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A Literature Review on Decarbonization Pathways and Operational Strategies for Sustainable Shipping

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Abstract:

International shipping represents 2% to 3% of worldwide greenhouse gas (GHG) emissions. It is being regulated more to meet international climate strategies. The International Maritime Organization (IMO) 2023 Revised Strategy targets net-zero GHG emissions for international shipping by 2050. Meeting this target will require operational, fuel type, and policy changes.

This study focuses on measures to operationalize decarbonization and on strategies for greater sustainability in shipping. The operational measures, alternative fuels, and policy approaches are examined through a systematic literature review of peer-reviewed literature (most current is 2025), compliant with PRISMA 2020, from 2015 to 2025. The literature describes operational efficiency, the role of Digitalization and coordination between ships and ports, the life cycle, or 'well-to-wake', of alternative marine fuels, and current and developing policies and regulations.

Operational measures will yield positive results and demonstrate the benefits of subsequent approaches, but will not achieve full or deep decarbonization. Long-lasting, or permanent, solutions will be economically unachievable without the use of zero- or near-zero-carbon fuels. The alternative to economically unachievable permanent solutions is the use of Ammonia, Methanol, hydrogen, and synthetic fuels, but their lifecycle impact must be addressed. The review also recognizes the value of market-based measures.

The policy recommendations, operational measures, and fuel-type changes should include the integrated lifecycle approaches. This study will serve to define future research on operational measures and strategies for the essential sustainability of shipping.

Keywords: Maritime decarbonization, Sustainable shipping, Operational efficiency, Alternative marine fuels, IMO GHG strategy.

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1. Introduction

Maritime shipping facilitates 80% of international trading and connects global producers to consumers (Tadros et al., 2023). Although the sector of the economy is comparatively more energy efficient, it is responsible for only 2–3% of global greenhouse gas (GHG) emissions; it is still a sector with a relative lack of efficiency and is faced with the unique and difficult challenge of ensuring future economic development while tackling climate change (Bullock et al., 2024). In July 2023, the International Maritime Organization (IMO) adopted a revised version of its 2018 Strategy on the Reduction of GHG Emissions from Ships and set the following targets for the sector: achieve net-zero GHG emissions by 2050; reduce total annual GHG emissions from the sector by a minimum of 20–30% in 2030 and 70–80% in 2040, both with 2008 as the base year; and have 5–10% of the shipped energy compose of zero, or near-zero GHG fuel by 2030 (IMO 2025a; IMO 2025b) To achieve this, the IMO in cooperation with international institutions such as the International Energy Agency (IEA), the World Bank, and the European Commission is establishing a 'basket' of midterm measures that is the combination of targeted fuel a goal-based marine fuel standard and economic incentives to drive decarbonization (Lloyd's Register 2025), Table 1 illustrates these aspects and targets.

Table 1: Summary of key maritime shipping aspects and IMO climate strategy

Aspect	Details
Global Trade Contribution	More than 80% of world merchandise by volume
GHG Emissions Contribution	Approximately 2–3% of global greenhouse gas emissions
Challenges	Sustaining economic growth while meeting climate objectives
IMO Revised Strategy Adoption Date	Adopted in July 2023; establishes net-zero GHG emissions by 2050, interim reduction checkpoints for 2030 and 2040, a shift to lifecycle accounting, and the development of fuel GHG intensity standards and market-based measures
Target Year for Net-Zero GHG Emissions	By or around 2050
GHG Emissions Reduction Target by 2030	At least 20–30% compared to 2008
GHG Emissions Reduction Target by 2040	70–80% compared to 2008
Zero or Near-Zero GHG Fuels Target by 2030	5–10% of shipping energy
Mid-Term Measures Development	A goal-based marine fuel standard combined with an economic mechanism

Though there is evidence supporting the proposed case, the industry is advised that it is likely to fail to meet net-zero targets without the rapid adoption of zero-carbon energy, supportive infrastructure, and effective governance. Recent studies indicate that shipping is likely to meet the 2030 carbon-intensity target but is not projected to reach net-zero by 2050 unless additional measures and faster fuel transitions are implemented (Laskar et al., 2025). Likewise, the analysis of climate policy concludes that the IMO's "strive" targets – 30% by 2030 and 80% by 2040 (considered the bare minimum to be on a 1.5 °C pathway) – demand the immediate implementation of all available efficiency measures on the existing vessels (Bullock et al., 2024). To prevent emissions leaking throughout the supply chain, the IMO published the Guidelines on Lifecycle GHG Intensity of Marine Fuels, which provide, for mitigation purposes, well-to-wake accounting on a full lifecycle basis (IMO, 2024).

The broad range of possible pathways proposed to achieve decarbonization, considering policy and regulatory frameworks, includes alternative fuels, energy efficiency (EE) upgrades and operational efficiency, onboard carbon capture, and digitalized ship–port coordination (Robalo-Cabrera et al., 2025). Lifecycle assessment studies have shown that, while there are operational measures that are capable of providing immediate mitigation potential and are low in capital costs, there are also deep operational measures, such as speed and routing, and port call management, that can be capitalized on within the current operational fleet (Degiuli et al., 2024; Kanchiralla et al., 2024; Y. Wang et al., 2025). Still, literature demonstrates fuel, infrastructure, safety, and cost tradeoffs in order to achieve operational scalability. Thus, without the varying integrations of all proposed operational mitigation measures, which add to the complexity of achieving decarbonization within the proposed pathways, there are limited opportunities to achieve decarbonization (Ezeh et al., 2024; Kondratenko et al., 2025). To achieve deep decarbonization, operational measures focused on immediate results should be combined with fuel switching and sufficient policy and market frameworks.

While there have been many reviews on decluttering the literature on maritime decarbonization, these reviews have become siloed, especially those focusing on alternative fuels and propulsion technologies, operational efficiency measures, and regulatory instruments. This siloed approach will make it difficult for policymakers and industry actors to assess the intersection of operational strategies, fuel transitions, and market-based measures for a certain vessel type and time frame. It is also important to note that a number of recent reviews were conducted prior to the adoption of IMO's 2023 revised GHG Strategy and the shift to lifecycle (well-to-wake) accounting (e.g., Tadros et al., 2023; Zanobetti et al., 2023). This creates a time lag in upstream evidence synthesis and is likely to be detrimental to the current regulatory landscape. Closing this gap would require a synthesis that is integrated with an up-to-date assessment and simultaneously reviews the best estimates of technological viability, operational efficiencies, and public policy iteratively.

