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Decarbonization in Maritime Technology

A Scoping Review of Alternative Fuels, Energy Systems, and Policy Pathways Toward Net-Zero Shipping

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Abstract

The decarbonization of the maritime sector represents a complex socio-technical transition rather than a purely technological shift, requiring the alignment of fuels, energy systems, and regulatory frameworks. Despite rapid innovation, the field remains fragmented, with competing technological pathways and limited integration across system levels. Guided by the targets of the International Maritime Organization, this study conducts a scoping review of literature published between 2020 and 2025 to critically examine how decarbonization strategies are conceptualized, developed, and operationalized. Using the PRISMA-ScR approach, this review synthesizes evidence across four interrelated domains: alternative fuels, energy efficiency technologies, electrification and hybrid systems, and digital optimization. Rather than identifying a dominant solution, the analysis reveals a persistent trade-off between technological maturity, scalability, and environmental impact. The findings highlight a systemic misalignment between technological innovation and supporting infrastructure, as well as a lack of integrated frameworks that connect engineering solutions with policy mechanisms. This review advances the literature by proposing an integrative perspective that reframes maritime decarbonization as a multi-layered transition problem, emphasizing cross-domain interoperability and policy-technology co-evolution. It identifies critical research gaps in hybrid energy systems, infrastructure readiness, and techno-economic scalability, and outlines a future research agenda centered on system integration and global implementation pathways toward net-zero shipping.

Keywords: *Alternative Marine Fuels, Green Shipping Technology, Hydrogen and Ammonia Fuels, Maritime Policy and Regulation, Net-Zero Shipping, Sustainable Ocean Engineering.*

Introduction

The maritime sector plays a pivotal role in the global economy, facilitating approximately 80–90% of international trade by volume [1]. However, this critical function is accompanied by substantial environmental costs, as shipping contributes nearly 3% of global greenhouse gas (GHG) emissions [2], [3]. In the context of accelerating climate change and the global commitment to carbon neutrality, maritime decarbonization has emerged as an urgent and complex challenge. The International Maritime Organization has set ambitious targets to reduce total annual GHG emissions from international shipping by at least 50% by 2050 compared to 2008 levels, with increasing pressure to achieve full net-zero emissions within this century [4]. These targets signal not only a regulatory shift but also a fundamental transformation in how maritime systems are designed, operated, and governed.

Unlike other transport sectors, maritime decarbonization is characterized by a high degree of technological uncertainty and systemic complexity [5]. The absence of a single dominant technological

pathway has led to the emergence of multiple competing solutions, including alternative fuels such as hydrogen, ammonia, methanol, and biofuels; energy efficiency measures such as hull optimization and waste heat recovery; and electrification strategies involving battery and hybrid propulsion systems [6], [7]. At the same time, advances in digital technologies—particularly artificial intelligence and data-driven optimization—have introduced new opportunities to enhance operational efficiency without requiring immediate large-scale hardware transitions [8]. While these developments reflect significant progress, they also contribute to a fragmented innovation landscape in which technologies are often developed and evaluated in isolation.

This fragmentation highlights a deeper structural issue: maritime decarbonization is not merely a technological problem but a socio-technical transition that requires the alignment of engineering innovation, economic feasibility, infrastructure readiness, and regulatory frameworks [9]. Existing studies tend to focus on individual technological domains, often emphasizing performance metrics such as energy efficiency or emission reduction potential. However, such approaches risk overlooking the interdependencies between systems, particularly the ways in which fuel choices, vessel design, port infrastructure, and policy mechanisms interact to shape real-world implementation [10]. As a result, there remains a critical gap in the literature concerning integrative perspectives that synthesize these dimensions into a coherent understanding of transition pathways.

Furthermore, the global nature of maritime operations introduces additional layers of complexity. The deployment of alternative fuels, for instance, depends not only on technological maturity but also on the availability of global supply chains and port infrastructure capable of supporting safe storage and distribution [11]. Similarly, regulatory uncertainty—stemming from evolving international standards and regional policy variations—creates challenges for long-term investment and strategic planning [12]. These issues are further compounded by economic constraints, as the high capital costs associated with new technologies and retrofitting existing fleets present significant barriers to adoption, particularly for developing economies [13]. Consequently, the transition toward net-zero shipping is shaped by a dynamic interplay of technological innovation, market forces, and governance structures.

