

Proceedings of the 2nd International Maritime Research, Education, and Training Conference

**Sharjah Maritime Academy,
Khorfakkan, Sharjah, United Arab Emirates**

05 February 2026

Editors:

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PROCEEDINGS

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Chancellor's Note

It is with immense pride and deep appreciation that I welcome you to the Proceedings of the Second International Maritime Education, Training, and Research Conference, held on 5 February 2026 at the Sharjah Maritime Academy (SMA). Following the success of our inaugural conference in 2025, this second edition confirms that SMA's ambition to serve as a maritime hub for thought leadership, innovation, and collaboration is not a single moment but a sustained direction.

This year's conference brought together more than 250 participants — a clear growth on our first gathering — representing academia, industry, regulatory authorities, and maritime enforcement bodies from across the globe. As one international delegate reflected, it was a privilege to join a gathering that brought together maritime leaders, educators, students, policymakers, and practitioners, all engaging in forward-looking and sustainable discussions about the future of the maritime sector. This kind of engagement continues to validate SMA's founding conviction: that the future of maritime safety, sustainability, and innovation depends on genuine synergy between academic institutions, industry stakeholders, and regulatory bodies.

Structured around the twin themes of collaboration and resilience, and sustainable practice, the program began by addressing questions ranging from seafarer well-being and mental health support for cadets, to the enduring commercial and safety dimensions of dhow shipping and trade. Turning to the sustainability agenda directly, speakers examined digital transformation for supply chain resilience, ports as blue economy hubs, ammonia as an alternative marine fuel, and engineering advances in fuel cell technology. Keynote contributions further broadened the lens, addressing maritime data, industry trends, and gender equity in maritime leadership.

The maritime sector continues to move through a period of rapid transformation. Smart ship operations, alternative fuels, and AI-driven safety systems are no longer emerging trends but active realities reshaping how we train seafarers and design policy. This conference reaffirmed that meeting these shifts requires sustained investment in research-driven dialogue and reimaged training frameworks — not a one-off response.

SMA remains honored to serve as the convening platform for this dialogue, now in its second year. Our aim continues to be an inclusive space that bridges policy and practice and catalyzes solutions for the maritime world of tomorrow. My sincere gratitude goes to our speakers, researchers, partners, and organizing teams who made this year's conference possible.

This year, SMA honoured its conference speakers not with words alone, but with impact. Each speaker has had a mangrove planted on their behalf, contributing directly to the protection and restoration of marine ecosystems. This initiative marks the beginning of a long-term collaboration focused on protecting the UAE's marine environments, engaging our students in environmental stewardship, and ensuring that the conversations held at IMRET continue to create value long after the conference concludes.

Let these proceedings stand not only as a record of academic excellence but as a continued call to deepen our cooperation across sectors and borders. Together, let us keep navigating the path forward, safely, sustainably, and inclusively.

Dr. Hashim Alzaabi

Chancellor, Sharjah Maritime Academy

Provost and Vice Chancellor's Note

It gives me great pleasure to introduce the proceedings of the Second International Maritime Education, Training, and Research Conference, held at Sharjah Maritime Academy on 5 February 2026. Following the success of our inaugural conference in 2025, this second edition confirms that our young but ambitious institution's place on the map of global maritime research is no passing achievement but a growing reality.

Once again, internationally renowned academics and leading industry professionals gathered to share cutting-edge research, debate sectoral priorities, and confront pressing issues in maritime safety, sustainability, and automation. As in our first year, the exchange proved genuinely reciprocal: industry colleagues gained fresh insight into emerging academic findings, while researchers heard directly from practitioners about the realities of implementation on the ground. One delegate captured this spirit well, noting that presentations are important but only to spark the wider discussion, to inspire, to provide reassurance, or to debunk the myths — and that they left the conference full of ideas and energy. This reciprocal exchange exemplifies the Academy's mission to bridge scholarship and industry on the challenges that matter most.

Our students once again played a full part in the academic exchange, engaging with delegates throughout the day and presenting their own research — a continuation of the promise shown by the first cohort in 2025, and a testament to the growing pipeline of maritime professionals and scholars we are cultivating at SMA. Several student contributions were recognised with industry-sponsored prizes, a welcome sign that the standard of student research at SMA is already earning recognition beyond the walls of the Academy.

As Provost, I was honored to preside over this year's sessions and to witness a spirit of intellectual curiosity and collaboration carry through from our first conference into our second. What began as a single ambitious event a year ago has become a gathering that our academic and industry community now looks forward to. I am confident that this year's dialogues, partnerships, and research collaborations will lay the foundation for an even stronger third edition.

I extend my sincere appreciation to all contributors, delegates, and partners whose expertise and commitment made this conference a success. These proceedings stand as a record of academic excellence and as a continuing beacon for the collective pursuit of knowledge that will shape the maritime world of tomorrow.

Prof. Capt. Syamantak Bhattacharya

Provost and Vice Chancellor Academic Affairs, Sharjah Maritime Academy

Building Maritime Resilience: Perspectives from the Second International Maritime Research, Education, and Training Conference

The maritime sector is currently evolving, with environmental targets, new technologies, changing patterns of trade, and growing attention to the human element all influencing how maritime activities are organised and managed. This year's conference papers examine these developments from different perspectives. Together, they show that the future of maritime transport depends not only on technological progress, but also on people, sound governance, safe operations, and the ability of the sector to adapt to changing conditions. The conference brought together participants from academia, industry, regulatory authorities, and maritime enforcement bodies, reflecting the value of examining these challenges from the perspectives of all the sector's key stakeholders.

The importance of the human element is strongly represented in this volume. Slišković examines seafarers' well-being and argues for a move beyond managing individual stress towards creating healthier maritime organisations. The study connects supportive organisational culture, working conditions, employee participation, and well-being with safety, performance, and organisational resilience. Ragab et al., approach the human element from another direction by examining the demands created by the maritime green transition. The contribution highlights how new environmental requirements can increase administrative workload, cognitive demands, and operational complexity for seafarers.

Two contributions focus on dhow shipping, an important form of regional maritime transport that remains less visible in mainstream maritime research. Prasad compares dhow trade with liner and tramp shipping and shows how stakeholders' relationships and trust perform functions that are normally supported by more formal documentation in conventional shipping. The study demonstrates both the commercial flexibility of this system and the challenges it creates for traceability, insurance, finance, and regulatory oversight. Lendjel places dhow operations within their wider commercial and geographical setting, showing their role in connecting smaller coastal markets and operating in areas where conventional shipping may have a more limited presence. Analysis also draws attention to the safety and security questions surrounding these operations and to the need for further research that recognises their particular operating context.

Sustainability is considered at both the port and ship-technology levels by Metwalli et al., who examine the potential of ports to act as Blue Economy hubs. Their study identifies progress in areas such as pollution control, emissions reduction, and environmental management, while also showing continuing differences in governance, monitoring capacity, and technological integration between regions. At the engineering level, Rawashdea explores the optimisation of fuel cells for maritime applications. The study considers how modifications to the microporous layer can improve efficiency, water management, and durability under marine operating conditions, contributing to the wider search for reliable low-emission energy technologies.

A common message emerges as maritime resilience cannot be achieved through a single technology, regulation, or management approach. It requires attention to the people who work at sea, the commercial systems through which maritime transport operates, the safety of both conventional and non-conventional activities, the changing role of ports, and the technologies needed for a lower-emission future. Research has an important role in understanding the relationships between these areas and in ensuring that change is informed by evidence as well as operational experience. The second IMRET conference provided a forum for bringing these perspectives together. These proceedings reflect an ongoing dialogue between research and maritime practice and demonstrate the value of bringing different disciplines, institutions, and professional experiences into the same discussion. As editors, we hope that the work presented here supports further research, cooperation, and informed debate on how the maritime sector can develop in ways that are safer, more sustainable, and more resilient.

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1. From Stress Management to Healthy Organisations: A Collaborative Approach to Enhancing Seafarers' Well-Being

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Abstract

Social-science research on seafaring has largely focused on stressors and their links to health, safety, performance, and family life, as well as individual and organisational factors that can moderate these effects. While such risk-oriented evidence remains essential, the growing difficulty of attracting and retaining qualified personnel in the shipping sector calls for a strategic shift toward understanding how organisations can actively foster well-being, thereby enhancing seafarers' health and the long-term resilience, operational performance, and sustainability of shipping companies. This need is further supported by data showing that stress and burnout among seafarers contribute not only to turnover intention, but also to reduced engagement or quiet quitting, both of which threaten safe and efficient operations.

This paper builds on the author's programme of research in maritime psychology, integrating earlier stress-focused findings with new insights on the key characteristics of a healthy shipping organisation. Although both seafarers and shipping company managers recognise the importance of a supportive organisational culture that promotes all dimensions of well-being, the study revealed differences in their perspectives regarding organisational health. These differences highlight the need for active collaboration between management and crew to build a healthy and resilient organisation that supports seafarers' well-being, thereby fulfilling both human-centred responsibilities and economic objectives.

Keywords: Healthy Organisation, Seafaring, Stress, Well-being, Collaboration, Organisational Resilience

1. Introduction

Although seafaring has undergone significant technological and organisational changes during recent decades, it continues to be widely recognised as a demanding, risky, and stressful occupation. A traditional Croatian saying describes seafaring as “bread with seven crusts”, reflecting the hardships associated with maritime work. Despite improvements in communication technologies, better safety standards, and shorter onboard stays compared to past, scientific evidence suggests that seafarers still face substantial occupational stressors with potentially serious consequences for health, safety, and organisational functioning (Brooks & Greenberg, 2022; Jonglertmontree et al., 2022; Nittari et al., 2024; Slišković, 2017; Slišković & Penezić, 2015a).

Globalisation of the maritime industry, economic pressures, reduction in crew size, multicultural crews, and increasing job insecurity have substantially transformed seafaring work (Slišković, 2017). Technological progress has simultaneously reduced some physical burdens while increasing administrative demands, communication obligations, and job complexity. Consequently, research in maritime psychology has increasingly focused on understanding occupational stress, well-being, and mental health among seafarers. Over the past decade, studies on seafarers' stress and health have grown significantly (Jiang et al., 2021; Sharma, 2021), particularly during and after the COVID-19 pandemic (Carrera-Arce et al., 2023; Çelik Maşalacı, 2024; Hayes-Mejia & Stafström, 2023) which exposed and intensified existing structural problems within the maritime sector. Nevertheless, much of the existing research has focused primarily on stressors and negative outcomes at the individual level, while organisational-level approaches remain less developed.

This paper builds on a programme of empirical research conducted by the author in maritime psychology, with a particular focus on occupational stress and well-being among seafarers. The aim of this paper is twofold. First, it provides a review of previous research on seafarers within the occupational stress framework, focusing on stressors, stress consequences, and individual differences. Second, it discusses the need to shift from traditional stress management approaches toward the development of healthy maritime organisations that proactively promote employee well-being and organisational sustainability.

2. Occupational Stress in Seafaring

This review is grounded in the transactional model of occupational stress (Slišković, 2017), which conceptualises stress as a dynamic process involving several interconnected phases. According to this model, occupational stress arises when individuals perceive that workplace demands exceed their coping resources. The model includes several important elements: sources of occupational stress (stressors), stress reactions, coping mechanisms, individual differences, and stress outcomes. Exposure to stressors may initially result in reversible psychological or physiological reactions. However, repeated or chronic exposure can contribute to long-term negative consequences for physical health, mental health, well-being, and organisational functioning. Importantly, not all individuals respond to stressors in the same way. The effects of occupational stress depend on individual characteristics, coping strategies, personality traits, and available organisational support.

2.1. Stressors in Seafaring

Research consistently identifies seafaring as an occupation characterised by multiple simultaneous stressors (Slišković, 2017; Slišković & Penezić, 2015a). Some of the most frequently cited stressors include long-term separation from family, social isolation, fatigue, sleep deprivation, environmental stressors, demanding work schedules, and limited control over working conditions. Seafarers spend extended periods away from home, which may lead to disruption of family relationships, loneliness, and difficulties in maintaining social connections. Isolation onboard may be intensified by hierarchical organisational structures and multicultural

crews, where communication barriers and interpersonal conflicts may occur. Environmental stressors also contribute significantly to occupational strain. Noise, vibrations, harsh weather conditions, and exposure to hazardous substances are common aspects of maritime work. Additionally, seafaring includes serious occupational risks such as accidents, piracy incidents, exposure to war conflicts, infectious diseases, and limited access to medical assistance while onboard.

Work organisation-related stressors are particularly prominent and represent an important issue in the context of building healthier work organisations. A study among Croatian seafarers demonstrated widespread dissatisfaction with living and working conditions onboard, including contract terms, excessive workload, poor internet access, food quality, and limited recreational opportunities (Slišković & Penezić, 2015b). Fatigue caused by overtime work and insufficient rest remains a major concern, especially given its direct implications for safety.

The COVID-19 pandemic further highlighted structural vulnerabilities within the maritime sector (Slišković, 2020). During the global crew change crisis, many seafarers experienced prolonged stays onboard or at home due to travel restrictions and disrupted crew rotations. Qualitative findings, based on an international sample of seafarers, indicated severe negative impacts on mental, physical, social, and economic well-being (Slišković, 2020). Importantly, the pandemic did not create entirely new stressors; rather, it intensified existing problems such as insecure contracts, prolonged onboard periods, and limited organisational support.

2.2. Consequences of Occupational Stress in Seafaring

The consequences of work-related stress are commonly divided in the literature into individual and organisational levels. Research on occupational stress among seafarers has predominantly focused on consequences at the individual level. Earlier studies mainly emphasised physical health outcomes, documenting higher mortality rates among seafarers compared with the general population (Slišković, 2017). Causes include accidents, cardiovascular diseases, unhealthy lifestyles, and suicides. More recent research has increasingly shifted toward mental health and well-being (Brooks & Greenberg, 2022; Nittari et al., 2024). Occupational stress in seafaring has been associated with anxiety, depression, burnout, psychosomatic symptoms, sleep problems, and reduced life satisfaction. Stress-related fatigue and impaired concentration may additionally contribute to accidents and injuries onboard. Studies conducted among Croatian seafarers (Galić et al., 2023a; Sić et al., 2023; Slišković & Penezić, 2016) demonstrated significant associations between specific seafaring stressors (e.g., unfavourable contract conditions, irregular onboard-home rotations, organisational injustice, and work overload) and stress outcomes (e.g., reduced job and life satisfaction, poorer mental health, increased stress levels, and impaired physical health).

