and long-term resilience. While green investments increase CAPEX and OPEX in the near term, failure to adapt exposes shipowners to regulatory penalties, declining asset values, and reduced market access. The literature suggests that proactive decarbonisation strategies, combined with technological flexibility and digital optimisation, enhance long-term competitiveness.

For Greek shipping, which operates at the intersection of global and European regulatory regimes, effective risk management depends on continuous monitoring of policy developments, fuel markets, and technological innovation. Incremental adaptation, rather than abrupt technological shifts, appears to be the prevailing strategy for maintaining competitiveness under uncertainty.

5. CASE STUDY: THE GREEK SHIPPING INDUSTRY IN THE CONTEXT OF DECARBONISATION

The Greek shipping industry occupies a dominant position in global maritime transport, controlling a substantial share of world deadweight tonnage across key market segments such as tankers, dry bulk carriers, and container vessels. This scale provides Greek shipowners with both strategic influence and heightened responsibility in the global effort to reduce greenhouse gas (GHG) emissions. As regulatory and market pressures intensify, the Greek fleet offers a particularly informative case for examining how decarbonisation strategies are implemented in practice.

5.1 Fleet Characteristics and Investment Patterns

Greek-owned fleets are characterised by relatively low average age and a strong orientation toward asset renewal. Over the past decade, investment strategies have increasingly incorporated environmental performance considerations alongside traditional commercial criteria. Newbuilding contracts frequently include dual-fuel engines or “fuel-ready” designs, allowing future conversion to alternative fuels such as LNG, methanol, or ammonia.

This investment behaviour reflects a pragmatic approach to uncertainty. Rather than committing prematurely to a single decarbonisation pathway, Greek shipowners prioritise flexibility, thereby reducing exposure to technological lock-in and potential stranded assets. The literature consistently identifies this optionality-driven strategy as a key factor underpinning the long-term competitiveness of Greek shipping.

5.2 Adoption of Clean Technologies and Operational Measures

Greek shipping companies have played a leading role in the adoption of cleaner propulsion technologies, particularly in segments where regulatory and commercial incentives are strongest. The Greek-controlled fleet holds a significant share of global LNG carrier capacity and has expanded investment in LNG-fuelled and dual-fuel vessels. In parallel, operational measures such as speed optimisation, digital fuel monitoring, and hull efficiency improvements are widely implemented to ensure compliance with the Carbon Intensity Indicator (CII).

These measures demonstrate that decarbonisation within the Greek fleet is not solely technology-driven but also operationally embedded. The integration of digital tools enables continuous performance optimisation, supporting both emissions reduction and cost efficiency.

5.3 Participation in Research, Innovation, and Partnerships

Beyond fleet investment, Greek shipping actively participates in international research and innovation initiatives. Greek companies, ports, and maritime clusters engage in EU-funded programmes such as Horizon Europe, focusing on hydrogen propulsion, alternative fuels, port electrification, and digital optimisation. Collaboration with classification societies and technology providers further facilitates knowledge transfer and risk sharing.

Such participation enhances the absorptive capacity of the Greek maritime sector, enabling early exposure to emerging technologies while mitigating investment risks. The literature emphasises that these collaborative networks play a crucial role in accelerating the diffusion of sustainable maritime technologies.

5.4 Port Infrastructure and National Readiness

Port infrastructure readiness constitutes a critical enabling factor for maritime decarbonisation. Major Greek ports, including Piraeus and Igoumenitsa, have initiated projects related to shore-side electricity, LNG bunkering, and alternative fuel readiness. These developments support compliance with EU climate policies and strengthen Greece’s strategic position within emerging European green shipping corridors.

Nevertheless, infrastructure development remains uneven, and the availability of alternative fuels is limited compared to Northern European ports. Addressing this gap requires coordinated public–private investment and long-term planning at both national and regional levels.

5.5 Key Challenges and Strategic Outlook

Despite notable progress, Greek shipowners face persistent challenges, including high capital costs for green vessels, uncertainty over future fuel availability and pricing, and the need for specialised crew training. At the same time, exposure to both global IMO regulations and advanced EU climate policies intensifies compliance complexity.

The literature suggests that the strategic response of Greek shipping is characterised by incremental adaptation rather than radical technological shifts. By combining flexible fleet design, operational optimisation, and active engagement in innovation networks, Greek shipowners position themselves to navigate the transition toward low- and zero-carbon shipping while preserving long-term competitiveness.