1.1. Aim and contribution

This study's objective is to depict in more detail the part operational measures, alternative fuels, and policy tools will play, where they impose constraints, and how they will interact with one another in the holistic lifecycle approaches needed to meet the IMO targets for greenhouse gas containment in the literature concerning the pathways and operational strategies for the sustainable shipping niche.

This research focuses on the following aspects in the literature on the decarbonization of shipping:

1. The operational efficiency measures, alternative fuel pathways, and policies and regulations related to the decarbonization of shipping, as well as the considerable peer-reviewed literature on this topic.

2. The operational measures for progressing to the next level of decarbonization and their value as short-term mitigation measures.

3. The alternative fuel pathways, with a well-to-wake analysis of lifecycle emissions, and how they should guide policy and investment decisions.

4. The findings are actionable, practical recommendations concerning policy relevant to the maritime sector with decarbonization targets set by the IMO to guide primary future research.

The study is organized in the following manner. Methodological approaches are outlined in Section 2, along with the PRISMA-based systematic review. Section 3 provides findings from the literature review concerning operational measures, alternative fuels, and policy frameworks. Finally, Section 4 analyzes the findings and their significance for maritime stakeholders. This section also concludes the study by offering recommendations for future research and industry practice.

2. Methodology

The study employs a systematic literature review (SLR) compliant with PRISMA 2020 (Page et al., 2021). In addition, it examines the available literature on decarbonization pathways and operational strategies for green shipping and analyzes the key themes, trends, and gaps.

2.1. Literature review

Between January 2015 and April 2025, a systematic review of the databases was conducted to identify the latest peer-reviewed publications on the decarbonization of the maritime sector available up to 2025. Purposeful search queries were designed to construct comprehensive meta-analyses on the operational dimensions of decarbonization, including Decarbonization and Sustainable Shipping in Policy and Technical analyses. To ensure all possible high-quality, peer-reviewed publications were identified and included from the fields of maritime research, engineering, energy systems, and policy research, the Web of Science, Scopus, and ScienceDirect databases were searched. To maximize accuracy and minimize duplication across the various dimensions of the review, the proposed search strategy was structured to comprise three interrelated analytical and conceptual frameworks using Boolean search techniques, as follows:

- **Scope Block. (The Sector):** Focuses on the description of the particular industry (e.g., shipping, maritime, vessel).

- **Goal Block. (The Problem):** Focuses on the main goal of the study (e.g., emissions decrease, decarbonization).

- **Measures Block. (The Solutions):** Focuses on a variety of technical, operational, and regulatory measures that could be employed.

The initial search query was built as follows: (Scope Block) AND (Goal Block) AND (Measures Block). Within the Measures Block, specific terms included key substitutable fuels (Ammonia, Methanol, hydrogen, LNG, biofuel), operational efficiency, and Digitalization (energy efficiency, voyage optimization, Artificial Intelligence (AI)). policy instruments (IMO strategy, Carbon Intensity Indicator (CII), Energy Efficiency Existing Ship Index (EEXI), policy).

The combined database search yielded an initial set of 737 records. These records were further explored through citation snowballing and forward searching before moving on to the formal screening and selection phases.

2.2. Screening and selection process

As guided by PRISMA (Page et al., 2021), literature selection followed a methodical, stepwise approach. The complete trail of studies from initial search to final inclusion decision is shown in the PRISMA diagram (Figure 1). This ensured that the final evidence base was selected in a transparent and reproducible manner.