An important but often neglected aspect of maritime stress concerns the impact of seafaring on family life. Research involving seafarers' partners revealed numerous negative effects associated with separation, including loneliness, overload with childcare and household responsibilities, adaptation difficulties, anxiety regarding the partner's safety, and reduced social support (Slišković & Juranko, 2019a). Some partners also reported subordinating their own careers to the demands of maritime employment. Data also showed associations between

organisational practices related to contracts and seafarers' partners' general mental health, further illustrating that stress in seafaring extends beyond the individual worker (Slišković & Juranko, 2019b).

Another important issue concerns stigma surrounding mental health and help-seeking behaviour. Pilot research among seafarers suggested that psychological difficulties are often minimised, particularly within the traditionally masculine maritime culture where discussing emotional problems remains socially discouraged (Galić et al., 2023b). Such stigma may prevent timely access to psychological support and contribute to the worsening of mental health problems.

The transactional model of occupational stress highlights the importance of individual differences in shaping stress outcomes (Slišković, 2017). Research in maritime psychology shows that personality traits shape stress perception and job satisfaction among seafarers (Slišković, 2022; Slišković et al., 2022a), while unhealthy lifestyle factors, including poor diet, physical inactivity, smoking, alcohol use, and sleep deprivation, further contribute to stress-related health problems (Slišković, 2021; Slišković & Penezić, 2017). In addition, autonomous forms of work motivation are associated with higher levels of work-related well-being among seafarers (Slišković et al., 2022b). Overall, these findings suggest that occupational stress results from interactions between organisational conditions, personal resources, coping capacities, and broader social contexts, rather than from exposure to stressors alone.

Compared with individual-level outcomes, organisational consequences of occupational stress in seafaring have received considerably less research attention. However, organisational impacts are highly relevant for shipping companies and the broader maritime industry, particularly given the ongoing workforce retention challenges faced by the maritime sector (BIMCO & ICS, 2021). Stress-related organisational consequences include reduced productivity, impaired work engagement, absenteeism, labour turnover, accidents, errors, and lower organisational morale (Slišković, 2017). These outcomes may eventually generate substantial financial costs and compromise operational safety.

A recent study by Slišković et al. (2026) examined how chronic stress and burnout contribute to turnover intentions and reduced work engagement. The findings suggest that many seafarers may wish to leave the profession but perceive this as unrealistic because of financial responsibilities, limited employment alternatives onshore, and stigma associated with leaving maritime work due to stress or burnout. As a result, some seafarers remain in their positions while reducing effort and engagement to the minimum required level, a phenomenon commonly referred to as “quiet quitting.” In the maritime context, such disengagement may have serious implications for safety, teamwork, organisational efficiency, and long-term sustainability.

3. Rethinking Stress Management: Towards Healthy Organisations

The presented research within the occupational stress model in seafaring provides clear practical implications for stress management. Occupational stress interventions are commonly categorised into three levels: tertiary, secondary, and primary interventions (Slišković, 2017). Tertiary interventions focus on helping individuals who already experience negative effects of stress. In

the maritime sector, examples include 24-hour helplines, counselling services, and educational materials regarding depression and anxiety. Secondary interventions aim to strengthen individual coping capacities and resilience. These approaches include psychosocial programmes, stress management workshops, and health promotion activities encouraging healthier lifestyles onboard. Primary interventions focus on reducing stressors within the work environment itself. In maritime settings, this may involve reducing contract duration, ensuring compliance with working and rest hours, increasing staffing levels, improving internet access, enhancing recreational opportunities, and promoting better living conditions onboard.

Although all three intervention levels are important, evidence from organisational psychology (Slišković et al., 2025) suggests that stress management alone is insufficient for long-term health and organizational performance. Many seafarers report frustration that despite extensive research on occupational stress, structural changes in practice remain limited.

3.1. Healthy Organisations as a Proactive Approach

Recent developments in organisational psychology emphasise the concept of healthy organisations. A healthy organisation is generally defined as one that promotes employee well-being in ways that simultaneously improve organisational performance (Canto et al., 2020; Di Fabio, 2017; Fielden et al., 2021; Jaimez & Bretones, 2011; Ryan & Burchell, 2023). The healthy organisation perspective represents a shift from reactive stress reduction toward proactive and holistic approaches to employee well-being. Rather than focusing solely on preventing illness, healthy organisations seek to create supportive environments that foster health, engagement, development, safety, inclusion, and sustainability (Slišković et al., 2025). This perspective is especially relevant in the maritime sector. Shipping companies increasingly struggle to attract and retain qualified seafarers, making employee well-being an important strategic issue rather than merely a welfare initiative. Investments in healthy working environments may improve recruitment, retention, safety, organisational commitment, and long-term sustainability.

Despite growing interest in seafarers' well-being, the concept of a “healthy shipping company” has remained relatively underexplored. To address this gap, a pilot study (Slišković & Katsounis, 2025) was conducted among seafarers and shipping company managers to examine how healthy shipping companies are perceived and which characteristics are considered essential. The study included 309 participants from the international shipping sector, comprising 238 seafarers and 71 shipping company managers. An exploratory mixed-methods design was used. The quantitative component involved the development of the Healthy Shipping Company Determinants Scale (HSCDS), a newly constructed 28-item questionnaire based on literature from organisational and maritime psychology. Participants rated the importance of various organisational characteristics for defining a healthy shipping company. The qualitative component included an open-ended question asking participants to provide their personal definition of a healthy shipping company. Quantitative results demonstrated that all examined characteristics were rated highly important by both seafarers and managers. The scale showed a one-factor structure, suggesting that respondents perceived all included dimensions as interconnected components of healthy organisations. Key determinants included supportive leadership and transparent communication, prioritisation of health and safety, effective fatigue

management and work–life balance, professional development opportunities, sustainability and ethical practices, safe and adequately staffed work environments, mental health awareness and support, an inclusive and respectful organisational culture, employee participation in decision-making, and crisis preparedness and organisational resilience.

Importantly, no significant differences emerged between seafarers and managers regarding average ratings of these dimensions. Qualitative findings further supported these results. Across the entire sample, participants emphasised employee well-being, safety, ethical culture, financial stability, and environmental responsibility as core characteristics of healthy shipping companies. However, the qualitative analysis of the open-ended responses also revealed some differences between the groups. Seafarers placed stronger emphasis on onboard working and living conditions, respect, communication, and career development opportunities. Managers more frequently highlighted financial management, digital innovation, sustainability strategies, and corporate governance. These findings indicate that developing healthy shipping organisations requires collaborative engagement among all stakeholders. There is no universal ‘recipe’ for healthy organisations (Slišković et al., 2025); rather, healthy organisational cultures emerge through continuous dialogue and a shared commitment between management and employees

3.2. Development of Healthy Shipping Companies: Conceptual Guidance

Building on empirical findings from Slišković and Katsounis (2025), the development of healthy shipping companies requires an integrated organisational perspective that aligns employee well-being with operational performance and long-term sustainability. In this framework, seafarers’ well-being is conceptualised as a strategic organisational resource with direct implications for safety, retention, engagement, and organisational resilience.

Leadership quality and communication transparency emerge as foundational determinants of organisational health, as they enable trust formation, psychological safety, and effective coordination across hierarchical levels. In parallel, opportunities for continuous professional development strengthen employee competence and foster sustained occupational commitment. Organisational health further depends on structurally adequate working conditions, including sufficient staffing levels, effective fatigue management systems, and policies that ensure work–life balance. In the maritime context, these factors are particularly salient given the operational constraints and extended periods at sea. Rest provision, workload regulation, and adequate living conditions represent core mechanisms for mitigating chronic occupational stress. Beyond structural factors, healthy shipping organisations are characterised by inclusive and respectful cultures that actively support employee participation in decision-making processes. Within such environments, mental health awareness and access to psychological support should be systematically integrated into occupational health and safety frameworks rather than treated as peripheral interventions. Moreover, organisational preparedness for external shocks, such as pandemics, geopolitical instability, or other disruptive events, represents a critical dimension of resilience. In this regard, sustainability and ethical responsibility extend beyond environmental considerations to include the long-term safeguarding of human capital.

Taken together, these findings support a mutually reinforcing relationship between organisational effectiveness and employee well-being. Shipping companies that systematically

invest in supportive leadership, healthy work design, and participatory organisational practices are more likely to achieve sustained safety performance, resilience, and long-term sustainability.

4. Conclusion

This paper highlights the need to move beyond a predominantly stress-oriented narrative in maritime research and practice towards a positive, resource-based, and collaborative framework for developing healthy organisations. Within this perspective, seafarers' well-being should be understood not only as a welfare or ethical concern, but also as a strategic organisational resource that supports long-term sustainability in the maritime industry. Investment in improved working and living conditions represents a key lever for enhancing organisational outcomes, including work engagement, performance, safety, and employer attractiveness in a context of persistent labour shortages. However, such outcomes depend on a systemic and context-sensitive approach rather than isolated interventions.

Developing a healthy shipping company therefore requires an internally driven and participatory process, in which organisational practices are co-created through the active involvement of key stakeholders across all stages, from assessment to implementation and evaluation. In this regard, seafarers' participation in defining needs and shaping solutions is essential for ensuring relevance and effectiveness. Consistent with Slišković et al. (2025), healthy organisations cannot be reduced to fixed models or externally imposed standards. Instead, they represent ongoing, adaptive processes aimed at strengthening organisational resilience and long-term sustainability. While regulatory frameworks establish minimum requirements, sustained organisational health depends on practices that extend beyond compliance and are embedded within organisational strategy and culture.

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2. Practices in Dhow Trade and Broader Ocean Transport: A Comparison

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Abstract

medium-sized consignments move through relational networks rather than through the fully documentary architecture of mainstream ocean carriage. The non-conventional vessels are also active in conflict areas such as Yemen, Somalia etc. and in ports where other restrictions such as sanction restrict regular maritime transport. This paper develops a comparative analysis of dhow cargo booking, documentation and delivery practices against the two dominant commercial forms of ocean carriage: liner shipping and tramp shipping. Drawing on a synthesis of maritime commercial practice, carriage-of-goods doctrine, and the authors' conference presentation materials, the paper argues that dhow carriage cannot be accurately classified as either liner or tramp trade. It combines liner-like cargo aggregation and recurrent trading relationships with tramp-like flexibility, negotiated employment and informality, but it departs from both because it commonly operates without a bill of lading or a standard written contract of carriage. Instead, cargo agents and Nakhoda (Master) use receipts, contact-based identification and trust-based delivery arrangements to coordinate shipment and release. The analysis shows that this substitution of relational governance for documentary governance lowers transactional barriers for small merchants, but it also weakens evidentiary certainty, negotiability, trade-finance compatibility, insurance integration, cargo-claim management and regulatory visibility. The paper contributes a conceptual framework for understanding dhow trade as a hybrid form of relational maritime carriage and proposes a proportionate formalisation pathway that enhances traceability and legal certainty without undermining the flexibility that makes dhow trade commercially viable. The findings have implications for maritime regulators, port authorities, insurers, trade-finance actors and researchers seeking to integrate informal maritime transport into safer, more transparent and more inclusive maritime governance systems.

Keywords: Dhow trade; Bill of lading; Cargo documentation; Trust-based governance; Informal maritime transport

1. Introduction

International trade depends heavily on maritime transport, which remains the backbone of cross-border goods movement with annual growth rate of 1-3% in volume of cargo (UNCTAD, 2019, 2024, 2025). Mainstream ocean carriage is commonly organised through two broad commercial modes: liner shipping, which provides regular services on published or semi-regular routes, and tramp shipping, in which vessels seek employment wherever suitable cargo is available (Stopford, 2009; Song & Panayides, 2015). These categories are useful because they capture

differences in vessel deployment, cargo parcel size, freight formation, contractual documentation, cargo aggregation and delivery practices. They also provide the conceptual foundation for the legal and commercial infrastructure that supports modern maritime trade, including bills of lading, booking notes, charter parties, marine insurance and cargo-finance arrangements.

Dhow trade sits uneasily within this conventional classification. Dhows are historically rooted, regionally embedded cargo vessels that continue to serve commercial functions in Gulf and Indian Ocean trading systems (Agius, 2005; McMaster, 1966; Lendjel & Mareï, 2021). They often carry consignments for multiple merchants, rely on cargo agents to aggregate shipments, and use recurrent routes and personal networks (AunAli & Khrbey, 2020; Lendjel & Mareï, 2021). Yet their commercial practices differ substantially from liner and tramp shipping because dhow trade has historically relied on documentary practices that differ from the formal documentary architecture of mainstream ocean carriage (Bishara, 2018), while delivery may depend on the identity of the named party, a telephone number, a personal relationship or a recognised agent. In this respect, dhow trade challenges the assumption that maritime carriage must be governed primarily through formal documentary instruments.

The central problem addressed in this paper is therefore both classificatory and regulatory. If dhows are treated as small versions of liner vessels, the analysis overlooks their flexible contracting, personal brokerage and weak documentary standardisation. If they are treated as small tramp vessels, the analysis overlooks their cargo aggregation, repeated trading relationships and agent-mediated distribution functions. If they are treated simply as informal or traditional transport, the analysis risks missing the sophisticated relational governance mechanisms that allow them to function despite the absence of a bill of lading. A more accurate account is needed for academic analysis and for practical policy design.

This paper asks three research questions. First, how do the cargo booking, contract formation and documentation practices of dhow trade compare with liner and tramp shipping? Second, what commercial and legal functions are performed by the bill of lading in mainstream ocean carriage, and what happens when dhow trade operates without it? Third, how can dhow trade be conceptualised in a way that recognises its hybrid character while identifying opportunities for proportionate improvement in traceability, legal certainty and risk management?

The paper makes three contributions. It provides a structured comparison of liner, tramp and dhow practices; it develops the concept of relational maritime carriage to explain how trust and intermediaries substitute for formal documentation; and it proposes a proportionate formalisation pathway that avoids the binary choice between leaving dhow trade entirely informal and imposing a documentary architecture designed for larger-scale ocean carriage. The aim is not to criticise dhow trade for failing to mirror modern shipping documentation, but to identify where its current practices support commercial inclusion and where they create vulnerabilities for cargo owners, carriers, insurers, regulators and port authorities.