6. DISCUSSION

The literature reviewed in this study illustrates that maritime decarbonisation is driven by a complex interaction of regulatory pressure, technological innovation, and market-based incentives. Rather than a linear transition toward a single dominant solution, the shipping sector is experiencing a multi-path transformation characterised by uncertainty, uneven regional implementation, and differentiated impacts across vessel types and trades.

A central finding is the decisive role of regulation as the primary catalyst for change. The evolving IMO framework, combined with increasingly stringent European policies such as the EU Emissions Trading System (ETS) and FuelEU Maritime, has effectively repositioned environmental performance as a core determinant of competitiveness. However, regulatory asymmetry between global and regional regimes creates distortions that may influence trade patterns, fleet deployment, and investment timing. The risk of carbon leakage and competitive imbalance underscores the importance of greater international policy alignment.

From a technological perspective, the analysis confirms that no single propulsion technology currently satisfies the combined criteria of scalability, safety, cost-effectiveness, and lifecycle emissions reduction. Transitional solutions such as LNG and biofuels play a meaningful role in near-term compliance, yet their long-term compatibility with net-zero targets remains conditional on lifecycle performance and regulatory treatment. In contrast, zero-carbon fuels such as hydrogen, ammonia, and renewable methanol offer stronger alignment with long-term climate objectives but face substantial barriers related to infrastructure, fuel availability, and technological maturity.

Economic considerations emerge as a critical constraint shaping adoption pathways. High capital expenditure requirements, combined with uncertainty over future fuel dominance, incentivise shipowners to prioritise technological flexibility. The growing influence of ESG criteria, charterer expectations, and green finance mechanisms reinforces this trend, effectively linking environmental performance to access to capital and market opportunities. Consequently, decarbonisation strategies are increasingly integrated into broader risk management and asset valuation frameworks.

The Greek shipping industry exemplifies these dynamics in practice. Operating at the intersection of global and European regulatory regimes, Greek shipowners demonstrate a strategic preference for incremental adaptation rather than radical technological commitment. Investments in fuel-ready vessels, operational optimisation, and participation in research initiatives reflect a balanced approach that preserves optionality while aligning with evolving regulatory trajectories. This behaviour supports the argument that flexibility constitutes a rational response to uncertainty rather than a reluctance to decarbonise.

Infrastructure readiness remains a systemic bottleneck across the sector. While European ports are advancing alternative fuel corridors, global coverage remains fragmented. Without coordinated investment in port infrastructure and fuel supply chains, the large-scale deployment of zero-carbon fuels will remain constrained. This challenge highlights the interdependence between ship-based technologies and shore-side systems, reinforcing the need for integrated policy design.

Finally, the discussion underscores that decarbonisation should be understood within a broader sustainability framework. Beyond greenhouse gas reduction, issues such as energy efficiency, digitalisation, crew training, safety, and lifecycle resource use are integral to the long-term resilience of maritime transport. Addressing these dimensions in a holistic manner will be essential for achieving both environmental objectives and sustained competitiveness.

7. CONCLUSIONS

The transition toward low- and zero-carbon maritime transport represents one of the most complex and consequential transformations in the history of the shipping industry. This literature review has demonstrated that decarbonisation is not driven by a single factor but emerges from the interaction of regulatory frameworks, technological innovation, economic constraints, and market expectations. As climate ambitions intensify, shipping is increasingly required to align environmental performance with long-term operational and financial sustainability.

The analysis confirms that regulatory pressure constitutes the primary driver of change. The evolving International Maritime Organization (IMO) framework, reinforced by more ambitious European Union policies, has transformed emissions reduction from a voluntary objective into a binding strategic requirement. Instruments such as EEXI, CII, EU ETS, and FuelEU Maritime have fundamentally altered the cost structure and decision-making environment for shipowners, accelerating the integration of decarbonisation into fleet planning and operations.

From a technological perspective, the findings highlight the absence of a universally dominant solution. Transitional fuels such as LNG and biofuels contribute to near-term emissions reduction, while zero-carbon alternatives—including hydrogen, ammonia, and renewable methanol—offer stronger alignment with long-term climate objectives but face significant barriers related to infrastructure, cost, and technological maturity. Consequently, a portfolio-based approach, combined with fuel-ready vessel designs, emerges as the most viable strategy under current conditions.

Economic and financial considerations play a decisive role in shaping adoption pathways. High capital expenditure requirements, uncertainty over future fuel pathways, and increasing reliance on ESG-based financing mechanisms incentivise shipowners to prioritise flexibility and risk management. Access to capital, charterer preferences, and regulatory compliance are increasingly interlinked, reinforcing the strategic importance of environmental performance.