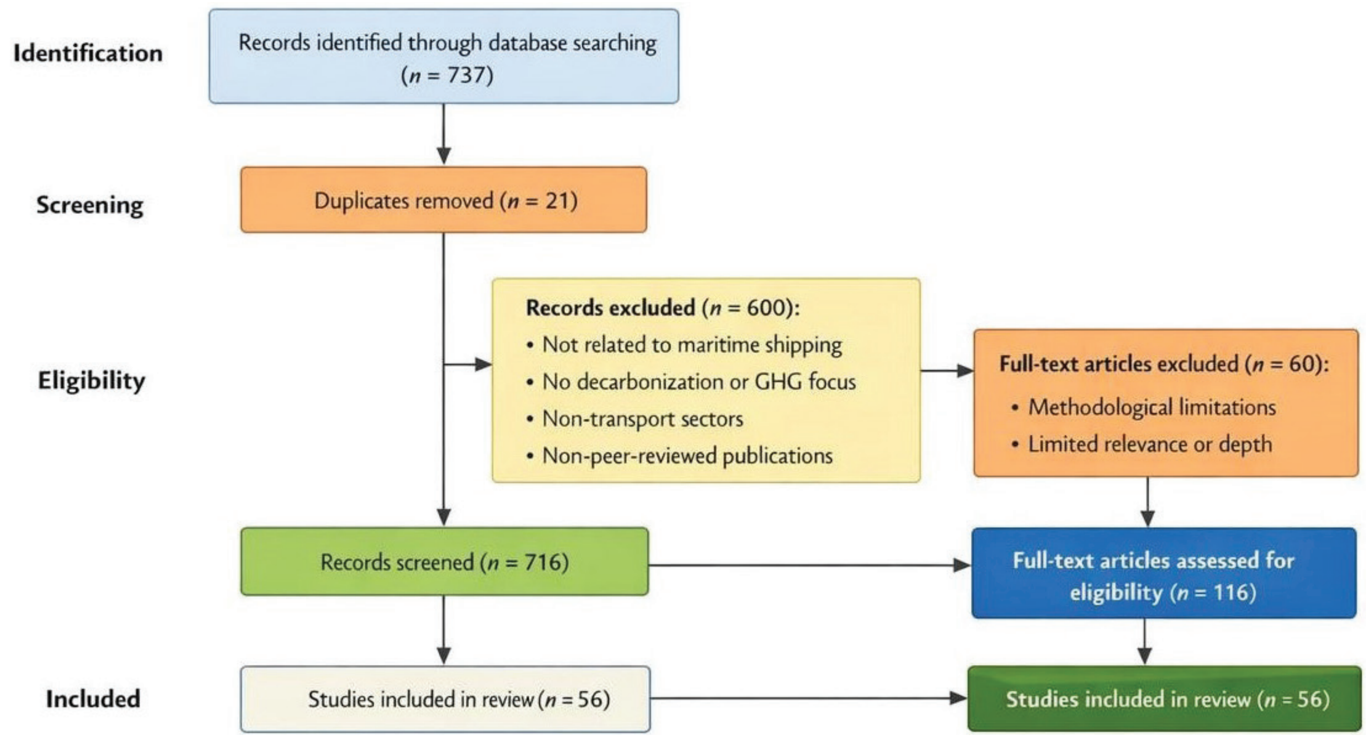

Figure 1: Flow diagram of the research selection process, Source: author

The first stage of the screening process started after the collection of 737 documents. A master spreadsheet was generated, and the documents began their systematic review. Automated and manual duplication checks were conducted using DOI and title filters, followed by manual checks, resulting in the removal of 21 duplicate records, leaving 716 documents for the first screening round. These documents were first screened by title and abstract to determine whether they were aligned with the review's focus on decarbonization pathways and operational strategies for sustainable shipping. 600 documents were removed in this screening round for various reasons that aligned with the custom exclusion criteria, leaving 116 documents for the next screening phase. These documents were fully screened for relevance and theme before a more in-depth scope of review was applied.

During the title and abstract screening phase, studies were excluded according to the predetermined eligibility criteria. Articles were excluded if they were not specifically about international maritime shipping, did not mention decarbonization or reduction of greenhouse gases, were about non-maritime transport sectors, or were unpublished or non-peer-reviewed. From the first screening stage, 600 records were excluded. 116 studies were advanced to full-text review. All of these documents were fully retrieved, and the full text was reviewed against the review's more detailed inclusion and exclusion criteria.

These documents were assessed for:

- Relevance and depth with a more insightful, thorough analysis of the decarbonization associated pathways (fuels/technology) or operational, policies, and strategies that were directly geared to international deep-sea shipping.
- **Methodological quality:** The study's quality must meet the requirements set by the quality evaluation checklist criteria (Section 2.4).
- **Data contribution:** The study has to provide new empirical evidence or analytical information of quality and depth, which has positive implications for the understanding of the sector's sustainable transition as regards diverse robust quantitative modeling.

Following the assessment results, the database removed 60 articles. The predominant rationale concerning the removal was due to the articles lacking primary empirical data, articles of low quality in terms of methodology, and articles lacking sufficient description of the processes of the transition in international shipping (these reasons are explained in the PRISMA flow diagram, Figure 1). Only these 56 articles, which are deemed to have met all the inclusion criteria, are the ones that make up the Final Evidence Base for this systematic review. At this point, the inclusion and exclusion decisions for each article have been made independently, based on the eligibility and quality criteria, and consistency checks have been conducted to address selection bias in the Final Evidence Base.

2.3. Data extraction and synthesis

After completing the final stage of selection, a standard protocol for data extraction was developed and consistently applied across the 56 samples included in the review. This stage aimed at obtaining a homogeneous set of relevant information for data synthesis and analysis.

The data below were extracted for each of the studies:

- **Complete reference:** Name(s) of Author(s), Year of Publication, Journal, and DOI.
- **Research design:** Determination of the type of research conducted as a Lifecycle Assessment (LCA), technical modeling, case study, survey, or economic analysis.
- **Research topic:** The specific decarbonization pathway, or the operational strategy, was studied.
- **Summary of the findings:** Principal conclusions of the study, including the relevant findings and policy recommendations.

Primarily, the articles underwent systematic coding through the mechanization of Thematic Tagging. This process, inductively, assigned tags based on the articles' emphases. The subsequent tags were then aggregated and organized into broader categories, which comprise the results of this review: Digitalization/AI, Policy/Regulation, Alternative Fuels, and Port Operations. The painstaking nature of this thematic classification, which was demonstrated by the counts in the Tag Summary, enables the integrated synthesis of knowledge gaps, convergence, and the possible fragmented trends in the reviewed literature. This is exactly the objective of this review. For the sake of the thematic tagging's analytical quality, the primary analytical focus was differentiated from the secondary or enabling themes. Only if the theme was the leading analytical focus, research question, methodological focus, or the main contribution of the paper was it coded to be primary. Themes like Digitalization, data analytics, or monitoring systems were often taken as enabling or cross-cutting themes. They were embedded within the primary focus of the studies, which were mostly about fuels, operational efficiency, and policy. Therefore, while digital technologies are seen in high frequency throughout the literature, it does not entail that the same level of analytical focus was given to them in each case. This was done in order to avoid the overrepresentation of transversal themes, which in turn would affect the interpretative reliability of the thematic synthesis, which in this case was to be.

2.4. Quality assessment and risk of bias

To provide the highest level of trust and confidence in the final findings, a quality assessment of the 56 included studies was conducted. Due to the heterogeneity of the literature, including technical modeling, LCA, and case studies, the studies were evaluated using the Bespoke Quality Checklist, based on systematic review quality evaluation standards (Page et al., 2021) and quality criteria. These criteria were: the purpose of the study was clearly stated, appropriate methods were used, the data source was reliable, and the conclusions drawn were trustworthy. Some studies did not meet these criteria, which led to the exclusion of 60 studies during the full-text review. Of these, 24 studies were excluded for insufficient methodological rigor, 18 for limited relevance to international maritime shipping decarbonization, and 18 for insufficient analysis or lack of substantial contribution. Thus, ensured that the findings of the thematic synthesis were drawn from accurate and reliable arguments.

3. Discussion and Review of findings

3.1. Policy and regulatory framework for maritime decarbonization

All decarbonization strategies that the maritime sector can pursue must work within the context of the policy and regulatory framework. Which of the international regulations, marketbased measures, and fuelintensity standards apply will determine compliance, dictate investment, and drive operational and technological change. Therefore, this subsection addresses the regulatory and economic instruments applicable to maritime decarbonization before discussing operational measures and alternative fuel solutions.