2. Ocean Carriage as a Documentary Commercial System

2.1 Liner shipping

Liner shipping is generally associated with regular services, repeated port calls, smaller cargo parcels and heterogeneous consignments carried on the same voyage. The commercial identity of liner operators also matters: shippers select services not only on price, but also on frequency, reliability, network coverage, service reputation and documentary efficiency. Cargo booking is typically handled through a carrier, freight forwarder, non-vessel operating common carrier or agent. The contract may be reflected in a booking note and is subsequently evidenced by a bill of lading or sea waybill issued after cargo acceptance or loading.

The liner model is therefore built around standardisation. Standardised containers, published schedules, carrier tariffs or rate agreements, established agency networks and standard-form documentation allow carriers to aggregate large numbers of smaller cargo interests into one transport system. In the liner context, the bill of lading performs a central coordination function: it records receipt of the goods, provides evidence of the contract of carriage and, where negotiable, operates as a document of title (Wilson, 2010/2018; Scrutton on Charterparties; Carver on Bills of Lading). Even where digital platforms or sea waybills reduce reliance on negotiable paper, the system remains documentary in the sense that cargo identity, carrier responsibility, delivery entitlement and claims pathways are recorded in formal instruments.

2.2 Tramp shipping

Tramp shipping differs in both commercial logic and contractual structure. Tramp vessels are not normally committed to fixed schedules and routes in the manner of liner services (Stopford, 2009). They are employed in response to cargo opportunities, often for bulk or breakbulk shipments large enough to justify the commercial employment of a whole vessel or substantial vessel space. Freight is more openly exposed to market conditions and is negotiated from voyage to voyage or through longer-term chartering arrangements.

The contract format used in tramp shipping is the charter party (Stopford, 2009; Scrutton on Charterparties). Voyage charter parties, time charter parties and other specialised forms allocate responsibilities for vessel employment, cargo operations, laytime, demurrage, freight, loading and discharging arrangements, exceptions, force majeure, strike risks, general average and dispute resolution. Shipbrokers play an important role by matching ships and cargoes, circulating market intelligence, supporting negotiations, assisting post-fixture operations and sometimes helping to manage disputes. Bills of lading issued under charter party arrangements often incorporate charter party terms, thereby connecting the cargo document to the underlying negotiated contract of carriage (Scrutton on Charterparties; Carver on Bills of Lading). Tramp shipping therefore combines market flexibility with documentary formalism. The vessel's employment may be highly responsive to cargo availability, but the legal architecture remains strongly contractual and documentary. This distinction is important when comparing tramp shipping with dhow trade, because the presence of flexibility does not itself indicate informality. Tramp shipping may be commercially flexible while still relying on detailed written contracts, standard forms and recognised cargo documents.

2.3 The bill of lading as infrastructure

The bill of lading is more than a receipt (Carver on Bills of Lading; Wilson, 2010/2018; Scrutton on Charterparties). In mainstream ocean carriage it has three classic functions: it is a receipt for the goods, evidence of the contract of carriage, and, where issued in negotiable form, a document of title. These functions link carriage to trade, finance and insurance (Carver on Bills of Lading; Gaskell et al., Bills of Lading: Law and Contracts). A buyer, bank, insurer or consignee does not need to know the cargo, witness loading or know the carrier personally; the document provides an institutional substitute for personal knowledge. Endorsement and presentation of an original bill of lading also provide a mechanism for transferring constructive possession and controlling delivery.

The documentary system reduces uncertainty by specifying the parties, vessel, voyage, cargo description, quantity, apparent condition, loading port, discharge port and delivery entitlement. It also creates a documentary trail that supports customs processes, cargo claims, marine insurance, trade finance and dispute resolution. Modern shipping law has evolved around this documentary architecture through conventions, national carriage-of-goods legislation, case law and standard-form contracts. The legal certainty of the documentary system does not eliminate disputes, but it provides recognised evidence and allocation rules when disputes arise.

This architecture matters because dhow trade, as a relational and agent-mediated system, appears to operate through less standardised documentary practices (Bishara, 2018; AunAli & Khrbey, 2020). The absence of a bill of lading does not mean that no contract exists; carriage can be agreed orally or through conduct. However, it changes the evidentiary and commercial position of the parties. It reduces the ability to transfer rights in transit, complicates the linkage between carriage and cargo finance, weakens formal claims management and places greater reliance on interpersonal trust and local enforcement mechanisms.

3. Methodology and Analytical Approach

This study uses a qualitative comparative and doctrinal-analytical approach. It synthesises the experience of the author with more than three decades of experience on dhow trade, liner shipping and tramp shipping with established principles of maritime commercial practice and carriage-of-goods law. The analysis is not presented as a statistical survey of dhow operations; rather, it is a conceptual paper intended to clarify categories, identify governance mechanisms and generate research propositions for future empirical work.

The comparison is organised around five analytical dimensions: vessel employment and routing; cargo parcel size and aggregation; contract formation; documentation and delivery; and risk allocation. These dimensions are selected because they are central to the distinction between liner and tramp shipping and because they reveal the distinctive position of dhow trade. The method is appropriate for a topic where formal datasets may be limited (Lendjel & Mareï, 2021) and where commercial practice is partly embedded in informal networks, customary understandings and port-specific arrangements (Bishara, 2018; Lendjel & Mareï, 2021; AunAli & Khrbey, 2020).

The paper adopts a functional perspective. Instead of asking only whether dhow trade has the same documents as mainstream shipping, it asks which commercial functions are performed by those documents in liner and tramp shipping and how equivalent functions are performed in dhow trade. This approach allows the analysis to recognise that trust, reputation, repeated dealings and cargo agents may perform real governance functions, while still identifying the legal and commercial gaps that arise when documentary instruments are absent or weak.

4. Comparative Analysis of Liner, Tramp and Dhow Practices

4.1 Cargo booking and market intermediation

In liner shipping, cargo booking is normally initiated when a shipper, trader, forwarder or charterer contacts the carrier or its agent for space on a scheduled service. Negotiation may occur over price or service terms, but the contractual framework is largely standardised. In tramp shipping, by contrast, shipowners circulate vessel positions and charterers circulate cargo orders through broking networks. Negotiation is central, and the fixture becomes firm only when the relevant subjects are lifted and the charter party terms are agreed.

Dhow trade uses a different intermediary structure (AunAli & Khrbey, 2020; Lendjel & Mareï, 2021) where cargo agents aggregate consignments from multiple customers and arrange their shipment on a dhow. The dhow owner or nakhoda may offer the whole dhow or available space to an agent, while the agent deals with individual merchants. In functional terms, the cargo agent performs some roles analogous to a liner agent, a forwarder and a local broker. However, the legal form is generally less standardised and the documentation less formal. The agent's commercial credibility and local knowledge therefore become central to the functioning of the trade (AunAli & Khrbey, 2020; Bishara, 2018).

Table 1. Functional comparison of liner, tramp and dhow cargo practices

Dimension	Liner shipping	Tramp shipping	Dhow trade
Service logic	Regular or semi-regular service; network reliability is commercially important.	Vessels seek employment where suitable cargoes are available.	Recurrent regional trading relationships with flexible, agent-mediated cargo aggregation.
Cargo profile	Smaller parcels; heterogeneous cargoes in a single voyage.	Large parcels; often homogeneous bulk or breakbulk cargo.	Multiple consignments from different customers; often breakbulk or general cargo suited to regional trade.
Intermediaries	Carrier agents, forwarders and NVOCCs.	Shipbrokers and chartering channels.	Cargo agents, dhow owners and nakhodas; personal networks are central.
Freight formation	Relatively stable rates with surcharges and service-based pricing.	Dynamic market rates negotiated voyage by voyage or through charter arrangements.	Negotiated or locally understood charges shaped by relationship, cargo type, route and available capacity.
Primary documents	Booking note, bill of lading or sea waybill.	Charter party and charter party bill of lading.	Receipt or informal record; frequently no bill of lading.
Delivery control	Delivery against original bill of lading or recognised release procedure.	Delivery against bill of lading or, in some cases, letter of indemnity arrangements.	Delivery to named party or contact identified through receipt and local trust mechanisms.

4.2 Contract formation and documentary evidence

The strongest contrast between mainstream ocean carriage and dhow trade lies in the documentary evidence of the contract. Liner and tramp trades generally operate through written documents that are capable of being interpreted by courts, arbitrators, insurers and banks. Even where negotiations are fast and commercially informal, the final legal architecture normally rests on a written booking note, charter party, bill of lading or sea waybill. These documents define rights and obligations beyond the immediate personal relationship between the parties.

Dhow trade, by contrast, may rely on a receipt issued after cargo is loaded. The receipt may identify the consignee or provide a contact number, but it does not normally perform the same legal, negotiability and financing functions as a bill of lading. In practice, the receipt may be sufficient for a local trade in which the cargo agent, nakhoda, shipper and receiver are known to each other or connected through a trusted network (AunAli & Khrbey, 2020; Bishara, 2018). The limitation is that the document may not provide robust evidence of contractual terms, cargo condition, liability allocation, delivery entitlement or dispute resolution mechanisms.

This difference does not make dhow trade irrational. On the contrary, it indicates that the trade has developed a lower-cost governance system suited to merchants, may prioritise speed, accessibility and relationship-based assurance over formal documentary control (Lendjel & Mareï, 2021). The problem is that this system becomes vulnerable when cargo is lost, damaged, delayed, misdelivered or contested; when the transaction requires bank finance; or when regulatory authorities need reliable shipment records.

4.3 Delivery and entitlement to cargo

Delivery is one of the most sensitive stages of cargo carriage because it is the point at which possession shifts from carrier to consignee or receiver. In documentary carriage, the carrier is generally expected to deliver to the party entitled under the relevant bill of lading or lawful release process. The document therefore operates as a control mechanism that protects carriers against misdelivery claims and protects cargo interests against unauthorised release.

In dhow trade, the party named in the receipt or known to the agent may receive the cargo, sometimes using a contact number or local identification practice. This system can be efficient where parties are known and cargo values are proportionate to the cost of formal documentation. However, it weakens the separation between personal trust and legal entitlement. If several parties assert competing rights to the cargo, or if a receipt is transferred informally, the Nakhoda or agent may lack a recognised documentary basis for determining the rightful receiver.

Letters of indemnity in mainstream shipping show that even formal trades sometimes deviate from bill-of-lading delivery requirements. However, the difference is that such deviations are recognised as exceptions and are normally managed through contractual indemnities and risk assessment. In dhow trade, documentary informality may be the default rather than the exception. This has implications for liability, insurance and port governance.

4.4 Risk allocation, insurance and claims

Formal carriage documents allocate risk before a dispute occurs (Carver on Bills of Lading; Scrutton on Charterparties; Wilson, 2010/2018). They identify who is carrier, who is shipper, what cargo was received, the apparent order and condition of the goods, the ports involved, the applicable terms and, often, the forum or law governing disputes. These details matter for cargo insurance, carrier liability and claims handling. A cargo insurer assessing loss or damage requires evidence of shipment, cargo description, loading condition and delivery failure. A carrier defending a claim requires evidence of contractual exceptions, cargo quantity, packaging, handling obligations and causation.

Dhow trade's reliance on receipts and trust complicates these processes (Bishara, 2018). A receipt may prove that a cargo was handed over, but it may not specify the full terms of carriage, limitations of liability, cargo condition, stowage requirements, dangerous goods declarations, responsibility for loading and discharge, or procedures for claims. In theory, this creates uncertainty for all parties. Merchants may face difficulty proving loss. Carriers may face difficulty defending themselves against inflated or unsupported claims. Insurers may price risk conservatively or avoid the segment. Regulators may lack a reliable documentary trail to understand trade flows and safety risks.

The commercial challenge is to improve risk allocation without destroying the low-cost accessibility of dhow trade. A full transfer of liner or tramp documentation may be disproportionate. However, a standardised cargo receipt or simplified carriage note could record core shipment data, identify parties, confirm cargo description and condition where practicable, specify delivery authority, and include basic terms on liability, claims notification and dispute resolution. Such a document would not need to replicate the full complexity of a bill of lading to deliver substantial governance benefits.

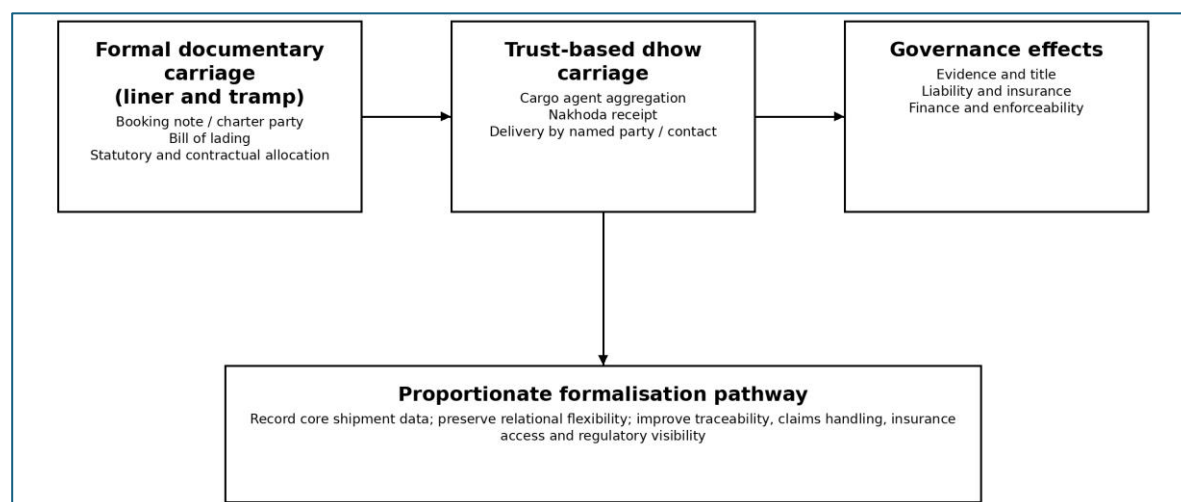


Figure 1. Conceptual framework for comparing formal documentary carriage and trust-based dhow carriage

5. Are Dhows Tramps or Liners?

The question of whether dhows are tramps or liners is useful because it reveals the limits of conventional maritime categories. Dhows share some features with liner shipping. They may serve recurrent regional trades, carry smaller cargo parcels from multiple customers, rely on

agents and support merchants who cannot fill a whole ship (Lendjel & Mareï, 2021; AunAli & Khrbey, 2020). These features resemble the aggregation function of liner shipping. However, dhows often lack the fixed schedules, standardised carrier documentation, formal booking systems, branded service networks and bill-of-lading-based delivery controls that define modern liner carriage.