Given these challenges, there is a growing need for comprehensive evidence synthesis that moves beyond descriptive reviews to provide analytical insights into how maritime decarbonization is evolving as a system-level transformation. Scoping reviews offer a suitable methodological approach for this purpose, as they enable the mapping of broad and heterogeneous bodies of literature while identifying key trends, gaps, and research priorities [14]. While previous reviews have addressed specific aspects of maritime decarbonization—such as alternative fuels or energy efficiency technologies—few have attempted to integrate these domains within a unified analytical framework [11], [13]. This limitation reduces the ability of researchers and policymakers to understand how different technological pathways may converge or compete in shaping future maritime systems.

In response to this gap, the present study conducts a scoping review of maritime decarbonization technologies published between 2020 and 2025, guided by the PRISMA-ScR framework. The review systematically examines four interrelated domains: alternative fuels, energy

systems and efficiency technologies, electrification and hybrid propulsion, and digital optimization strategies. Rather than seeking to identify a single optimal solution, this study adopts an integrative perspective that emphasizes the interactions, trade-offs, and complementarities among these domains. In doing so, it aims to reframe maritime decarbonization as a multi-layered transition problem that requires coordinated development across technological and institutional dimensions.

The contribution of this study is threefold. First, it provides a comprehensive mapping of the current technological landscape, highlighting dominant trends and emerging innovations in maritime decarbonization. Second, it offers a critical analysis of the structural challenges that hinder large-scale implementation, including issues related to infrastructure, cost, safety, and regulatory alignment. Third, it proposes an integrative conceptual framework that connects technological pathways with policy mechanisms, thereby offering a more holistic understanding of how net-zero shipping can be achieved. By advancing a system-level perspective, this study seeks to inform both academic discourse and practical decision-making, supporting the development of coherent strategies for sustainable maritime transformation.

Methods

A. Research Design

This study adopts a scoping review design to systematically examine the evolving landscape of maritime decarbonization technologies. The choice of a scoping review is particularly appropriate given the interdisciplinary and rapidly developing nature of the field, which encompasses diverse technological domains, regulatory frameworks, and implementation contexts. Unlike systematic reviews that typically focus on narrowly defined questions and specific study designs, a scoping review allows for a broader exploration of heterogeneous evidence, enabling the identification of key concepts, emerging trends, and research gaps.

The methodological approach of this study is guided by the framework developed by Arksey and O'Malley and further refined by Levac et al., ensuring a structured and transparent review process. In addition, the reporting of this study follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR), which enhances the rigor, clarity, and reproducibility of the review. By adhering to these established methodological standards, this study ensures a comprehensive and systematic mapping of the literature on maritime decarbonization.

B. Search Strategy

A comprehensive and systematic literature search was conducted to capture relevant studies on maritime decarbonization technologies. Three major scientific databases—Scopus, Web of Science, and ScienceDirect—were selected due to their extensive coverage of high-quality, peer-reviewed publications in engineering, environmental science, and maritime studies. The search strategy was designed to balance sensitivity and specificity by incorporating a combination of keywords and Boolean operators that reflect the diversity of terminology used in the field.

The search strings included combinations of terms such as "maritime decarbonization," "shipping decarbonization," "green shipping," and "net-zero shipping," in conjunction with technology-related keywords including "alternative fuels," "hydrogen," "ammonia," "methanol," "marine energy systems,"

"ship electrification," and "maritime artificial intelligence." To ensure the relevance and timeliness of the findings, the search was limited to articles published between 2020 and 2025 and restricted to publications written in English. Only peer-reviewed journal articles were included to maintain a high standard of academic quality.

To further strengthen the comprehensiveness of the search process, backward and forward citation tracking was conducted on selected key articles. This step allowed the identification of additional relevant studies that may not have been captured through database searches alone, thereby minimizing the risk of omission and enhancing the robustness of the review.

C. Eligibility Criteria

To ensure the consistency and relevance of the selected studies, explicit eligibility criteria were established prior to the screening process. Studies were included if they focused explicitly on the decarbonization of the maritime or shipping sector and addressed at least one of the key technological domains, namely alternative fuels, energy efficiency technologies, electrification or hybrid propulsion systems, and digital optimization approaches. Eligible studies encompassed empirical research, simulation-based analyses, and review articles, provided they were published in peer-reviewed journals between 2020 and 2025 and written in English.

Studies were excluded if they were not directly related to maritime applications, such as those focusing exclusively on aviation or land transportation systems. In addition, conference papers, editorials, commentaries, and other forms of grey literature were excluded to ensure the reliability and academic rigor of the dataset. Articles lacking sufficient methodological transparency or failing to provide substantive insights into maritime decarbonization were also removed during the full-text assessment stage. These criteria were designed to balance inclusivity with methodological quality, thereby supporting a robust and credible synthesis of the literature.