This chapter presents the summaries from the 31 studies on Policy and Economics (Sun et al., 2026; W. Wang et al., 2025; Zeng et al., 2025). Among the research components, this one is most critical to addressing market failures that impede the transition and are associated with the costs of both conventional and zero-emission fuels and the insufficient level of investment in new technologies. The operational and technological measures, coupled with the existence of global frameworks, are, according to the literature, the only solutions to the problem of the high price of carbon (Carral et al., 2020; Ng et al., 2022).

3.1.1. Policy instruments: Driving the market signal

Studies examining Carbon Pricing Mechanisms, such as a global Carbon Levy or Emission Trading Schemes (ETS), are numerous (Fadiga et al., 2024; Kondratenko et al., 2025; Zincir, 2025). There exists an academic consensus regarding the efficacy of Market-Based Measures (MBMs) in closing the cost parity gap and steering industry focus and investments (Chen et al., 2024; Ng et al., 2022; W. Wang et al., 2025). There is no disputing that a high carbon price of over $100/ton of CO2-equivalent is required to alter the cost differential between HFO and provide a financially viable alternative for the production of green hydrogen/Ammonia. (Robalo-Cabrera et al., 2025; Tadros et al., 2023; Zeng et al., 2025). The breadth of coverage for such mechanisms is important to avoid carbon leakage and a competitive gap (e.g., the EU ETS) (Carral et al., 2020; W. Wang et al., 2025).

There have been several studies analyzing the Fuel EU Maritime Initiative along with the carbon pricing framework (Kondratenko et al., 2025; Li & Tang, 2024; Ng et al., 2022). These studies show that these regulations that require a decreasing average GHG intensity of the energy consumed on board are essential in providing a demand signal for clean fuels, addressing the chicken-and-egg dilemma of the ship investment for the production of fuel (Ezeh et al., 2024; Soltani Motlagh et al., 2023; Xiao et al., 2025). The studies suggest that the optimal approach to hastening the decarbonization of the industry is to simultaneously implement fuel regulations (Non-MBM) and carbon pricing (MBM) measures (Carral et al., 2020; Chen et al., 2024; Sun et al., 2026). Among the studies, market-based measures are in the lead as the principal enabling factor, while fuel regulations are the essential supportive factor that mitigates investment risk and demand volatility.

The output of the IMO Marine Environment Protection Committee (MEPC) 83 meeting advanced the implementation of the new GHG strategy of the organization, within the current regulatory framework. MEPC 83 advanced the Annual GHG Fuel Intensity (GFI) target, which sets an increasingly stringent GHG fuel lifecycle GHG emissions cap on the use of maritime fuels. MEPC 83 shifted to a target-based approach to fuel GHG emissions. This approach directly targets the fuel used and energy sources, regulating the extent to which lifecycle fuel GHG emissions are mitigated. MEPC 83 proposed mechanisms on top of other integrated market measures to offer both an economic and regulatory framework to scale performance targets focused on the use of low and no-cost carbon alternatives (IMO, MEPC83).

3.1.2. Economic challenges and investment

Within the literature, there is a consensus that the greatest investment barrier that comes with the process of decarbonization is the substantial long-term Capital Expenditure (CAPEX) needed for the construction of new vessels, as well as the new shore-side infrastructure that will be needed as well (Bolat, 2026; Ng et al., 2022; W. Wang et al., 2025; Zeng et al., 2025). Studies demonstrate the need for innovative financial models, particularly public-private alliances and Green Shipping Funds, to alleviate the risks of financing new technologies (ammonia engines and hydrogen bunkering) (Tadros et al., 2023; Vakili et al., 2023). Under investment risk, there is the possibility of deserting the assets where the vessels that are procured today (i.e., LNG carriers) will be at a high risk of being economically unfit in the course of over two decades due to increased enforcement of policies that are geared towards the environment, highlighting the need for policies to address the issue to protect and encourage investment (Bolat, 2026; Dong et al., 2025).

It is clear that there is growing concern regarding the appropriate allocation of the proceeds from (MBMs). (Liu et al., 2024; Vakili et al., 2023; Y. Wang et al., 2025; Zincir, 2025), discuss how the literature provides compelling justification for the proceeds (for example, from a carbon tax) to be retained within the maritime industry and directed towards the financing and establishment of the production of zero-emission fuels, as opposed to the unrestricted disposal of the funds into a country's general revenue account. For a variety of reasons (Carral et al., 2020; Chen et al., 2024; Ng et al., 2022), this approach is essential for ensuring that the industry is able to innovate, reduce the economic impacts on poorer countries, and increase the speed at which technologies necessary for the transition can be made available.

In combination with legislative actions, financial institutions influence the course of maritime decarbonization, especially through their lending and investing activities, the most recent of which are the Poseidon Principles. These Principles are the first voluntary framework adopted by leading banks in the shipping industry to align their maritime finance portfolios with the decarbonization objectives of the International Maritime Organization. By stipulating that borrowers must have, at a minimum, certain vessel-level emissions-performance and climate alignment scores, the Poseidon Principles introduce a positive financial risk that works in conjunction with other regulations and market mechanisms. This serves to motivate shipowners to consider emissions performance in their decisions with respect to renewing and operating their fleets; in addition, it improves the transparency and accountability of maritime finance. Thus, the Poseidon Principles demonstrate how financial governance in the private sector, in combination with regulations, can stimulate the faster realization of low-carbon pathways in shipping. In this sense, the Poseidon Principles reinforce the policy recommendations presented in Section 4.2 by aligning financial decision-making with regulatory decarbonization objectives (Poseidon Principles, 2023).

As per Section 2.2, this section examines the guided systematic synthesis of all 56 articles. As per the most recent findings received from (IMO, 2023; Laskar et al., 2025), the global shipping industry is now optimized towards achieving net-zero GHG emission by 2050, which further solidifies the academic output towards the 3 key, and inter-related, themes of operational efficiency, technical fuel pathway, and regulation (W. Wang et al., 2025) For the purpose of systematic synthesis, this section examines the findings that were organized regarding the data extraction themed tags per Section 2.3 and provide a summary of the concentration of evidence and the remaining evidence areas that were systematic and objective. The analysis first examines the concentration of evidence per thematic distribution (3.1) and proceeds towards the findings

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on the most dominant approaches towards decarbonization for the remaining evidence areas. Throughout the research, the analysis and findings for operational efficiency, technical fuel pathway, and regulation are based on cycle time, either the short (more operational) or the long (more structural), to determine the decarbonization closure, whether shallow or deep. For IMO's 2050 net-zero goal, the closure to be achieved here would be based on the operational measures and those with deep decarbonization, for the remaining based on the long cycle time. This will enhance the removal of the temporal ambiguity affecting compliance and cost optimization.