Dhows also share some features with tramp shipping (Lendjel & Mareï, 2021). Vessel employment and freight arrangements can be flexible; cargo opportunities may shape routes and voyages; and negotiations may depend on available capacity, cargo type and commercial relationships. Yet dhows do not normally replicate the documentary structure of tramp shipping. Tramp trades rely on charter parties, brokered fixtures, standard forms and charter party bills of lading. Dhows may rely instead on cargo agents, Nakhodas, receipts and trust. The similarity is therefore stronger at the level of operational flexibility than at the level of contractual governance.

The most accurate classification is therefore hybrid, but hybrid should not be used as a residual label. Dhow trade is better understood as relational maritime carriage: a mode of transport in which repeated relationships, reputation, cargo agents and local knowledge perform governance functions that are performed by formal documents in mainstream ocean carriage. Relational maritime carriage is not lawless; it is governed through different mechanisms. However, those mechanisms are less visible to external actors such as banks, insurers, courts and regulators. This invisibility is the source of both its commercial flexibility and its institutional vulnerability.

Table 2. Documentary functions and dhow-trade substitutes

Function	Bill of lading/formal document	Dhow-trade substitute	Resulting vulnerability
Receipt for goods	Records goods received or shipped and apparent condition.	Receipt after loading; agent or Nakhoda acknowledgement.	Cargo description and condition may be incomplete or contested.
Evidence of contract	Connects carriage to standard or negotiated terms.	Oral agreement, local practice and relationship-based understanding.	Uncertainty over liability, exceptions, claims process and dispute forum.
Document of title	Supports transfer and delivery control through endorsement and presentation. Establishes negotiability	Delivery to named party, contact number or recognised receiver. Not negotiable	Reduced negotiability and increased misdelivery risk.
Finance interface	Allows banks and traders to control goods during payment cycles.	Personal credit and relationship-based assurance.	Limited access to trade finance and formal credit instruments.
Insurance and claims	Provides documentary evidence for underwriting and claims.	Receipts, port records and witness evidence. Usually not insured	Higher evidentiary burden and potentially conservative insurance treatment.
Regulatory visibility	Creates auditable cargo trail.	Fragmented local records.	Limited data for safety, customs, compliance and policy analysis.

6. Discussion: Trust, Transaction Costs and Proportionate Formalisation

The absence of the bill of lading in dhow trade should be analysed through the lens of transaction costs and institutional fit. Formal documentation reduces certain risks, but it also imposes costs:

drafting, printing or digitisation, administrative processing, compliance checks, banking requirements, legal literacy and delays. For small merchants moving regional consignments, the documentary architecture of mainstream shipping may be too expensive, too slow or too distant from everyday commercial practice. Trust-based carriage can reduce entry barriers by allowing merchants to rely on known agents and established local channels (Lendjel & Mareï, 2021; AunAli & Khrbey, 2020). Trust, however, is not a complete substitute for documentation. It works best where transactions are repeated, parties are identifiable, cargo values are manageable, routes are familiar and disputes can be resolved through reputation or local negotiation. It works less well where cargo changes hands during transit, where the consignee is unknown to the carrier, where bank finance is required, where insurance claims must be documented, or where regulatory authorities need transparent cargo records. The policy challenge is therefore to identify the minimum documentary improvements that would preserve trust-based efficiency while reducing avoidable uncertainty.

A proportionate formalisation pathway would have four features. First, it would be function-based rather than form-based: the aim would be to record essential data and allocate basic responsibility, not necessarily to impose a full negotiable bill of lading system. Second, it would be incremental: a standardised dhow cargo receipt could be introduced before more complex instruments. Third, it would be digital where appropriate but not digitally exclusionary: paper and mobile-based systems could coexist. Fourth, it would be co-designed with cargo agents, Nakhodas, port authorities and merchants, because a system that ignores existing relationships is unlikely to be used (Bishara, 2018; Lendjel & Mareï, 2021).

Such a pathway could include a simplified carriage note stating the carrier or dhow, Nakhoda, cargo agent, shipper, receiver, cargo description, quantity, packaging, loading place, intended discharge place, freight status, delivery instruction and claims-notification period. It could include optional clauses for dangerous goods, fragile cargo, perishables and high-value cargo. It could also link to port records or QR-coded entries where feasible. The objective would not be to transform dhow trade into container shipping, but to make its existing transactions more visible and more resilient.

7. Implications for Policy, Industry and Research

For port authorities, the analysis suggests that dhow trade should be governed through tailored instruments. Regulatory strategies designed for conventional liner and tramp shipping may be ineffective if they assume the presence of bills of lading, charter parties, standard manifests and corporate carriers. Port authorities can improve safety and compliance by developing documentation templates, cargo declaration processes and agent registration systems that fit the actual structure of dhow trade.

For insurers and cargo interests, the paper highlights the need for evidence-sensitive products. Insurance access may improve if core shipment data can be captured consistently. A standardised receipt would help demonstrate shipment, cargo description and delivery instructions, making claims assessment more reliable. It may also reduce disputes between cargo owners, agents and Nakhodas by clarifying who accepted what responsibility and at which point.

For trade-finance actors, the absence of a bill of lading is a structural constraint. Negotiable documents support control over goods and payment security. Dhow trade may not require full negotiability in every transaction, but improved shipment records could support alternative finance products for small merchants. This is particularly relevant where regional trade inclusion depends on enabling smaller traders to participate without imposing documentary costs designed for large-scale shipments.

For researchers, the paper identifies the need for empirical work on dhow cargo flows, documentation practices, dispute patterns, insurance access, delivery failures, port procedures and the role of agents. Future studies could combine interviews, port records, cargo-receipt analysis and network mapping to test the propositions developed here. The concept of relational maritime carriage may also be applicable to other informal or semi-formal maritime transport systems, including small-island cargo services, domestic wooden-vessel trades and coastal breakbulk networks.

8. Research Propositions

Proposition 1: Dhow trade is best conceptualised as relational maritime carriage rather than as a sub-type of liner or tramp shipping.

Proposition 2: The cargo agent is the central governance actor in dhow trade because the agent aggregates cargo, coordinates merchants and provides reputational assurance.

Proposition 3: The absence of a bill of lading reduces transaction costs for small merchants but increases evidentiary, delivery, insurance and finance risks.

Proposition 4: Proportionate standardisation of cargo receipts can improve legal certainty and regulatory visibility without eliminating the commercial flexibility of dhow trade.

Proposition 5: Regulatory interventions are more likely to succeed when they formalise existing relational practices rather than replace them with documentary systems designed for large-scale ocean carriage.

9. Conclusion

Dhow trade occupies an important position in regional maritime transport, but it cannot be adequately understood through the conventional binary of liner and tramp shipping. It has liner-like features because it aggregates smaller consignments and often depends on recurrent trading relationships. It has tramp-like features because vessel employment, routing and freight arrangements can be flexible and responsive to cargo opportunities. Yet it differs fundamentally from both because its contractual governance is often based on receipts, agents, Nakhodas and trust rather than on bills of lading, booking notes, charter parties and standard documentary release procedures.

This distinctive structure provides commercial advantages. It lowers barriers for smaller traders, supports flexible regional cargo movement and allows transactions to proceed through relationships rather than complex paperwork. At the same time, it creates vulnerabilities in relation to evidence, delivery entitlement, claims, insurance, finance and regulatory visibility. These vulnerabilities are not best addressed by simply imposing mainstream shipping

documentation. A more appropriate response is proportionate formalisation: strengthening the minimum documentary functions required for traceability and risk allocation while preserving the relational mechanisms that make dhow trade viable.

The paper therefore proposes relational maritime carriage as a conceptual category for dhow trade and similar informal maritime systems. This category recognises that trust and reputation are not merely cultural features; they are governance mechanisms. However, it also recognises that relational governance has limits when transactions become more complex, higher value or more exposed to formal legal and financial systems. By clarifying these limits, the paper provides a foundation for future empirical research and for practical reforms that can make dhow trade safer, more transparent and more inclusive without erasing its distinctive commercial logic.

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3. Commercial, Safety and Security Aspects of Dhow Shipping

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Abstract

The current study provides a rigorous analytical study of the characteristic changes of the microporous layers in PEMFCs for changing and enhancing their efficiency and life expectancy. This work strictly investigates numerous electrochemical factors influencing the MPL architecture to perform the investigations on the influence of structural improvements on the properties of the MPL such as porosity or hydrophatibility and electrical conductivity using state-of-art X-ray imaging and real-experiment comparison. Evidenced priorities highlight the centrality of updating MPL design for flood prevention, better reactant distribution and superior cell performance in various operational environments without exception with an emphasis on such advanced concepts as gradient porosity and surface modification for the highest PEMFC performance. In addition, this work offers prescriptive knowledge into the specificities of MPL modification for future industrial uses, identifying issues that define the feasibility and applicability of MPL modifications for industrial use. Therefore, this work successfully synthesises the major material science knowledge with real engineering foundation and sets the benchmark for further development of PEMFC technology in the global efforts to develop sustainable and highly efficiency energy systems as well as identifying innovative solutions to improve energy conversion efficiency and lifespan of next generation PEMFCs.

Keywords: PEMFCs technology; MPL modification; Hydrophatibility; X-ray imaging; Energy systems.

1. Introduction

1.1 Dhows, what's this?

Plenty of merchant vessels such as dhows (Figure 1) are operating in the Arabian Sea. These wooden-made - or more recently fiberglass - artisanal boats supply coastal populations of the Horn of Africa and the Arabian Peninsula with various goods.

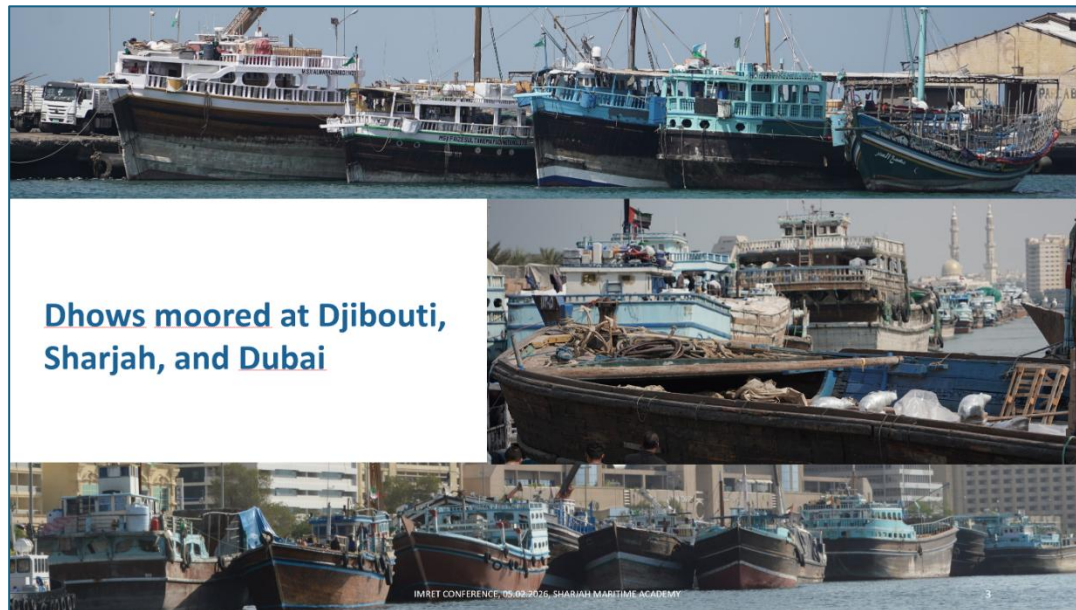


Figure 1. dhows moored at Djibouti, Sharjah and Dubai (author, 2026)

While major ports are supplied by containerized shipping lines, numerous smaller coastal settlements may not have the necessary port infrastructure to accommodate them. Often, these small towns have only a jetty or, at best, a shallow draft quay. Small-sized vessels like dhows can supplement container ships by supplying small ports from major ports and trading hubs such as Dubai or Sharjah in the United Arab Emirates (Lendjel and Marei, 2021). Dhows have a carrying capacity that, depending on their size (from 20m to 60m), ranges from a few tens of tons to over 2,000 tons for the largest among them. Although they have evolved since the 1970s by definitively abandoning sail propulsion in favor of diesel engines, they retain many attributes of their millennia-old history: a human-scale size, craft-built vessels, and therefore highly heterogeneous, versatile, an identity logic where each vessel is different from others both in shape and decorations. Dhow shipping has its own operational and organizational rules, as well as specific markets.

1.2 Why bothering with dhows ?

While conforming to social and technical norms, dhows do not tip over into a standardization similar to that of containerized transport. Their activity does not comply with International Maritime Organization (IMO) and International Labour Organization (ILO) regulations. For instance, at sea for ten months a year, sailors only return home during the summer, during the dhow's dry-dock maintenance phase. Labor standards aboard a dhow are more in line with those of its country of registration (India, Iran, Pakistan, Somalia, Yemen).

Despite being non-compliant, dhows face the same safety issues as other merchant ships. To help them improve their processes in a way that is tailored to their specific needs, it is essential to first understand the specific characteristics of their business and market. This paper presents a synthesis of the last research studies on these aspects, from the span of dhows network, the commodities they carry and their market areas.

2. The span of dhows network

To fully grasp the significance of this form of maritime freight transport, it is important to have a first approximation of the number of ships involved.

2.1 Data and methodology to assess the span of dhows network

Data on dhows are missing or difficult to get in most ports. In the absence of official statistics, a close examination of satellite pictures provided by Google Earth makes it possible to get a rough estimate of dhows' activity around the Arabian Peninsula. Indeed, dhows have characteristics that make their identification possible: an ogival-shaped hull, within a size range of 15m to 55m, a superstructure at the stern of the boat, and the shape of their clustering. For this study (Lendjel and Marei, 2021), we were therefore able to count and sort them by size class. The classification used includes six classes: very small (< 15m), small (15-20m), medium (20-25m), big (25-40m), very big (40-50m or more) and long boats (40-50m boats that are long but narrower than typical dhows). In order to avoid any confusion between fisher and cargo dhows, we set an arbitrary 20m long threshold value under which dhows are not counted. Long dhows have been included in the census because of their presence in clusters of dhows, even if their shape does not match the usual dhow shape.