The Greek shipping industry illustrates these dynamics in practice. As a global market leader operating across diverse regulatory environments, Greek shipowners have adopted a pragmatic approach characterised by incremental adaptation, operational optimisation, and active participation in research and innovation initiatives. This strategy enables alignment with decarbonisation objectives while preserving competitiveness and long-term asset value.

In conclusion, achieving meaningful decarbonisation in shipping will require coordinated action among regulators, industry stakeholders, technology providers, and financial institutions. Infrastructure development, lifecycle-based emissions assessment, and international policy alignment will be critical enablers of progress. Future research should focus on fuel scalability, cost trajectories, and integrated modelling of regulatory and market impacts to support evidence-based decision-making as the sector advances toward its 2050 climate goals.

References

Acciaro, M., Vanelslander, T., Sys, C., Ferrari, C., Roumboutsos, A., & Kapros, S. (2020). Environmental sustainability in maritime transport: Policy and market perspectives. Maritime Policy & Management, 47(1), 1–17.

Atilhan, S., Park, S., El-Halwagi, M., & Moore, M. (2021). Ammonia as a marine fuel: Challenges and opportunities. Journal of Cleaner Production, 299, 126964.

Balcombe, P., Brierley, J., Lewis, C., Skatvedt, L., Speirs, J., Hawkes, A., & Staffell, I. (2019). How to decarbonise international shipping: Options and challenges. Energy Conversion and Management, 182, 72–88.

Bouman, E. A., Lindstad, E., Rialland, A. I., & Strømman, A. H. (2017). State-of-the-art technologies, measures, and potential for reducing greenhouse gas emissions from shipping. Transportation Research Part D, 52, 408–421.

Brynolf, S., Fridell, E., & Andersson, K. (2018). Environmental assessment of marine fuels: LNG, methanol and biofuels. Energy Policy, 112, 526–538.

Brynolf, S., Taljegard, M., Grahn, M., & Hansson, J. (2022). Electrofuels for the transport sector: A review of production costs. Energy Conversion and Management, 259, 115499.

Cullinane, K., & Bergqvist, R. (2023). Decarbonisation and competitiveness in maritime transport. Maritime Economics & Logistics, 25(2), 137–155.

DNV (2022). Alternative Fuels Insight Platform Report. Høvik: DNV.

DNV (2023). Maritime Forecast to 2050. Høvik: DNV.

EMSA (2021). European Maritime Transport Environmental Report. Lisbon: European Maritime Safety Agency.

Gilbert, P., Walsh, C., Traut, M., Kesieme, U., Pazouki, K., & Murphy, A. (2018). Assessment of full lifecycle air emissions of alternative shipping fuels. Energy Policy, 112, 95–105.

Hansson, J., Brynolf, S., Fridell, E., & Lehtveer, M. (2020). The potential role of ammonia as a marine fuel. Renewable and Sustainable Energy Reviews, 130, 109937.

IMO (2018). Initial IMO Strategy on Reduction of GHG Emissions from Ships. London: International Maritime Organization.

IMO (2023). Fourth IMO Greenhouse Gas Study. London: International Maritime Organization.

Kontovas, C. A., & Psaraftis, H. N. (2020). Decarbonization of maritime transport: Is there light at the end of the tunnel? Sustainability, 12(9), 3728.
Lagouvardou, S., Psaraftis, H. N., & Zis, T. (2021). The impact of IMO regulations on ship emissions and operational strategies. Transportation Research Part D, 92, 102718.
Lagouvardou, S., Zis, T., & Psaraftis, H. N. (2022). Shipping decarbonisation in the Mediterranean region. Marine Policy, 137, 104946.
Methanol Institute (2022). Renewable Methanol Report. Washington, DC.
OECD/ITF (2022). Decarbonising Maritime Transport: Pathways to Zero-Carbon Shipping. Paris: OECD Publishing.
Poseidon Principles Association (2023). Annual Disclosure Report.
Psaraftis, H. N., & Kontovas, C. A. (2022). Decarbonization of maritime transport: To be or not to be? Maritime Economics & Logistics, 24(1), 1–23.
Smith, T. W. P., Raucci, C., Hosking, J., Rojon, I., & Dodds, P. (2023). The role of regulation in shipping decarbonisation pathways. Marine Policy, 148, 105463.
Stopford, M. (2020). Maritime Economics (4th ed.). London: Routledge.
World Bank (2021). The Role of Zero-Carbon Fuels in Global Maritime Decarbonisation. Washington, DC: World Bank Group.