The following analysis is oriented towards understanding not only which policies are effective, but rather when and under what circumstances these policies lead to the greatest change.

3.2. Overview of thematic distribution

The thematic coding process revealed an uneven distribution of research focus across the three primary branches of maritime decarbonization studies. Table 2, thematic distribution and frequency of decarbonization research focus (56 Included Studies). This table presents the main thematic tags inductively attached to the 56 articles included in the final synthesis. The number indicates how many studies had the particular tag as a primary research focus. The fields of interest are subdivided into Operational, Technical, or Regulatory. Given that papers cover many themes, the total number of tags exceeds the number of studies included.

Table 2: Thematic distribution and frequency of decarbonization research focus (Based on 56 included studies)

Rank	Thematic Tag	Count of Studies	Focus Area
1	Digitalization / AI / Machine Learning (ML)	55	Operational
2	Ports & shore power	44	Operational
3	Alternative fuels (general)	41	Technical
4	Policy/IMO/CII/EEXI	31	Regulatory
5	Hydrogen	10	Technical (Specific Fuel)
6	LNG	9	Technical (Specific Fuel)
7	Operational measures	9	Operational
8	Lifecycle assessment (LCA)	8	Technical/Method

There is significant interest in the area of Operational Strategies (Digitalization and Ports), which has the most publications, in stark contrast to the relative interest in the technical fuel pathways (Bolat, 2026; Wang et al., 2025). Digitalization is present in most of the studies reviewed, albeit usually as an enabling or crosscutting theme and not as the main focus of analysis, which accounts for the high incidence.

3.3. Synthesis of operational strategies

The research gap confirms that the scholarly community has operational strategies as the most popular research topic driven by Digitalization (55 papers) and Ports (44 papers). This rush is a testament that the industry is desperate for solutions that have minimal capital investments but are significantly impactful given the immediate requirements posed by the CII and EEXI (Robalo-Cabrera et al., 2025).

3.3.1. Ship-level optimization and digitalization

Vessel-level optimization clearly supports the claim that digital and AI technologies are the most efficient and effective means of improving energy efficiency (EE) across the fleet (Kondratenko et al., 2025; Xiao et al., 2025; Zeng et al., 2025). This research supports the United Nations sustainable development goals SDG 7 (Affordable and clean energy. The analysis identifies three strategies used to manage the immediate emissions reduction:

- **Passage plan optimization and slow steaming:** Rapid speed reductions (slow steaming) have been quantitatively proven as the most effective short-term operational measure that can be implemented at the fleet level and have an immediate impact on GHG emissions reduction (Dong et al., 2025;

Soltani Motlagh et al., 2023). In this measure, the ships are also provided with advanced weather routing and tracking systems to optimize the fuel and emissions efficiency across the weather and sea state, as the systems are adapted to the fuel-efficient and optimum cruise speeds (Dong et al., 2025; Soltani Motlagh et al., 2023; W. Wang et al., 2025). Other digital models have also been used to optimize the operational variables of trim and ballast for the complete hull-form resistance (Carral et al., 2020).

- **Predictive performance monitoring:** The contributions of the synthesized literature on Predictive Performance Monitoring, focusing on Machine Learning (ML) and Artificial Intelligence (AI), are designed to achieve real-time prediction and optimization of vessel operational performance and fuel consumption (Chen et al., 2024). The models provide operational emissions prediction with sufficient accuracy needed to compute and implement changes for real-time operational compliance in the EEXI and the CII regulatory compliance.

- **Efficiency without propulsion & retrofitting:** In addition to primary propulsion, there is also a focus in literature on optimizing the energy use through the incorporation of upgraded Waste Heat Recovery (WHR) systems and the improved power control of ancillary devices (Dong et al., 2025; Vakili et al., 2025). Moreover, there is further corroboration on the potential of Wind-Assisted Propulsion (WAP) technologies as a first-tier retrofitting solution for current vessels (Kondratenko et al., 2025; Li & Tang, 2024).

Altogether, the literature posits operational optimization, especially speed control enabled by digital instruments, as the most effective temporary mitigation measure for the current fleet, and simultaneously outlines the measure's drawback as solely efficiency-focused, rather than aiming for a total zero-emissions solution.

3.3.2. Port call optimization and the land-sea interface

The extent of research on decarbonization of maritime transport clearly demonstrates recognition of the challenge posed by the incorporation of maritime operations into global supply chains (Çağlayan & Aymelek, 2024; Elkafas & Seddiek, 2024; Fadiga et al., 2024; Parvasi et al., 2025). The port is the critical point of integration where ship operational tactics interface with onshore energy and logistics systems, and is therefore the focus of complex optimization problems that span the land and sea legs of the extended supply chain (Elhussieny, 2025; Liu et al., 2024; Qi et al., 2025). The literature reviewed suggests that the port is more than a point of cargo transfer; it is the primary node of a system that achieves substantial efficiency gains through Just-In-Time (JIT) planning and a complete shift to zero-emission operational technologies, supplemented by Shore Power and future port bunkering. Therefore, the focus on the land-sea interface is motivated by the need to streamline the movement of ships, energy, and data to achieve a reduction of emissions at berth and during the approach phase, and hence result in an overall reduction of the carbon footprint of the voyage.

- **Just-In-Time (JIT) Arrival:** JIT Arrival strategies (W. Wang et al., 2025), as the predominant research stream at the port interface, focus on the optimization of the ship-queuing process. Researchers show through various sophisticated optimization techniques that the JIT method is a feasible improvement over the extremely inefficient First Come, First Served (FCFS) method as a result of a tremendous reduction in anchorages waiting time and their emissions (Dong et al., 2025; Parvasi et al., 2025). Case studies show operational compliance in terms of attaining a reduction of 32.8% to 45% of CO2 emissions during the approach and waiting intervals, which confirms JIT to be instantly operationalized (Sun et al., 2026).