Thanks to several interviews made in Djibouti (March 2019) and in the UAE (December 2019), and to previous literature, we were also able to associate each size class to an average tonnage (200 tonnes (t) for small dhows, 300t for medium dhows, 600t for big dhows, 1,000t for long dhows and 1,200t for very big dhows) to provide an initial assessment of dhows' transport capacity in each country. Indeed, medium dhows usually have the equivalent "capacity of 16 to 18 trucks", i.e. 300-400 tonnes, according to Said (a dhow shipping agent interviewed in Djibouti). But the largest seen at Sharjah reached a payload of "110 containers or 2,200 tons", according to a shipping agent interviewed there (UAE, in December 2019). Djibouti port data in 2017 confirm this order of magnitude (DPFZA, 2017; Lendjel and Abdillahi Ahmed, 2021).

This data collection method implies a careful scrutiny of thousands of kilometres of coastline and even of rivers, and would have required much more time if ports and jetties did not have very identifiable characteristics shapes. Only a limited number of countries was thus included in the perimeter of this study (Table 1).

Table 1. Perimeter of the data in 2019

Country	Cities	Identified Ports
Bahrein	2	2
Iran	38	93
Kuwait	2	2
Oman	19	24
UAE	4	19
Yemen	10	22
Djibouti	1	2
Iraq	1	1
Pakistan	2	4
Qatar	2	3
Somalia	2	4
Total	83	176

The data collected allows an initial appraisal to be made of the importance of dhows in the region.

2.2 Dhows network in several figures

Several results were extracted from this data. Overall, we identified 4,301 dhows of 20m long and more in the survey (Table 2). Two in three dhows are medium-size dhows and one in three is large or very large.

Table 2. The distribution of dhows per size class in the Arabian Peninsula and the Persian Gulf (Source: Lendjel and Marei, 2021)

Size of dhows	Quantity of dhows	% of total	Estimated static capacity (in tons)	% of total tons	Cumulated % of tons
Medium (20-25m)	2,929	68,1%	878,700	48,7%	48,7%
Big (>25m)	1,187	27,6%	712,200	39,5%	88,1%
Very big (>40m)	147	3,4%	176,400	9,8%	97,9%
Long (>40m)	38	0,9%	38,000	2,1%	100,0%
Total	4,301	100,0%	1 805,300	100,0%	

Dhows' transport capacity is not as anecdotal as one might expect (Figure 2). In order to provide an indication of its importance, a comparison was made with the total transport capacity of CMA-CGM services (in DWT) for the countries within the perimeter of this study in 2019. Dhows' total capacity approximately matches the capacity of this major container line operator in the region (2 million tonnes (mt) for CMA-CGM in the region, compared to 1.8mt for dhows).

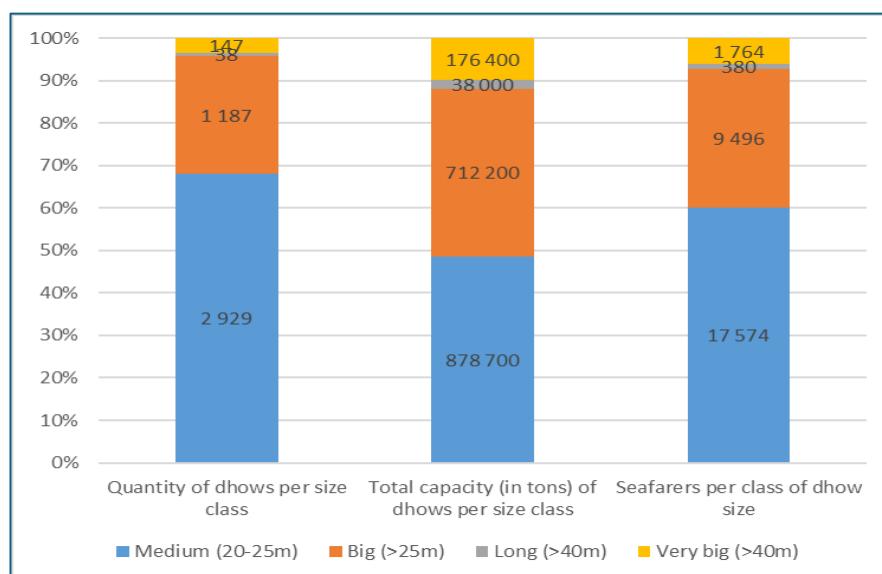


Figure 2. Dhow fleet characteristics (Source: Lendjel and Marei, 2021)

Using several assumptions about the composition of dhow crews, we also estimated the number of seafarers for both activities. Whereas a container ship crew has 20 seafarers (Stopford, 2009, p. 228), the smallest dhow needs only 6 seamen and the biggest 15. Thus, it may be estimated that there are 30,000 seafarers on board dhows in the region, compared to only 700 on the CMA-CGM's regional fleet. Dhow transport is approximately 43 times more labour intensive

than container transport, which implies a greater social visibility of dhow seafarers. But, with an almost similar static transport capacity, the potential level of labour productivity of a dhow seafarer is thus 43 times lower than his colleague on board a container ship...

Dhows are spread in many cities around the Persian Gulf, the Indian Ocean and the Red Sea, even in the Arvand Roud/Shatt al-Arab delta along the Iran-Iraq border, thus proving their ability to interconnect many destinations (Figure 3).

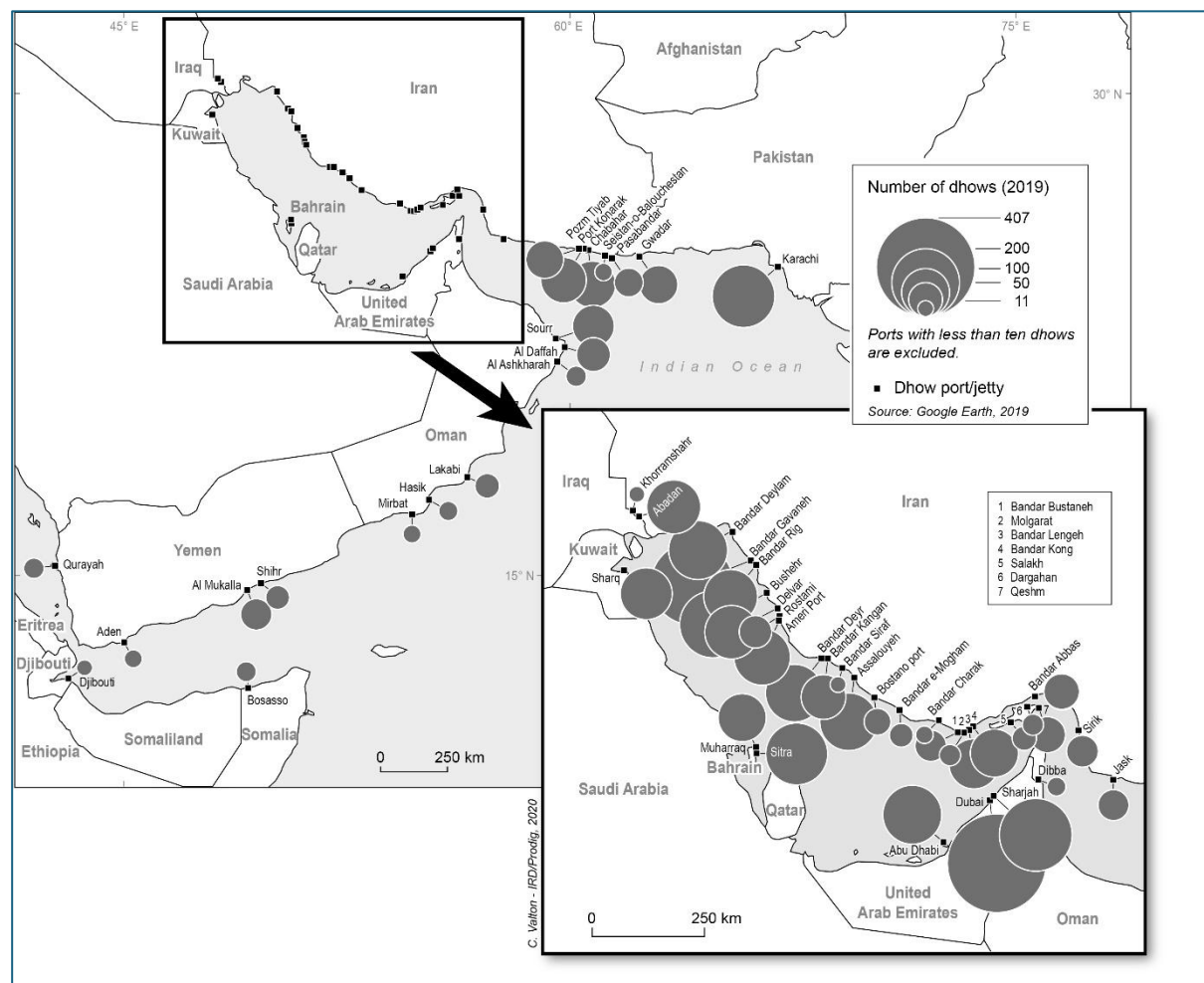


Figure 3. Distribution of dhows around the Arabian Peninsula and the Persian Gulf (Source: Lendjel and Marei, 2021)

Dubai and Sharjah appear to be the centre of gravity of the overall dhow network. But the UAE is not the country with the most dhows. We counted three times more dhows in Iran than in the UAE. Ten Iranian ports each shelter more than 100 dhows. And if dhows are often clustered, this is also true for the largest dhows, because almost two in three very large dhows are clustered in three cities (Sharjah, UEA; Bushehr, Iran; Al Mukalla, Yemen). Only one out of six dhow ports hosts very large dhows.

3. Which market for dhows ?

Lendjel and Abdillahi Ahmed (2021) demonstrates that dhows perform a kind of downstream logistic tramping, i. e. a capillary distribution of consumer goods to coastal retailers. As shown

in pictures taken at Djibouti and in the UAE (Figure 4), dhows are carrying various goods on demand.



Figure 4. On demand transport (tramping) by dhows of various goods (author, 2026)

Dhows and containerships – even the small ones - are in the same “competitive” situation as close small local grocers and large supermarkets on the outskirts of towns. They carry the same kind of merchandises – sometimes directly unloaded from a container to be loaded on a dhow –, but in different markets or with different transaction costs. But the shrinking size of their market area leads dhows to accept transport under increasingly risky safety and security conditions. By supplying conflict regions (where container ships no longer call), embargoed countries like Iran, or even sometimes embargoed products (Schuler, 2024), dhows indeed assume security risks that regular shipping lines and insurers refuse to bear (Lendjel et al., 2025). To demonstrate this hypothesis, Lendjel et al. (2025) link the data transmitted by the port of Djibouti and the AIS readings of about thirty dhows observed in the UAE and Djibouti with the index of level of security of the areas crossed and/or served provided by the CESAM.

3.1 Data and methodology

The primary sources utilized are those provided by port authorities willing to transmit detailed data on this market segment.

Djibouti Multipurpose Port (DMP) and his subsidiary, the Port Autonome International de Djibouti (PAID) where dhows moore, has supplied data on 3857 calls over ten years (January 2014 – May 2024) including dhows' origins and destinations (from 2018 onwards for 2260 calls), their departure date (but not their arrival, impeding any evaluation of the duration of their stopovers), the main cargo transported (from 2015 onwards), the loaded and/or unloaded tonnage, their carrying capacity, and the maritime agent responsible for the vessel's administrative

processing. Given Djibouti's central location in the Horn of Africa's flows of goods, this port serves as an excellent vantage point for observing dhow traffic.

The port of Aden, one of the two largest ports in Yemen (the second, Hodeidah, spelled in various ways, does not provide such data), offers less comprehensive statistics on a monthly basis for the period 2016-2022, indicating the number of dhows and the tonnages loaded and unloaded¹.

On the risk assessment side, CESAM, a risk monitoring organization for insurers in France, provides a systematic assessment by country and maritime zone of "high risk areas" involving a war risk insurance (either "waterborne" coverage, limited to the maritime part including ports, or "extended" coverage, which also includes the land part of transportation). These data are monthly and date back to September, 1, 2018. The Joint War Committee of the Lloyd's Market Association produces the same kind of index, but less systematically than CESAM's one. Several countries are not included in their index, or are temporarily, reason why we finally rely on CESAM's one.

3.2 The evolution of the security context

The market niches of dhows depend in part on that left by containerized maritime transport, itself dependent on the evolution of the security context of the maritime zones crossed. Two kinds of risk – on shore and off-shore - have to be taken into account for shipping business.

On shore risks are quite obvious in Somalia, Sudan and Yemen, the three main destinations of dhows from Djibouti. On shore risks have significantly risen in Sudan since the coup (October 2021) and then the following civil war (April 2023), even if the Sudanese Armed Forces of the Republic of the Sudan are controlling all the ports of the country (Verhoeven, 2023). In Somalia, the recent Memorandum of Understanding (MoU) between Somaliland and Ethiopia aimed at granting the latter a zone to establish a military naval base has reignited tensions between the federal government of Somalia and Somaliland, leading to an increase in activity of the Al-Shabaab movement (Stepputat and Norman, 2024). The region is characterized by chronic instability, marked by the fragility of neighboring states such as Somalia and Yemen, thus favoring the reemergence of maritime terrorism and piracy despite a decrease of piracy acts in recent years (Le Gouriellec, 2020; Miganeh Hadi, 2024).

CESAM's index of war risks (used for insurance with "extended warranties", i.e. including sea and land transport) displays an average risk rating for countries in the dhow's catchment area that increases from 4.4 in 2020 to 4.9 in 2024 (on a scale of 1 to 8), i.e. a "very high" level on the ranking established by the Lloyd's Market Association (Table 3).