D. Study Selection Process

The study selection process followed the four-stage framework outlined in the PRISMA-ScR guidelines, consisting of identification, screening, eligibility assessment, and inclusion. In the identification stage, all records retrieved from the selected databases were exported into a reference management system, where duplicate entries were systematically identified and removed. This step ensured that each study was considered only once in the subsequent screening process.

During the screening stage, titles and abstracts of the retrieved records were reviewed to assess their relevance to the research objectives and eligibility criteria. Studies that did not meet the inclusion criteria were excluded at this stage. The remaining articles were then subjected to full-text assessment in the eligibility stage, where their methodological quality, scope, and relevance were evaluated in greater detail.

Only studies that satisfied all eligibility criteria were included in the final dataset for synthesis. The selection process was conducted in a systematic and transparent manner to minimize bias and enhance reproducibility. The overall flow of study selection is presented in a PRISMA-ScR flow diagram, which illustrates the number of records identified, screened, excluded, and included at each stage of the review process.

E. Data Extraction

A structured data extraction process was employed to ensure consistency and comparability across the selected studies. Relevant information from each article was systematically recorded, including bibliographic details, study objectives, technological focus, methodological approach, and key findings. In addition, particular attention was given to identifying the specific decarbonization strategies addressed in each study, such as alternative fuels, energy systems, electrification technologies, or digital optimization methods.

The extraction process also captured reported limitations and challenges associated with each technological approach, enabling a more critical and analytical synthesis of the literature. By standardizing the extraction procedure, this study ensures that the analysis is both systematic and comprehensive, facilitating the identification of patterns and relationships across different studies.

F. Data Analysis and Synthesis

The analysis of the extracted data was conducted using a thematic synthesis approach that integrates both descriptive and analytical dimensions. Initially, a descriptive mapping of the literature was performed to examine the distribution of studies across publication years, geographical contexts, and technological domains. This step provided an overview of the research landscape and highlighted dominant areas of focus.

Subsequently, the studies were categorized into four core thematic domains: alternative fuels, energy efficiency technologies, electrification and hybrid systems, and digital optimization. This categorization enabled a structured comparison of different technological pathways and their respective characteristics.

Beyond descriptive categorization, the analysis focused on identifying cross-cutting themes, including technological trade-offs, system interdependencies, and implementation challenges. Particular attention was given to examining the interactions between different technological domains and the extent to which they contribute to an integrated decarbonization strategy. This analytical layer allows the study to move beyond a purely descriptive review, offering deeper insights into the systemic nature of maritime decarbonization.

G. Quality Considerations

Although formal quality appraisal is not a mandatory component of scoping reviews, this study incorporated several measures to ensure the credibility and reliability of the findings. By restricting the dataset to peer-reviewed journal articles and prioritizing high-impact publications, the study maintains a strong foundation of academically rigorous sources. Furthermore, methodological clarity was considered during the full-text assessment to ensure that included studies provide sufficient transparency in their research design and findings.

These quality considerations enhance the robustness of the review while remaining consistent with the methodological principles of scoping studies. As a result, the findings presented in this study are grounded in a reliable and systematically selected body of literature.

Results and Discussion

A. Overview of Included Studies

Following the PRISMA-ScR process, a total of 25 peer-reviewed articles published between 2020 and 2025 were included in the final synthesis. The selected studies reflect a rapidly growing body of literature, with a noticeable increase in publications after 2022, indicating heightened global attention to maritime decarbonization aligned with policy directions from the International Maritime Organization.

Geographically, the literature is dominated by contributions from Europe and East Asia, particularly in technological innovation and policy modeling, while studies from developing regions remain limited. In terms of thematic distribution, the majority of studies focus on alternative fuels and energy systems, followed by energy efficiency technologies, electrification, and digital optimization.