- **Shore power supply (HVSC) and decarbonizing berthing:** The use of High Voltage Shore Connection (HVSC) "cold ironing" is confirmed to be a crucial component to attain zero-emission berthing (Elkafas & Seddiek, 2024; Fadiga et al., 2024; Liu et al., 2024). However, techno-economic studies emphasize that the environmental benefit must be based on the port electricity supply being genuinely renewable, thus avoiding the full cycle of Tank-to-Wake (TTW) emissions being landed on a fossil fuel source, as this is critical.

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3.4. Technical pathways and fuel adoption: The systemic transition challenge

This section presents conclusions on the basis of a systematic, structured comparison of the studies on alternative marine fuels in the final evidence base. The authors of the reviewed studies were asked to clarify their position on a number of recurring analytical dimensions, including energy density, storage and handling requirements, safety, technological maturity, compatibility with existing infrastructure, and lifecycle greenhouse gas emissions (Ezeh et al., 2024; Kondratenko et al., 2025; W. Wang et al., 2025). The authors demonstrated how the dimensions influenced the type of vessel, the operational profile, and the trade route, which allowed the authors to identify the areas of convergence and divergence in the reviewed literature (Robalo-Cabrera et al., 2025; Sarbanha et al., 2023). This type of analysis justifies the widely reported conclusion in recent reviews that there is, and likely will be, no single alternative fuel pathway that can be applied to the entire global shipping fleet.

No single alternative fuel pathway can be seen as a structural transition, rather than a transitional change, to be able to fully replace conventional marine fuels for all vessel types, trading routes, and operational patterns. The other key area of focus is the zero-emission shipping fuels-related transition to alternative fuels and the needed infrastructure, which is considered to be the most long-term and expensive component of decarbonization of shipping (Bolat, 2026; W. Wang et al., 2025; Wei et al., 2026). This area of research comprises 41 works about Alternative Fuels (General) and another 19 about specific zero- and low-carbon carriers. The category of “Alternative Fuels (General)” encompasses those works that likely belong to the general systems perspective of alternative maritime fuels as opposed to a fuel systems approach or a fuel-technology approach focusing on a single fuel. These works analyze several of the leading candidate marine fuels (see Ammonia, Methanol, hydrogen, biofuels, synthetic fuels (e-fuels), liquefied natural gas (LNG)) and seek to identify, understand, and explain, to what extent the various fuels have advantages, disadvantages, and tradeoffs associated with each fuel within different types of vessels, operational profiles, and transition time frames. Hence, the body of literature has cross-cutting considerations on energy density, storage, handling, safety, infrastructure, and other constraints, along with scalability, cost, and life cycle greenhouse gas emissions, thereby justifying a strategic assessment to optimize fuel selection rather than a fuel-centric approach.

The large number of works produced in this field reflects the industry’s recognition that operational efficiencies alone will not drive the transition needed to meet net-zero targets by 2050. The research responds to the growing body of review work on the high level of technical and rival competitiveness in the diverse fuel offerings (Ammonia, Methanol, hydrogen) and the unavoidable compromises in energy content, safety, and the essential clarity required in determining an accurate lifecycle environmental impact (Ezeh et al., 2024; Ismail et al., 2025; Kondratenko et al., 2025; Sarbanha et al., 2023; Zincir, 2025).

3.4.1. Technical viability of alternative fuels

The literature analysis supports the premise that the future mix of fuels will be complex and heterogeneous, with no ‘silver bullet’ alternative to Heavy Fuel Oil (HFO) being capable of supplanting all the HFO uses across the global fleet (Ezeh et al., 2024; Kondratenko et al., 2025; W. Wang et al., 2025). This is an inevitable consequence of a technical requirement. Different types of vessels have different priorities and tradeoffs. For example, large, long-distance container vessels have a necessity for high energy density (fuels that are Ammonia or Methanol), whereas short-sea ferries and coastal vessels have a lower energy density (batteries or hydrogen) as they have shorter cycles for refueling (Sarbanha et al., 2023; Soltani Motlagh et al., 2023). The technical tradeoffs around fuel storage volume and the safety measures required, the engine retrofitting, and the complexity of safety measures required fuel the need for a complex multi-fuel system to be developed and diversifies the system of tradeoffs to be developed in a segmented transition pathway (Bolat, 2026; Çağlayan & Aymelek, 2024; Li & Tang, 2024).

Among the papers regarding hydrogen (10) and its derivative, Ammonia (7), the most popular debate is the specific storage, handling, and safety intricacies related to high risk (Chen et al., 2024; Kondratenko et al., 2025; Sarbanha et al., 2023; Soltani Motlagh et al., 2023; W. Wang et al., 2025). The studies emphasize that the required cryogenic (-253 C) storage for liquid hydrogen is challenging as it has relatively low volumetric energy density and thus, involves a complex redesign and a reduction of storage capacity (Li & Tang, 2024). While Ammonia has relatively high storage density, its toxicity and high corrosion rate (the required inhibition, as well as extensive crew training, serve as a ventilation system's barrier) are noted as some of the most significant obstacles for deploying Ammonia at scale(Bolat, 2026; Kondratenko et al., 2025). Because hydrogen storage poses significant technical challenges, Ammonia is validated repeatedly as a promising long-term carrier for especially deep-sea routes.

One of those areas is research on Methanol (6 papers) and Biofuels/e-fuels. Among them, Methanol is relatively more mature and possesses lower barriers to adoption. Methanol has been studied more on account of supply chain maturity, lower risks of combustion, and more versatile and straightforward engine retrofitting, as opposed to the more complicated hydrogen and ammonia storage cryo- or pressurized (Ezeh et al., 2024; Li & Tang, 2024; W. Wang et al., 2025). However, the literature on sustainable Biofuels and synthetic fuels (e-fuels) virtually unanimously expresses concerns with the feedstock sustainability and global scalability (Soltani Motlagh et al., 2023; W. Wang et al., 2025). Analyses show that the projected total global supply of sustainable biomass feedstock is likely to be insufficient to meet the demands needed to decarbonize the entire global fleet, and there will be resource competition with other sectors, especially aviation and road transport (Ezeh et al., 2024; Robalo-Cabrera et al., 2025).