Table 3. Risk index (average) by country and maritime zone (CESAM, 2018-2024; Lendjel *et al.*, 2025)

	2018	2019	2020	2021	2022	2023	2024
Red Sea (north)	1	1	1	1	1	1,2	4
Aden Gulf, Red Sea south	1	1	6	6	6	6	8
Indian Ocean	1	1	5	5	4.75	4	6

¹ <https://www.portofaden.net/en/statistics/list>

Persian Gulf, Oman Gulf	1	2.8	5	5	5	5	6
Somalia (zone A - South)	7	7	8	8	8	8	8
Somalia (zone B - Somaliland)	7	7	6	6	6	6	6
Eritrea	7	7	4	5	5	5	5
Djibouti	3	3	3	3	3	3	4
Sudan	9	9	6	5	5.75	7.2	8
Yemen	7	7	8	8	8	8	8
Oman	3	3	2	2	2	2	2
UAE	3	3	3	3	3	3	3
<u>Qatar</u>	3	3	3	3	2	2	2
Bahrein	3	3	3	3	3	3	3
Kuwait	3	2	2	2	2	2	2
Iran	9	9	5	5	5	6	7
Pakistan	3	3.75	5.5	6	6	6	6
India	2	2.75	4.5	5	5	5	5
Sri Lanka	3	3	3	3	4	4	4
Mean (4 marine areas)	1	1.45	4.25	4.25	4.19	4.05	6
Mean (15 countries)	4.80	4.83	4.40	4.47	4.52	4.68	4.87

In 2024, the level of risk in Yemen (8 in average), Somalia (7), and Iran (7) (dhows' three main destinations for years) is significantly higher than elsewhere in the world (2 in the European Union, North America, and Australia; 4 in China Sea and Indonesia,...).

CESAM issues the same kind of index for sea transport risks for each maritime areas around the globe. It displays a sharp increase in 2024 with a higher level for dhows' catchment areas (up to 6 in November 2024!) than countries' indices, contrary to the previous years. December, the 18th, 2023, the Joint War Committee of the LLOYD's Market Association released a circular (JWLA-032) defining a zone (by hatched lines on Figure 5, below) with a risk of "Hull War, Piracy, Terrorism and Related Perils" for shipowners and insurance companies³.

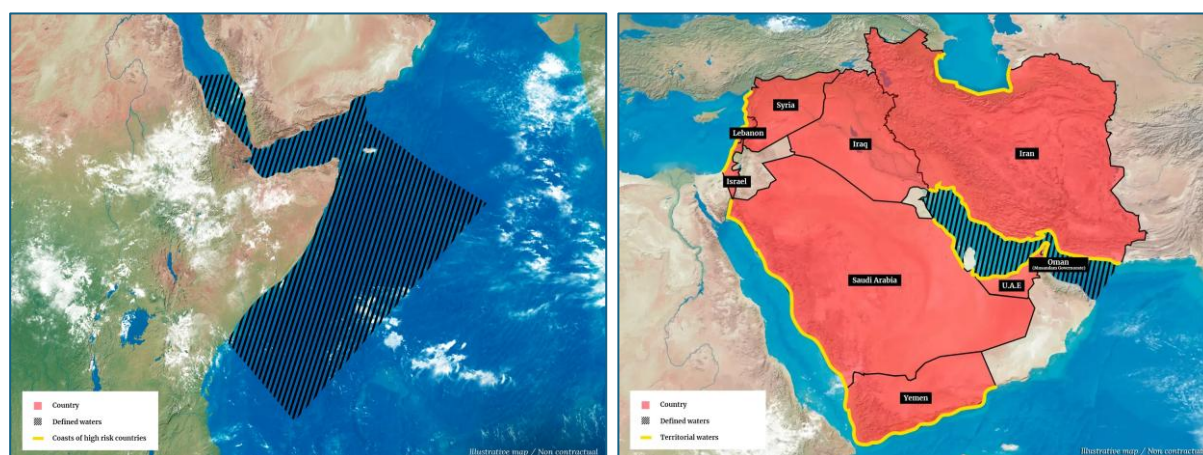


Figure 5. High Risk Areas (hatched zones) of "Hull War, Piracy, Terrorism and Related Perils" (Garex, 2024⁴)

³ <https://britanniapandi.com/wp-content/uploads/2023/12/JWLA2023-032-12-2023.pdf>

⁴ <https://www.garex.fr/corps-zone-a-risque-aggrave/indian-ocean-gulf-of-aden-and-southern-red-sea/>;
<https://www.garex.fr/corps-zone-a-risque-aggrave/middle-east/>

For compliant ships, a “High Risk Area” (HRA) involves that the shipowner subscribes an additional insurance called “CONWARTIME 2013” paid by the charterer. But this is not the case for dhow’s shipowner deprived of the support of any insurer that has to bear (and share with the shipper) those additional risks.

3.3 Evolution of territories of dhows

The evolutions of the security context and the containerships catchment area influence the extent of the dhow territory. This can be assessed through port data and AIS transponder data.

Djibouti and his Doraleh Container Terminal is one of the three major container terminals of East Africa with almost 1 million TEUs handled in 2018 (870,746 TEUs in 2018; Djibouti Port and Free Zone Authority, 2019). This port and its data are a good leverage to assess dhows’ activity in the region, particularly after the sharp fall of containership traffic through the Suez Canal since November 2023. After a decreasing trend in the 2010’s, Djibouti port records a rebound in the number of dhows calling in the “old” part of the port with 50 dhows in December 2023, compared to 36 in average per month in 2022 and 46 in 2023.

Significantly, the vast majority of transport is to Yemen, with Djibouti presenting itself as an export port for commodities carried by dhows, whereas containerized ones are mostly imported (Lendjel and Abdillahi-Ahmed, 2021). But as shown in Figure 6, 2022 and 2023 display a diversification of the destinations with a growing number of dhows sailing from Djibouti toward Sudan (42% of the destinations in 2023).

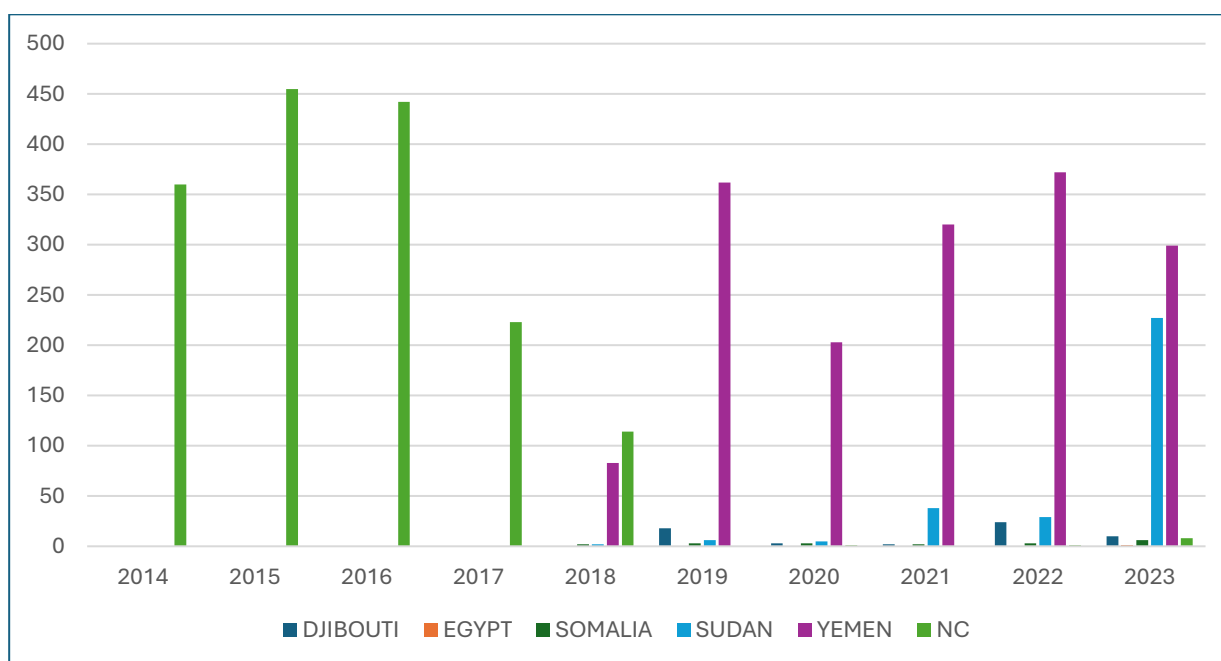


Figure 6. Number of outbound dhows per destination from Djibouti between 2014 and 2023 (source: Djibouti Port data)

The surge of dhow transport with Sudan cannot but be related to the tragic civil war that started in April 2023. The number of dhows making stopovers in Sudan on average each month

increases from 2.8 in 2021-2022 to 18.9 in 2023. While Yemen remains the primary destination for dhows departing from Djibouti, Sudan has become a major one in 2023, increasing from 7% to 42% of destinations and from 1% to 48% of tonnages. The territory of dhows has thus clearly extended with the civil war, also explaining the increase in the volume of activity over this period. But its decline starting from January 2024 coincides with the resumption of containerized maritime transport services in the Red Sea by major operators like CMA-CGM.

In the end, port data on the 2,260 calls of dhows at Djibouti during the period 2018-2024 reveal a territory located 98.8% within the HRA identified by the JWLA (Maps 2 and 3). Only dhows from India (1%) or Sri Lanka (0.2%) navigate (partially) through areas with a lower level of risk.

Considering now AIS transponder data, MarineTraffic data on the 61 dhows observed in 2019-2021 and 2024 confirm the expansion of their territory. The number of ports reached in 2023-2024 by the 30 dhows observed in the Emirates in 2019-2021 increases by 56%, while the 31 observed in Djibouti in 2024 increase by 38%. The number of the destinations (Figure 7) of the sample increases, probably along the number of rotations per year and per dhow. Bahrein, Kuwait, Iran weren't among the list of destinations in 2021. Dhows of the sample have doubled the number of ports supplied in Oman, Somalia, Qatar and almost India in 2024 in comparison to 2021.

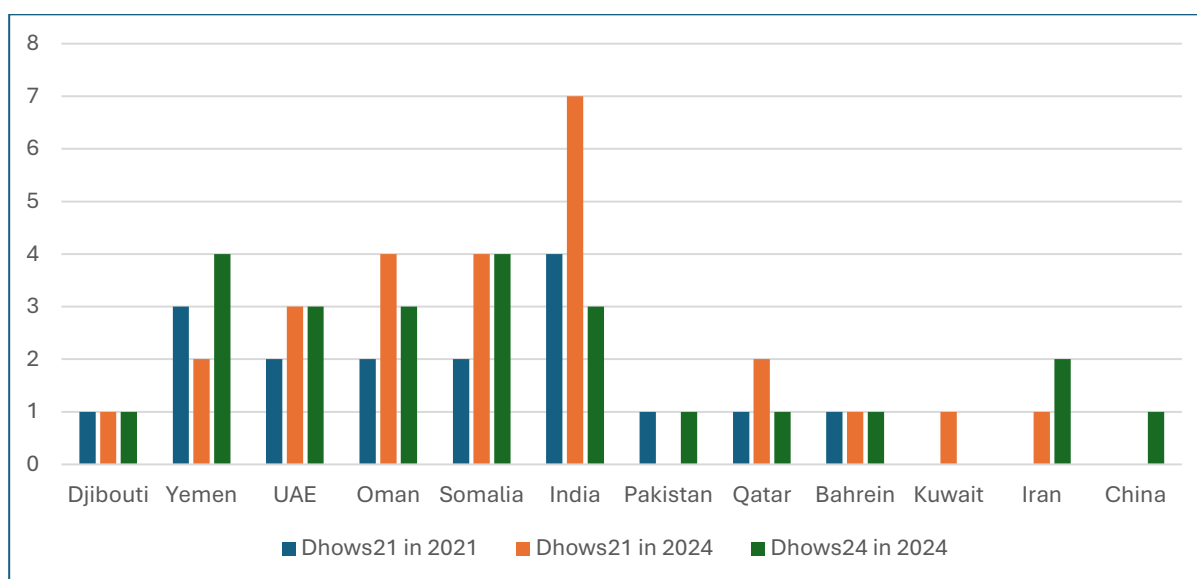


Figure 7. Number of dhows ports per country (MarineTraffic data on 61 dhows in 2021 and 2024; Lendjel *et al.*, 2025)

Among these countries, three are evidently high-risk: Somalia, Yemen, and Iran; four are loading destinations for dhows, as they possess significant regional container ports: UAE (Jebel Ali), Oman (Salalah), India (Mundra) and Djibouti; the other Indian ports are the homeland of many large dhows, so it is logical that they regularly make stopovers there; finally, the other Gulf countries (Qatar, Bahrain, Kuwait) are likely to be included in the exchange network between the UAE and Iran.

If we measure the distances of the route connecting these ports together, we get a 11,240 kilometers route along the coasts (excluding China, Figure 8).



Figure 8. Shortest route (in white) connecting dhows' ports (distance on GoogleMaps; Lendjel *et al.*, 2025)

In total, 40% of it (4,500 km) is located in the High Risk Area (HRA) of the Gulf of Aden and 31% (3,500 km) in the HRA of the Middle East, according to JWLA/Garex's Figure 5. In other words, 71% of the dhow territory as revealed by AIS data is considered high-risk.

4. Conclusion: what about the security on board ? DHOWSAFE project

Change in security levels in the maritime transport seems to favour dhow transport which otherwise would suffer from the relentless domination of containerships. Dhows' territory is thus directly function of insecurity issues in the region they supply. But this overview of the state of research on dhows reveals, by contrast, a major area that has not been addressed: their safety.

Obviously, as non-compliant vessels with ILO standards, working conditions on board are likely to be challenging. Measuring the gap between international standards (IMO/ILO) and crew practices on board (in terms of working hours, nature, and scope of tasks to be performed on board) would help estimate the additional cost of compliance and thereby evaluate the economy enabled by informality in maritime freight transportation. The same applies to hygiene and safety on board. Assessing and improving the level of safety of dhows is the very purpose of the ongoing international research program called DHOWSAFE.

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4. Human Impacts of the Maritime Green Transition: Quantifying Workload, Cognitive Burden, and Safety Risks

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Abstract

Maritime decarbonisation accelerates through a combination of the International Maritime Organization's (IMO) 2023 GHG Strategy, amendments to MARPOL Annex VI, and regional regulatory drivers including the EU Monitoring, Reporting and Verification (MRV) Regulation and FuelEU Maritime. While these frameworks focus on emissions reduction and technological compliance, their human-element implications are not systematically assessed within current regulatory development. This paper assesses the operational and psychological workload consequences of the green transition for seafarers. It draws on MARPOL Annex VI documentation, relevant IMO circulars, ILO labour provisions, published workload/fatigue studies, and incident evidence. The analysis identifies significant increases in administrative burden, cognitive complexity, and procedural tasks stemming from fuel changeovers, emissions monitoring, data reporting, and power-limitation systems. Findings highlight a gap between regulatory ambition and human capacity, with emerging patterns of eco-fatigue, reduced situational awareness, and latent safety risks. The paper proposes a risk-based human-element integration model centred on realistic manning standards, competence reform, simulator-based training, and human-centred system design. The argument advanced is that a just, safe, and effective green transition cannot be achieved by technology and regulation alone; it requires structural support for the resilience, wellbeing, and authority of the seafarers whose labour sustains maritime operations.