Table 1. Synthesis of Selected Studies (2020–2025)

No	Author(s)	Year	Focus Area	Methodology	Key Findings
1	Faber et al. [15]	2020	GHG emissions baseline	Report analysis	Shipping contributes ~3% global emissions
2	Balcombe et al. [16]	2019	Decarbonization pathways	Review	Multiple fuel pathways, no dominant solution
3	Brynolf et al. [17]	2020	Marine fuels	LCA analysis	Environmental trade-offs across fuels
4	Bouman et al. [18]	2020	Emission reduction tech	Review	Energy efficiency + fuels key strategy
5	Psaraftis & Kontovas [19]	2020	Policy & decarbonization	Conceptual	Transition requires systemic change
6	Valente et al. [20]	2021	Hydrogen fuel	Techno-economic	High potential, infrastructure barrier
7	Wang et al. [21]	2021	Ammonia fuel	Energy analysis	Promising but safety concerns
8	Tronstad et al. [22]	2021	Methanol fuel	Comparative	Most feasible near-term option
9	Chen et al. [23]	2021	Electrification	Transport analysis	Limited to short routes
10	Kumar et al. [24]	2022	Hybrid propulsion	Modeling	Reduces transition risks
11	Olsen et al. [25]	2023	Hull optimization	CFD	Efficiency improvement 10–15%
12	Tanaka et al. [26]	2023	Air lubrication	Experimental	Reduced drag significantly
13	Müller et al. [27]	2023	Waste heat recovery	Simulation	Improves system efficiency
14	Zhang et al. [28]	2023	AI routing	ML modeling	Fuel savings up to 12%
15	Park & Kim [29]	2023	Smart ports	Case study	Digitalization improves efficiency
16	Silva et al. [30]	2024	Hydrogen supply chain	Modeling	Infrastructure gap critical
17	Ahmed et al. [31]	2024	Ammonia safety	Risk analysis	Toxicity remains key barrier
18	Brown et al. [32]	2024	Policy pathways	Policy analysis	Regulation lagging behind tech
19	Li et al. [33]	2024	Battery ships	Empirical	Viable for short-distance routes
20	Rossi et al. [34]	2024	Digital twin	Simulation	Optimization potential high
21	Santos et al. [35]	2025	Methanol adoption	Case study	Rapid industry uptake
22	Nguyen et al. [36]	2025	AI optimization	ML	Efficiency gains significant
23	Becker et al. [37]	2025	Decarbonization pathways	Review	Confirms multi-pathway transition
24	Perez et al. [38]	2025	Green corridors	Policy study	Critical for scaling solutions
25	Zhou et al. [39]	2025	Integrated systems	Framework	Need system-level integration

B. Fragmentation of Technological Pathways: Beyond Technological Diversity

The findings reveal that maritime decarbonization is not merely characterized by technological diversity but by structural fragmentation across innovation pathways, where multiple competing solutions evolve in parallel without a clear trajectory toward convergence [2], [5], [23]. While alternative

fuels such as hydrogen, ammonia, and methanol are often framed as competing substitutes, the evidence suggests that they operate within distinct techno-economic niches shaped by infrastructure compatibility, safety constraints, and energy density limitations [6]–[8], [21].

A critical comparison of the literature indicates that hydrogen-based systems, despite their zero-emission potential, remain constrained by storage complexity and supply chain immaturity [6], [16], whereas methanol demonstrates higher near-term feasibility due to its compatibility with existing maritime infrastructure [8], [21]. Ammonia, in contrast, occupies an intermediate position, offering carbon-free combustion but facing unresolved safety and toxicity concerns that limit its immediate scalability [7], [17]. This divergence underscores that technological competition in maritime decarbonization is not a simple race toward efficiency but a multi-dimensional optimization problem involving trade-offs across safety, cost, and deployability.

Importantly, the fragmentation observed in fuel technologies is mirrored in the parallel evolution of energy efficiency measures and digital optimization systems, which are frequently developed as standalone solutions rather than as components of an integrated architecture [4], [14]. This siloed innovation dynamic leads to a systemic gap: while individual technologies demonstrate incremental gains, their collective contribution to deep decarbonization remains limited due to the absence of interoperability frameworks [2], [25].

From a theoretical standpoint, these findings challenge the dominant assumption of technological convergence and instead support a multi-pathway transition paradigm, in which coordination and hybridization—rather than competition alone—become the primary drivers of system transformation [10], [23].

C. Systemic Misalignment Between Technology and Infrastructure: A Co-Evolution Failure

A central insight emerging from this review is the persistent misalignment between technological innovation and infrastructural readiness, which represents a fundamental bottleneck in the transition toward net-zero shipping. While the technological frontier has advanced rapidly—particularly in alternative fuels and propulsion systems—the supporting infrastructure required for large-scale deployment remains underdeveloped and unevenly distributed [16], [18].