On the other hand, the research on Liquefied Natural Gas (LNG) (9 papers) has been mainly focused on the role that LNG plays as a necessary transition fuel. Although LNG allows for a considerable drop in local air contaminants such as SOx, NOx, and particulate matter, multiple techno-economic and environmental assessments have raised serious questions about its expected function in attaining net-zero objectives on account of its capacity for methane slip (methane in its unburnt for, a very harmful GHG) (Liu et al., 2024; W. Wang et al., 2025). Studies argue that the net climate impact of LNG, if any, is case-specific to the kind of engine technology in use (e.g., high-pressure versus low-pressure injection) and, most importantly, is negative when the fuel is obtained from systems that have no oversight of upstream methane leakage (Fadiga et al., 2024).

3.4.2. Environmental accounting: The Well-to-Wake (WTW) imperative

Across all 41 fuel papers and particularly 8 Lifecycle Assessment (LCA) focused papers, the predominant and overarching finding/service is the scientific necessity and soon-to-be universal acceptance of the Well-to-Wake (WTW) accounting methodology (Chen et al., 2024; W. Wang et al., 2025; Y. Wang et al., 2025). WTW methodology is the primary, and possibly the most important, analytical output of technical research, as it serves as the most authoritative scientific bulwark against which the long-term climate viability of a fuel can be assessed (Fadiga et al., 2024). In the absence of WTW, the risks associated with the substitution of emissions, termed "emissions leakage" in the literature, are left unchecked (Kondratenko et al., 2025; Li & Tang, 2024; Sun et al., 2026).

Numerous primary documents in the LCA literature indicate that the (TTW) approach, which focuses solely on the emissions released from the ship's fuel nozzle, is the current and historically prevailing regulatory standard. Regulatory standards that allow only TTW calculations are TTW vs. WTW the biggest policy fault line in the literature, as they incentivize the use of 'clean' ship-level fuels that have carbon-intensive production, processing, or transport (Ezeh et al., 2024; Vakili et al., 2023; W. Wang et al., 2025). Research indicates that the TTW approach to regulation 'locks' the industry into suboptimal solutions and that it is critical to move to a full lifecycle approach to regulation in order to satisfy the IMO's net-zero goals.

The requirement can be fulfilled by thoroughly conducting Emissions Transfers as well as Full Scope analysis. WTW accounting requires Well-to-Tank (WTT) emissions of all greenhouse gases emitted while the fuel is being extracted, refined, and transported (Fadiga et al., 2024; Wang et al., 2025). Literature has shown that a fuel such as fossil (LNG) that is TTW compliant can have a total WTW footprint equal to, or worse than, a conventional HFO if upstream methane leakage and production energy sources are poorly mitigated (Liu et al., 2024; Sarbanha et al., 2023; Sun et al., 2026). This evidence directly contradicts policy approaches that assume effective

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decarbonization can be achieved through fuel switching based solely on local TTW performance.

Across individual fuel pathways, the literature consistently shows that (TTW) accounting on its own is insufficient to guide long-term decarbonization, highlighting the need for comprehensive (WTW) assessment frameworks.

Table 3 summarizes the well-to-wake environmental outcomes for alternative marine fuel pathways as reported in the reviewed literature.

Table 3: Summary of well-to-wake (WTW) environmental outcomes reported in the reviewed literature for alternative marine fuel pathways

Fuel pathway	Reported WTW emissions performance	Key environmental considerations highlighted	Main insights from the reviewed studies	Representative studies
Hydrogen	Reported WTW emissions vary significantly depending on the production pathway	High upstream energy demand and dependence on electricity carbon intensity	Studies emphasize that the environmental performance of hydrogen is strongly contingent on lowcarbon or renewable production pathways	Sarbanha et al., 2023; Wang et al., 2025
Ammonia	Potential for low WTW emissions when produced from green hydrogen	Energyintensive production processes and safetyrelated considerations	The literature frequently identifies Ammonia as a viable longterm option under WTW accounting, subject to production pathway and safety constraints	Kondratenko et al., 2025; Ezeh et al., 2024
Methanol	WTW emissions outcomes depend on feedstock and production route	Risks of limited lifecycle benefits when derived from fossil sources	Reviewed studies highlight that Methanol offers meaningful WTW reductions primarily when produced from renewable or lowcarbon feedstocks	Ismail et al., 2025; Wang et al., 2025
Biofuels	WTW emissions show high variability across fuel types and feedstocks	Feedstock sustainability and scalability limitations	The literature suggests that biofuels may provide shortterm mitigation potential, although longterm scalability remains uncertain	Ezeh et al., 2024; Sarbanha et al., 2023
(LNG)	WTW emissions reductions are often lower than expected	Methane slip during combustion and upstream leakage	Multiple studies indicate that methane emissions can offset TTW benefits, raising concerns regarding LNG's longterm role under WTW frameworks	Liu et al., 2024; Wang et al., 2025

4. Conclusion and Future research

This segment aims to provide a summary of the research findings and articulate the primary findings to regulators, industry stakeholders, and infrastructure developers. Provided findings are summary findings, not restatements of the studies, but drawn from the consolidated evidence in Section 3, placing the findings in the context of the wider implications of the IMO decarbonization framework. This particular part of the research outlines the major gaps in the existing research and identifies the urgent need for further research.

4.1. Overarching conclusion and review of Findings

In the context of maritime shipping, decarbonization refers not only to the reduction of greenhouse gas emissions from vessel operations but also to a systemic transition involving changes in energy carriers, operational practices, infrastructure, regulatory frameworks, and investment decision-making across the maritime sector.

The purpose of the analysis was to understand academic writings published in recent years relating to the framework of the decarbonization of shipping industries and the operational decisions on the industries to achieve the target of the International Maritime Organization to attain net-zero GHG emissions by the year 2050. The operational efficiency studies found that it is possible to improve and achieve cost-effective emission reductions at a faster pace with the prevailing fleet in the shipping industry. However, operational efficiency improvements will be key to achieving deep long-term decarbonization of the shipping industry.