Keywords: Decarbonisation; MARPOL VI; human element; crew workload; fatigue; CII; EEXI; fuel changeover; MET; safety risk.

1. Introduction: Regulation Without Human-Centred Integration

International maritime decarbonisation has accelerated through statutory, operational, and market-driven mechanisms. The IMO's 2023 GHG Strategy mandates substantial reductions in greenhouse-gas intensity by 2030 and 2040, supported by amendments to MARPOL Annex VI that introduced EEXI technical limits and CII annual performance ratings (IMO, 2021; IMO, 2023a). Beyond IMO, regional measures such as the EU MRV and FuelEU Maritime regimes impose additional documentation and lifecycle requirements, expanding administrative and monitoring workloads on board (European Union, 2023b; 2023c).

Existing literature primarily analyses technology availability, fuel pathways, cost burdens, and macroeconomic impact. However, empirical examination of the human dimension remains limited. Quantitative workload studies and incident analyses indicate increasing administrative hours, cognitive saturation, and compressed decision-making windows across shipboard operations (Poulsen & Sampson, 2019; Sampson & Ellis, 2020).

The central argument advanced is that regulatory ambition has accelerated faster than the mechanisms that support human performance. Without systematic integration of the human element—through workload modelling, competence alignment, ergonomic design, and manning review—decarbonisation risks generating latent operational hazards.

This study adopts a structured analytical review methodology combining regulatory analysis, published empirical workload and fatigue studies, incident investigation reports, and documented operator reporting practices. Quantitative values presented are derived from aggregated findings across these sources rather than from a single primary dataset.

2. Regulatory Architecture Shaping Gulf Decisions

3.4 IMO short- and mid-term measures.

The IMO regulatory package introduces multiple concurrent obligations:

- EEXI introduces technical compliance tied to engine power limitation and efficiency baselines.
- CII imposes annual efficiency ratings (A-E), with D/E ratings requiring corrective actions.
- SEEMP Part III mandates continuous performance monitoring and documentation.
- DCS obliges detailed reporting of fuel consumption, distance travelled, and operational parameters.

Combined, these systems generate a structural increase in documentation volume, cross-check requirements, and supervisory tasks. Officers must reconcile logs, verify calculations, and ensure alignment with both company and statutory reporting pathways. This administrative burden is quantifiable: empirical studies suggest three to five additional hours of monthly compliance tasks per officer per regulatory layer (Bloor et al., 2022).

3.5 EU measures with extraterritorial reach

The EU regulatory package expands the workload further through:

- MRV inclusion of methane and nitrous oxide, increasing the granularity of fuel documentation.
- FuelEU Maritime lifecycle verification requirements for renewable fuels.
- Dual reporting obligations when trading with EU ports, requiring consistency between DCS, MRV, and commercial systems.

This introduces a data-governance challenge because discrepancies generate penalties under EU law. Seafarers, particularly deck and engineering officers, now perform cross-system reconciliation tasks with limited digital integration tools.

3.6 ILO misalignment

ILO and STCW work–rest provisions set clear numerical limits: maximum 14 hours of work in any 24-hour period, 72 hours in any seven days, and minimum 10 hours of rest in 24 hours and 77 hours in seven days (mirrored in STCW VIII/1). These limits were incorporated into MLC 2006 without any subsequent recalibration to reflect the cumulative task load added by environmental compliance (e.g. CII monitoring, SEEMP III documentation, dual DCS/MRV reporting). The formal regulatory framework therefore assumes a static workload while the actual number and complexity of tasks has increased.

Empirical evidence shows that even under the “old” workload, compliance with MLC work–rest limits is fragile. A recent WMU-associated study reported that seafarers frequently work far beyond ILO limits, with some respondents indicating workloads approaching double the stipulated hours. A global survey cited by the UN and industry bodies reported that 74% of seafarers felt overworked and 87.6% perceived an imbalance between work demands and crewing levels, despite technological advances. These findings indicate that the baseline manning and workload assumptions embedded in MLC are already strained before decarbonisation-related tasks are added.

The disparity between “paper compliance” and lived reality is now well quantified. Bhatia et al. (2024) compared Port State Control (PSC) inspection data with a global seafarer survey and showed that while PSC recorded 90.0–99.3% compliance with work–rest regulations, only 11.7–16.1% of seafarers reported actual compliance. A systematic review of 12 primary studies on work–rest record adjustment concludes that the adjustment (i.e., falsification) of hours has become “widespread” and “an integral aspect of shipping culture”, driven by inadequate crewing levels, unenforceable recording systems, and strong pressure to demonstrate formal compliance. Earlier quantitative work found that only 37.3% of seafarers “never under-recorded” work, while other studies reported that around half routinely distorted records.

Parallel evidence on administrative burden reinforces this misalignment. The Danish Maritime Authority’s international survey on administrative burdens among seafarers showed that 71% of respondents felt port and pre-arrival documentation tasks were repeated too often, and 79% believed these tasks required excessive paperwork; similar majorities reported that inspections, internal management systems, and ISPS work involved too much documentation, with seafarers explicitly warning that paperwork was “exploding” and taking time away from safety-critical duties. More recent industry polling indicates that one-third to one-half of seafarers feel that administrative tasks and inspections dominate port calls, leaving minimal time or energy for rest or shore leave.

Taken together, these data demonstrate a structural contradiction: MLC work–rest limits and associated manning models are calibrated against an older operational workload, while empirical evidence already shows systematic overwork, pervasive record adjustment, and high

administrative burden. Environmental compliance adds further documentation, monitoring, and data-handling requirements, yet neither MLC minimum rest standards nor minimum safe manning formulations have been revised to account for this. The misalignment is therefore not only conceptual but measurable: a regulatory framework that presumes compliance under fixed numerical limits is being applied to an environment where workload has increased significantly and where objective evidence shows that those limits are routinely breached and often concealed.

3. The Human Burden of Environmental Compliance

3.1 Administrative workload inflation

Table 1 Compliance task categories and estimated time demand per officer per voyage cycle

Task category	Key compliance tasks	Average time demand per voyage cycle (per officer)	Source basis (aggregated empirical findings)
SEEMP III	corrective action plan drafting; performance deviation justification; annual target review	3–5 hours	Winchester & Rehmatulla 2023; DMA; Safety4Sea workforce survey
CII	attained vs required CII calculation; speed–consumption analysis; daily log validation	6–10 hours	Company fleet reports; WMU fatigue study
MRV	fuel/emissions data matching; BDN verification; cross-check with logbooks; voyage emissions summary	5–8 hours	MRV operator reporting data; EU compliance templates
DCS	fuel/distance aggregation; error correction; alignment with noon reports; audit preparation	4–7 hours	IMO DCS audit feedback; fleet managers' compliance logs
Alternative fuel documentation	lifecycle certificates; sampling; compatibility checks; WtW validation	2–4 hours	Class guidance notes; operator internal guidance
Internal SMS reporting	near-miss documentation; safety checklists; audit preparation; internal benchmarking	4–6 hours	SMS compliance audits; operator documentation
Charterer/port paperwork	port pre-arrival forms; terminal safety checklists; cargo declarations; duplicated forms	4–10 hours	DMA 2013; terminal reporting requirements

Total estimated administrative time per voyage cycle: 28–50 hours per officer, depending on trade pattern and fuel mix. This represents a 40–70% increase in administrative time compared with pre-2020 compliance burdens.

Table 2 Daily time distribution comparison: pre-decarbonisation vs post-CII baseline

Work activity	Pre-2020 daily average	Post-CII daily average	Change
Watchkeeping	6–8 h	6–8 h	unchanged
Navigation/route planning	1–2 h	0.5–1.2 h	↓ reduced by 30-40%
Technical oversight (E/R or bridge systems)	1–2 h	0.5–1.5 h	↓ reduced by 25-40%

Safety/maintenance routines	1–2 h	0.5–1 h	↓ reduced by 35-50%
Administrative/compliance tasks	0.7–1 h	1.5–2.2 h	↑ increased 120-180%

This distribution suggests a structural shift: compliance tasks grow at the expense of operational and safety-critical activities. Officers cannot expand the total number of hours in the day; therefore, administrative inflation directly displaces operational vigilance.

Table 3 Examples of duplicated or triplicated reporting requirements

Data item	Reported in	Frequency	Duplication factor
Fuel consumption	logbook, DCS, MRV, internal platform	daily–voyage	x3–x4
Distance travelled	logbook, DCS, MRV	daily	x2–x3
Bunker quality data	BDN, MRV, internal audit	per bunkering	x2–x3
CII corrective notes	SEEMP III, internal efficiency reporting	monthly–annual	x2
Speed–consumption curves	CII optimisation tool, bridge log, charterer portal	voyage	x3

Limited interoperability between systems results in redundant data entry, increasing clerical load without corresponding gains in accuracy.

Table 4 Example of documented “peak-load points” for administrative burden

N o.	Operational phase	Administrative load characteristics	Risk consequence
1	Port approach	Compliance dashboards; reporting preparation; pilot-exchange paperwork	Navigational distraction; reduced situational awareness
2	Arrival / port stay	Port forms; terminal checklists; safety declarations; audits	Fatigue accumulation; missed rest; reduced recovery time
3	Voyage end	CII summary; DCS aggregation; log corrections; audit readiness tasks	Compressed workload; increased documentation errors
4	Bunkering operations	Fuel-sampling certificates; lifecycle/GHG documentation; safety forms	Task overload during high-risk operations; elevated procedural error probability

Peak-load periods coincide with phases requiring high attention, increasing latent accident potential.

3.2 Quantified risk implications

Based on the combined datasets, three operational consequences become measurable:

- 1. Reduced navigational oversight:** Administrative inflation reallocates officer attention away from navigation. Studies show up to a 30–40% reduction in effective time available for route monitoring and hazard scanning, especially during port approaches.
- 2. Increased rest-hour violations:** Work–rest logs are frequently adjusted to maintain formal compliance (concealment) because compliance tasks exceed allotted administrative time.

Evidence shows only 11.7–16.1% of real compliance with ILO/MLC rest-hour standards despite 90% “paper compliance”.

3. Elevated near-miss frequency: Operator datasets indicate that 28% of navigational near misses involved distraction by documentation or digital entries during watch.

Thus, environmental compliance burden cannot be considered a minor inconvenience; it is an operational safety risk that produces systematic rest-hour violations, attention fragmentation, and reduced vigilance.

3.3 Cognitive load and task interference

Digitalisation has introduced parallel information streams into bridge and engine-room environments, increasing the number of concurrent cognitive tasks required. These systems operate in parallel with traditional navigational displays, alarms, and radar/ARPA layers.

Quantitative human-factors studies confirm that multi-source digital environments increase cognitive load:

- A WMU/ITF-backed bridge resource management study (2022) found in simulator-based trials that officers experienced up to 40% higher visual-attention fragmentation when environmental-system alerts run concurrently with navigational alerts.
- Research summarised in Safety Science showed that multi-layer system alerts increase reaction time by 250–400 ms, a small delay but one considered operationally significant in congested waters (Poulsen & Sampson, 2019).
- A 2023 study by the Korean Maritime Safety Research Institute found that environmental performance dashboards produce “false urgency” alerts that are misinterpreted as safety alarms in 27% of simulated bridge scenarios.

Alarm fatigue—long recognised in aviation and healthcare—now appears in maritime operations due to the frequency and layering of emissions alerts. When these coincide with collision-avoidance, engine-load, or navigational warnings, officers must prioritise under stress. This increases the likelihood of:

- misclassification of alerts.
- delayed response in collision-avoidance actions.
- unintentional dismissal of critical alarms.
- decision conflict between safety and environmental targets.

Recent incident investigations indicate that these cognitive-load interactions have operational relevance: incident investigations in 2021–2023 identified several groundings and near-misses where officers were occupied with digital performance tasks at the time of navigational deviation. These patterns demonstrate how decarbonisation-linked digitalisation reshapes cognitive workload in measurable ways.

3.4 Operational risks during fuel transitions

Fuel changeovers to low-sulphur or blended fuels require precise control of viscosity, temperature, compatibility, and flow stability. These transitions typically occur during manoeuvring phases—pilot boarding, port entry, or ECA boundary crossings—when workload is already at maximum.

Documented technical risks include:

- Main-engine stall during changeover: MEPC submissions (2020–2023) recorded multiple cases where rapid temperature shifts caused fuel seizure, leading to engine failure during confined-water navigation.
- Compatibility-induced filter clogging: class societies (DNV, LR) report that up to 60% of tested fuel samples show partial incompatibility when switching between low-sulphur blends, increasing risk of clogging and fuel starvation.
- Pressure fluctuations from mismanaged tank switching: Investigations show that manual switching errors or inadequate settling time can cause combustion instability or temporary power loss.

These problems are well-documented in casualty databases:

- The UK MAIB noted several incidents where engine power dropped immediately after fuel changeover, with one case resulting in a collision with a berth (MAIB Bulletin, 2021).
- The US NTSB investigated a grounding where VLSFO incompatibility caused filter blockage during approach, reducing propulsion to idle.
- Japanese transport authority reports from 2022 found that vessels transitioning from HFO to low-sulphur blends experienced a 3–5× increase in unplanned propulsion power fluctuations.

The operational risk arises from the convergence of technical vulnerability and peak human workload during manoeuvring phases. Changeovers require precise monitoring and manual control at exactly the moments when navigational risk is highest. This conjunction magnifies the risk envelope and increases the probability of cascading failures.

3.5 Eco-fatigue as a cumulative condition

Eco-fatigue refers to a fatigue subtype created by continuous environmental compliance pressure, persistent documentation cycles, and real-time monitoring of emissions performance. Unlike traditional fatigue—rooted in physical overwork or sleep deficit—eco-fatigue is cognitive and psychological in origin.

Several data sources confirm its emergence:

- A 2024 Marine Insight survey reported that 63% of officers felt environmental reporting requirements significantly increased mental strain.

- A WMU fatigue study (2023) found that officers engaged in CII and SEEMP documentation tasks showed 25–35% higher cognitive load scores than baseline operations.
- Research by Bhatia et al. (2024) demonstrated that increasing administrative demand correlates statistically with increased hours-of-rest violations, even when recorded logs falsely indicate compliance.
- A 2022 ITF crew welfare report found that emissions-related documentation was consistently named as a major stressor, with officers describing the pressure to “hit environmental targets” as “constant” and “intrusive”.