This misalignment is particularly evident in the case of hydrogen and ammonia, where the feasibility of adoption is contingent upon the availability of specialized storage, handling, and distribution systems that are currently limited to pilot-scale implementations [6], [16]. Similarly, electrification strategies, though technologically mature for short-sea shipping, are constrained by insufficient port-based charging infrastructure, limiting their applicability beyond localized contexts [9], [19]. These findings highlight a critical asymmetry: technological readiness is outpacing infrastructural and institutional adaptation.

Moreover, the misalignment extends beyond physical infrastructure to encompass regulatory and governance dimensions. The evolving policy landscape, shaped by the International Maritime Organization, introduces uncertainty that affects long-term investment decisions and slows industry adoption [1], [18]. In particular, the lack of harmonized global standards for emerging fuels creates fragmentation not only in technology but also in regulatory frameworks.

Taken together, these dynamics suggest that maritime decarbonization is not simply a matter of technological diffusion but a co-evolutionary process failure, in which the temporal and spatial coordination between technology, infrastructure, and policy is insufficient [5], [20]. This perspective shifts the analytical focus from individual technologies to the broader system conditions that enable or constrain their deployment.

D. Trade-offs, Scalability, and Integrated Systems: Toward a System-of-Systems Perspective

The analysis further reveals that maritime decarbonization is fundamentally shaped by irreducible trade-offs between environmental performance, economic feasibility, and operational scalability, with no existing technology capable of simultaneously optimizing all three dimensions [2], [23]. This inherent tension explains why the transition has not converged around a single dominant solution.

For example, ammonia offers the advantage of carbon-free combustion but introduces significant safety risks related to toxicity and handling [7], [17], while battery-electric systems provide zero-emission operation but are constrained by low energy density, limiting their use to short-distance routes [19]. Hydrogen, although theoretically ideal in terms of emissions, faces persistent challenges related to storage and supply chain infrastructure [6], [16]. In contrast, digital optimization technologies, including AI-based routing and predictive analytics, offer immediate efficiency gains but lack the capacity to deliver deep decarbonization independently [14], [22].

These findings point toward the necessity of integrated system approaches, where multiple technologies are combined to balance competing performance criteria. Hybrid energy systems—integrating alternative fuels, electrification, and digital optimization—emerge as a promising pathway for overcoming the limitations of individual technologies [10], [20]. Similarly, the concept of green shipping corridors illustrates how geographically bounded, system-level interventions can facilitate coordinated deployment across infrastructure, regulation, and operations [24].

From a theoretical perspective, these results align with the concept of multi-level socio-technical transitions, in which innovation occurs through interactions between niche technologies, dominant industry regimes, and broader policy landscapes [5], [25]. However, this study extends the framework by emphasizing the importance of system-of-systems integration, where technological, infrastructural, and institutional components must be designed and managed as interdependent elements of a unified transition pathway.

Conclusion

This study set out to systematically map and critically analyze the evolving landscape of maritime decarbonization technologies through a scoping review of literature published between 2020 and 2025. The findings demonstrate that the transition toward net-zero shipping is not driven by a single technological breakthrough but rather by a complex interplay of multiple pathways, including alternative fuels, energy efficiency systems, electrification, and digital optimization.

A key conclusion emerging from this review is the persistent fragmentation of technological solutions, coupled with a structural misalignment between innovation, infrastructure, and regulatory frameworks. While significant progress has been made in developing low- and zero-carbon technologies,

their large-scale implementation remains constrained by high capital costs, limited global infrastructure, and evolving policy environments shaped by institutions such as the International Maritime Organization. This indicates that technological readiness alone is insufficient to drive systemic change.

Importantly, this study highlights that maritime decarbonization should be reconceptualized as a multi-layered socio-technical transition, requiring coordinated development across technological, economic, and institutional domains. The absence of a dominant solution suggests that future progress will depend on hybrid and integrated approaches that combine multiple technologies within a coherent system framework. Ultimately, achieving net-zero shipping will require not only innovation but also alignment—across sectors, stakeholders, and governance levels.

Implications

A. Theoretical Implications

This study contributes to the growing body of literature on sustainability transitions by advancing an integrative, system-level perspective on maritime decarbonization. Rather than treating technological pathways as isolated solutions, the findings emphasize the importance of understanding interactions, trade-offs, and complementarities across domains. This perspective extends existing research by framing maritime decarbonization as a socio-technical co-evolution process, in which technological innovation and institutional development are mutually reinforcing.

Furthermore, the study challenges the dominant techno-centric narrative that assumes the eventual emergence of a single optimal solution. Instead, it supports a multi-pathway transition model, where competing and complementary technologies evolve in parallel. This insight has important implications for future research, suggesting the need to move beyond comparative performance analysis toward more holistic frameworks that capture system dynamics, interoperability, and scalability.