The literature demonstrates that decarbonization of the shipping industry is the first in a series of systemic transition challenges to be addressed. The industry must move beyond a focus on incremental technological improvements. It is clear that speed and routing operational efficiencies found in the use of weather optimization and digital support systems for operational decision-making will help the industry achieve emission mitigation and operational compliance. However, with the use of zero and near-zero-carbon fuels, the industry will be able to remove the cap on emissions reduction and improve the decarbonization safety and support of global resources, which at present are lacking.

In conclusion, the review demonstrates that meeting the IMO's interim and long-term targets calls for 'commitment and combination'. This means that in the absence of any one of the three prerequisites, operational optimization, fuel transition pathways with binding regulations that consider the cost of carbon, meeting the targets will be unachievable. Within the operational context of the measures being examined, operational measures act as demand-reduction levers, fuel transition is the determined emissions ceiling, and the regulations control transformation at all levels of the system.

4.2. Definitive outcomes and practical recommendations

These changes have direct implications for both shipping companies and ports. Shipowners face strategic decisions regarding fleet renewal, retrofitting, fuel choice, and compliance costs, while ports are increasingly required to invest in energy infrastructure, shore power, digital coordination, and alternative fuel bunkering systems. As such, decarbonization affects not only vessel operations but the broader maritime logistics and port ecosystem. The findings detailed in section 3 of the review support the following recommendations for effective and plausible decarbonization of the maritime industry.

Recommendation 1: Mandatory adoption of Well-to-Wake accounting

WTW accounting must be the single metric that regulatory bodies, such as the IMO and regional authorities, must implement as a statutory requirement for carbon price and fuel standards compliance. This requirement is on par with the policy analyses and fuel lifecycle assessments synthesized in Section 3, which demonstrates that tank-to-wake accounting neglects and even misinterprets the climate impacts of alternative fuels. This could lead to perverse policy designs that encourage options with little or negative net emissions reductions, and even climate impact mitigation, on a system-wide level. WTW is the appropriate accounting methodology that confirms that the selection of fuels, investments, and operational strategies is directed to true, sustained, and long-term decarbonization, as opposed to mere superficial compliance.

Recommendation 2: Implementation of mandatory market-based measures

Mandatory market-based measures are needed, including government-coordinated carbon pricing, to offset the enduring cost difference between conventional marine fuels and zero-carbon fuels. Evidence suggests that carbon priced over USD 100 per tonne of CO_2-equivalent will potentially make fuel selections more affordable and accelerate the fleet transition. Such measures should aim to reduce market inefficiencies and are complemented by transparent revenue retention mechanisms that aid in developmental research. Furthermore, the tradeoff impacts on the most vulnerable transport sectors are integrated into infrastructure development. The lack of imposition of market-based measures on the shipping industry will make the voluntary uptake of low-carbon fuels impractical. This will jeopardize the IMO's decarbonization framework.

Policy interventions can accelerate the effectiveness of marketbased measures by providinglongtermregulatorycertainty,harmonized international enforcement, and targeted recycling of revenues toward zeroemission fuel production and supporting infrastructure. In particular, predictable and internationally coordinated carbon pricing signals can reduce investment risk and facilitate earlier adoption of alternative fuels by shipping companies. Coordination between global and regional policy instruments is also critical to avoid market fragmentation and carbon leakage.

Recommendation 3: Strategic investment in fuel and port infrastructure

It is recommended that the government and authorities at the ports consider triaging and target their near-term liquid fuel infrastructure investments (2025-2035) towards the creation and implementation of scalable, bunkering and fuel supply, and zero-emission (Ammonia and methanol) fuel supply infrastructure, as well as shore-side electricity infrastructure at key global maritime centers. This recommendation is based on the synthesized evidence that infrastructure is critical and that investments in infrastructure that have already been delayed are likely to 'trap' the sector in intermediate investments of low potential viable transitional infrastructure. Ports, energy suppliers, and shipping companies should focus on adapting their respective infrastructures to the technological renewal of the fleets and the new policies to be signed and implemented.

Given the situation at the ports, the potential to construct bunkering infrastructure for alternative fuels is an important consideration for the adoption of fully and near-zero-carbon fuels. The first major, scalable investments in bunkering for ammonia and methanol fuels at hub and gateway ports will reduce the uncertainty in decision-making for shipowners and therefore support coordinated fleet transition. With this in mind, strategic planning and collaboration among ports, energy providers, and regulators are of utmost importance to prevent stranded assets, promote effective regional interoperability, and ensure safe and efficient alternatives to traditional marine fuels.

4.3. Limitations and avenues for future research

The peer-reviewed literature constrains this review of existing literature, the diversity of methods in existing literature, and the fast pace of change in technologies and regulations in the field of maritime decarbonization.

This review has been conducted meticulously, yet several gaps in the existing literature, which have been reviewed, have had a significant impact and are important for future research. This includes the clear absence of well-to-wake data that is standardized and transparent, and relevant to emerging fuel pathways, particularly upstream electricity sourcing and fuel production pathways, as well as across different regions. The most crucial gap to be closed is for comprehensive analysis, regulation evaluation, and the most efficient and effective regulation.

Prioritized areas of study include the systemic interrelationships of fuel, infrastructure, and regulation systems at a fleet and trade-route level, and not at an individual vessel level, as well as the safety, operational, and human factors of the use of Ammonia and other alternative fuels, which require more profound interdisciplinary studies.

Additionally, the effect of the interactions between the Global Market-based Instruments and the regional regulations, their interplay, and the resulting impact on competitiveness, modal shift, and trade, requires additional research focus and is fundamental to achieving the right level of regulation, investment, and safety to support the decarbonization of the maritime sector.

A more systems-based approach to the shipping industry and the broader maritime cluster as interdependent networks of ships, ports, energy, regulation, and finance is warranted. There is a need to focus more on fleet-level pathway transitions, the concurrent development of ports and other infrastructure, alternative fuel supply chains, the interrelations, and co-impacts between global and regional policy instruments. Finally, real-world longitudinal studies of outcomes, investment, and operational performance are necessary to provide the empirical evidence to reduce the unknowns related to the maritime decarbonization transition.

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