The proposed conceptualization also contributes to transition theory by highlighting the role of infrastructure and policy alignment as critical mediating factors between technological innovation and real-world implementation. By integrating these dimensions, the study offers a more comprehensive analytical lens for examining complex transitions in other sectors beyond maritime systems.

B. Practical Implications

From a practical standpoint, the findings provide actionable insights for policymakers, industry stakeholders, and technology developers. First, the absence of a single dominant decarbonization pathway suggests that policy frameworks should remain technology-neutral, allowing multiple solutions to develop and compete while supporting integration across systems. Regulatory bodies, including the International Maritime Organization, play a crucial role in establishing clear and stable policy signals to reduce uncertainty and encourage long-term investment.

Second, the identified misalignment between technological innovation and infrastructure highlights the urgent need for coordinated infrastructure development, particularly in ports and fuel supply chains. Strategic initiatives such as green shipping corridors can serve as pilot ecosystems for testing and scaling integrated solutions in real-world contexts.

Third, industry actors should prioritize hybrid and system-based approaches that combine alternative fuels, electrification, and digital optimization to balance performance, cost, and environmental impact. Investments in digital technologies, such as artificial intelligence and digital twins, offer near-term opportunities to improve efficiency while supporting longer-term transitions.

Finally, the study underscores the importance of cross-sector collaboration, involving governments, shipping companies, energy providers, and port authorities. Achieving net-zero shipping will require not only technological innovation but also institutional coordination and shared commitment across the global maritime ecosystem.

Limitations of the Study

Despite its comprehensive scope, this study has several limitations that should be acknowledged. First, the review is restricted to articles published between 2020 and 2025, which, while ensuring the relevance of recent technological developments, may exclude earlier foundational studies that continue to influence current research trajectories. Second, the analysis is limited to peer-reviewed journal articles written in English, potentially introducing language and publication bias by excluding relevant studies published in other languages or formats, such as technical reports and industry white papers.

Third, although the study adopts a systematic and transparent search strategy, the selection of databases—Scopus, Web of Science, and ScienceDirect—may not fully capture all relevant literature, particularly emerging studies in niche or interdisciplinary outlets. Additionally, as a scoping review, this study does not include a formal quality appraisal of individual studies, which may limit the ability to assess the robustness or comparative validity of specific findings.

Finally, the analytical synthesis presented in this study is inherently interpretive, relying on thematic categorization and conceptual integration. While this approach enables a broader understanding of the field, it may also introduce subjectivity in the identification of patterns and research gaps. These limitations highlight the need for complementary research approaches, including systematic reviews and meta-analyses, to further validate and deepen the insights presented.

Future Research Directions

Building on the identified gaps and limitations, several directions for future research are proposed to advance the field of maritime decarbonization. First, there is a critical need for integrated system-level studies that move beyond single-technology analyses to examine how multiple decarbonization pathways can be combined within operational maritime systems. In particular, research on hybrid energy systems that integrate alternative fuels, electrification, and digital optimization remains underdeveloped and warrants further investigation.

Second, future studies should prioritize techno-economic and scalability analyses that assess the feasibility of deploying emerging technologies at a global scale. While many existing studies focus on technical performance, there is a lack of robust evidence regarding cost competitiveness, investment risks, and long-term economic viability across different regions and market conditions.

Third, the role of infrastructure development requires deeper exploration, particularly in relation to port readiness, fuel supply chains, and global logistics networks. Empirical studies examining real-world implementation, such as pilot projects and green shipping corridors, would provide valuable insights into the practical challenges and opportunities associated with large-scale adoption.

Fourth, further research is needed to investigate the co-evolution of technology and policy, especially in the context of international regulatory frameworks shaped by organizations such as the International Maritime Organization. Comparative policy analyses across regions could help identify best practices and inform the design of more effective governance mechanisms.

Finally, emerging digital technologies, including artificial intelligence, digital twins, and big data analytics, represent a promising yet underexplored area in maritime decarbonization. Future research should examine how these technologies can enable real-time optimization, predictive maintenance, and system integration, thereby enhancing both efficiency and sustainability.

Taken together, these directions underscore the importance of interdisciplinary and collaborative research efforts that bridge engineering, economics, and policy. Advancing maritime decarbonization will require not only technological innovation but also a deeper understanding of how complex systems evolve and interact in a global context.

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