Symptoms of eco-fatigue are behaviourally measurable:

- reduced vigilance (observed reduction of scanning frequency by up to 20% in simulator trials).
- slower reaction times (delay of 250–400 ms when multitasking environmental dashboards).
- compromised situational awareness, especially in port manoeuvres.
- increased reliance on autopilot and automated systems due to cognitive depletion.

These characteristics have operational significance. When officers' attention becomes preoccupied by emissions, optimisation metrics, or digital checklists, vigilance declines in areas where human oversight is still essential—collision avoidance, proximity detection, and early hazard recognition.

Eco-fatigue therefore represents a new and measurable fatigue pathway specific to decarbonisation-era operations. It accumulates over time, particularly on vessels with high reporting loads, tight schedules, or complex fuel-handling requirements, and poses long-term risks to crew decision quality and vessel safety.

4. Competence Gaps and Training Deficits

4.1 Outdated STCW alignment

The STCW Convention has not been updated to include core competencies required for decarbonised operations. Missing elements include emissions-monitoring literacy (CII, DCS, MRV), lifecycle-based fuel assessment, digital data validation, and hazard management for low-flashpoint and toxic alternative fuels beyond LNG. IMO HTW/9 working papers in 2023 noted that current STCW provisions do not reflect emerging digital and alternative-fuel competencies (IMO HTW/9, 2023). Industry surveys indicate that 78% of officers have not received structured training on emissions-reporting systems, relying instead on informal on-board familiarisation (DNV Maritime Competence Report, 2022). This produces competence variability and inconsistent operational outcomes during audits and PSC inspections.

4.2 Alternative fuel knowledge deficits

Emerging fuels—methanol, ammonia, hydrogen, and LPG—carry distinct hazard profiles requiring specialist competence. Comparative assessments by ABS (2023) and IMO interim guidance (MSC.1/Circ.1621; MSC.1/Circ.1687) highlight risks including invisible flames (methanol), acute toxicity and corrosive exposure (ammonia), low ignition-energy and embrittlement (hydrogen), and rapid vapour expansion (LPG). However, global MET capacity remains insufficient: IMO analysis and independent fleet-transition modelling estimate that 600,000–800,000 seafarers will require upskilling by 2030, far exceeding current training throughput (Reuters, 2024; WMU MET Trends, 2023). This mismatch creates systemic exposure to managing unfamiliar fuels without standardised certification pathways.

4.3 Lack of simulator integration

Simulation training has not kept pace with operational risks associated with environmental compliance or alternative fuels. According to WMU–ITF institutional survey data, fewer than 20% of assessed MET institutions offer simulated fuel-changeover malfunction scenarios, fewer than 10% cover EEXI-related engine derating events, and none include CII-vs-COLREG decision-conflict scenarios. Only 14% simulate emissions-sensor failure or DCS/MRV data-discrepancy events. Without structured exposure to these failure modes, officers encounter critical situations operationally for the first time, increasing the likelihood of misjudgement under high workload conditions.

5. Manning Levels and Organisational Constraints

5.1 Minimum safe manning misalignment

Minimum Safe Manning (MSM) determinations are based on operational assumptions predating CII, EEXI, SEEMP Part III, and MRV/DCS reporting cycles. These frameworks did not account for continuous digital data monitoring, emissions documentation, or alternative-fuel safety routines. Available empirical evidence suggests that current MSM levels may no longer align with actual task loads. Bhatia et al. (2024) showed consistent under-recording of work hours during periods of environmental reporting, with officers exceeding legal MLC limits by 10–14 hours per week despite “formal compliance” records. MAIB (2022) similarly noted that fatigue-related causal factors increased in parallel with expanded administrative duties, demonstrating structural misalignment between regulated manning levels and modern operational demands.

5.2 Cross-departmental coordination burden

Environmental compliance requires coordination between deck officers (voyage data input), engineering teams (fuel quality, changeover logs, emissions-sensor calibration), and shore-based compliance units (MRV/ETS submissions, DCS corrections). A DNV vessel-operations survey (2023) found that 64% of officers experienced recurring discrepancies between shipboard and shore-recorded emissions data, requiring additional verification cycles and extending administrative workload. This interdepartmental dependency contributes to increased

communication load, raises the risk of misalignment in logged parameters, and intensifies time pressure during port operations, where documentation and operational tasks peak simultaneously.

5.3 Latent safety consequences

Reduced manning resilience magnifies latent risk across the operational system. MAIB (2022) attributes 49% of navigational incidents to fatigue as a contributory factor, many occurring during periods of high administrative density or fuel-transition operations. EMSA incident analysis (2022) further shows that concurrent environmental and navigational alerts increase misinterpretation probability by 22%, particularly on vessels with minimal officer redundancy. Understaffing also reduces emergency-response capacity: alternative-fuel leaks, sensor failures, or propulsion fluctuations require rapid multi-person intervention, yet current MSM assumptions do not incorporate these additional demands. The cumulative effect is an erosion of operational margins and increased vulnerability to compound failure pathways.

6. Human-Centred Redesign Framework

A structured approach is required to realign regulatory ambition with human-system capabilities, the proposed approach presented below.

6.1 Workload impact assessment

Current regulatory proposals do not undergo structured human-element workload modelling prior to adoption. In contrast, aviation and nuclear sectors routinely apply validated tools such as NASA-TLX and SWAT to quantify task density and cognitive demand before operational rollout. Applying equivalent assessment models may allow IMO and administrations to anticipate cumulative workload effects, including additional administrative hours per regulation, peak workload collision points during port calls, and shifts in cognitive bandwidth during critical manoeuvring. EMSA (2022) and WMU human-element studies (2023) both recommend integrating workload-modelling mechanisms into future IMO regulatory impact assessments to prevent cumulative task overload.

6.2 Competence and training reform

Revised competence standards are required to align training with decarbonisation-era operations. These should include:

- emissions-monitoring competence aligned with CII, DCS, and MRV data structures.
- alternative-fuel hazard mitigation consistent with IGF-Code interim guidelines.
- understanding algorithmic optimisation logic (e.g., EEXI power-limiter behaviour, speed–fuel efficiency models).

- digital documentation proficiency, including error-detection, reconciliation, and audit-readiness.

Survey data from DNV (2022) show that only 21% of officers have received formal emissions-reporting training, confirming the need for structural amendments to STCW supported by recurrent training cycles like aviation-sector regulatory practices.

6.3 Manning recalibration

Manning standards must be recalculated using empirical task analyses rather than legacy vessel-type templates. Environmental reporting adds 8–12 hours of weekly administrative load per navigating officer (Bhatia et al., 2024), not currently reflected in Minimum Safe Manning certificates. Recalibration must incorporate:

- quantified administrative workload.
- simultaneous monitoring of environmental and safety systems.
- alternative-fuel emergency routines.
- fatigue-risk controls and redundancy requirements.

A data-driven manning recalibration would reduce concealed MLC violations and restore functional resilience during high-demand operations.

6.4 Human-centred system design

Environmental compliance systems require redesign to reduce cognitive burden and align with bridge-resource-management principles. Priority improvements include:

- Consolidated interfaces integrating fuel, emissions, and voyage-efficiency data into a single display.
- Harmonised alert hierarchies and colour coding across manufacturers to reduce misinterpretation risk.
- Reduced documentation duplication across operator, charterer, and regulatory platforms.
- Decision-support clarity, ensuring efficiency-driven prompts cannot obscure or conflict with COLREG-mandated manoeuvring priorities.

DNV's Human-Machine Interface Review (2023) shows that interface harmonisation alone can reduce misinterpretation rates by up to 40%, demonstrating the safety value of standardised design principles.

7. Conclusion

Decarbonisation measures have fundamentally altered the operational profile of contemporary shipping, yet regulatory development has progressed faster than the systems that support human performance. The findings of this paper demonstrate that environmental compliance introduces

substantial administrative load, elevates cognitive and attentional demands, and increases technical risk during fuel-transition and optimisation processes. These increases have not been matched by corresponding adjustments in STCW competence standards, MET infrastructure, simulator curricula, or Minimum Safe Manning levels.

Empirical evidence shows that crews routinely exceed MLC work-hour limits during peak reporting periods, that incident investigations increasingly identify cognitive overload as a contributing factor, and that simulator and training capacity lags the complexity of alternative fuel systems. The interplay of these deficits produces eco-fatigue, degraded situational awareness, and higher likelihood of latent failure accumulation—conditions already reflected in MAIB, EMSA, and WMU safety analyses.

A viable and safe pathway to maritime decarbonisation requires structural reforms that embed human-system limitations into regulatory design. These reforms include mandatory workload-impact assessment for new regulations, revised STCW competencies reflecting digital and alternative-fuel requirements, recalibrated manning models based on empirical task analysis, and human-centred redesign of monitoring and reporting systems. Without these measures, the industry risks achieving environmental gains at the cost of operational resilience and crew wellbeing.

Limitations: This study is based on secondary data synthesis and documented reports. Primary onboard observational studies would be required to further validate the quantified workload estimates presented.

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5. The Role of Ports as Blue Economy Hubs: Sustainability, Innovation, and Policy Alignment

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Abstract

Oceans contribute by approximately 3–5% to the global gross domestic product (GDP) and support a range of economic activities in coastal states. To balance environmental protection and economic rise, the Blue Economy concept was introduced. The blue economy concepts have been addressed via multiple literatures, however, there is a need for a systematic literature review to identify and assess the consolidated factors and existing research gaps. In this study, the research provides an observational assessment of port capacities to function as transformative pillars of the Blue Economy, focusing on their environmental performance and operational sustainability. The research results indicate that while many ports have adopted key environmental enablers, such as improved pollution control, ballast-water management, and emissions-reduction measures, their implementation varies significantly across regions, revealing persistent gaps related to governance, monitoring capability, and technological integration. From a broader perspective, the findings underscore the need for harmonized frameworks, strengthened regulatory alignment, and greater investment in green and smart port technologies to ensure that ports can fully support national and regional Blue Economy ambitions. This work contributes to the ongoing discourse by highlighting where progress has been made and where further research and policy innovation are critically required.

Keywords: Blue Economy- Environmental Performance -Operational Sustainability- Green and Smart Ports- Port Governance

1. Introduction

The stabilization of the earth's climate requires the support of the ocean as it plays a vital role for human life through the provision of essential natural resources, including food, raw materials, valuable substances and energy, moreover it is fundamental to global trade too. However, the expansion of the economic growth and the human development have placed the marine ecosystems into an increasing strain through the open and intensive use of ocean resources and services, this pressure is driven by activities such as overfishing, resource extraction and pollution related disruption of coastal and marine environment (Vega-Muñoz et al., 2021). Whereas ports sit at the heart of how societies access and benefit from ocean services, they function as primary gateways through which these resources are transferred, processed, and distributed, thereby supporting local and global economies by providing the infrastructure and connectivity that enable ocean-based activities at scale. However, as key nodes in maritime

logistics and coastal developments, ports can contribute to environmental impacts through ship emissions, ballast water discharge, waste streams, coastal industrial expansions, dredging activities and pollution risks, placing intensive pressure on marine and coastal environments if not managed properly.

Ports are increasingly overstressed by the rapid growth in cruise tourism calls, which, while economically attractive, generate environmental pressures that often exceed local waste management and monitoring capacities. This situation poses a significant environmental threat with long-term consequences when systems and controls are insufficient, leading to the failure of ports to maintain adequate facilities and remain tourism nodes rather than evolving into sustainable blue economy hubs (Sliškovíc et al., 2018). For this reason, ports are not merely passive transport facilities; they play a critical role in shaping whether ocean use supports a sustainable blue economy or accelerates environmental degradation.

Ports can become blue economy hubs capable of balancing economic growth with marine ecosystem protection when they (a) enable green value creation, (b) reduce environmental externalities, (c) coordinate policies and investments across public and private stakeholders, and (d) integrate stronger environmental governance supported by effective monitoring systems and sustainable green technologies.

The integration of efficient port functions as blue economy hubs typically exhibits several multi-level characteristics, including:

1. Institutionalized environmental management and disclosure, such as the adoption of Environmental Management Systems (EMS), systematic monitoring, and priority setting, with tools tailored to the specific needs, risks, and operational realities of European ports—particularly the EcoPorts Port Environmental Review System (PERS) and the Self-Diagnosis Method (SDM) (ESPO, 2025).
2. Decarbonization pathways covering port operations, the ship–port interface, and hinterland connections, supported by realistic implementation and governance frameworks (World Bank, 2025).
3. Innovation governance, which views green and digital innovation as integrated systems to enable widespread adoption and implementation (Liu et al., 2025).
4. Policy alignment across multiple governance levels, supported by strong port–city integration and coordinated governance mechanisms (OECD, 2024).

2. Research background

Ports are not only transport nodes but also institutional and infrastructural platforms that connect shipping, logistics, coastal industry, tourism, fisheries, and emerging ocean energy and data services. This positioning makes ports natural candidates to operate as blue economy hubs within an increasingly place-based blue economy development agenda that depends on local governance capacity and cross-sector coordination.

The OECD highlights that blue economy outcomes at the local and regional levels depend strongly on territorial characteristics and coordinated governance across multiple levels,

underscoring the direct and influential role that port authorities must play in shaping these outcomes (OECD, 2024).

International decarbonization pressures further elevate the enabling role of ports. The IMO's 2023 GHG Strategy sets ambitious targets and calls for measures that encourage port developments and activities supporting efficient ship–shore interfaces, including onshore power supply and the uptake of zero- and near-zero-emission fuels (IMO, 2023).

Reinforcing sustainability as a core operational priority, the World Bank's Port Reform Toolkit (Module 8) emphasizes the need for ports to integrate environmental sustainability into planning, infrastructure, and operations, addressing issues such as air emissions, water impacts, biodiversity loss, and climate risks (World Bank, 2025).

2.1 Problem Statement

Many ports have introduced sustainability measures and modernization initiatives; however, implementation varies significantly across contexts due to uneven governance capacity, monitoring systems, financing mechanisms, and technology integration. While ports may demonstrate policy adoption, formal commitments, and pilot projects, these efforts do not always translate into consistent delivery capacity. This gap undermines ports' ability to support national and regional blue economy ambitions.

2.2 Research Gap

- Decarbonization and innovation efforts frequently face governance challenges and funding constraints in regions with limited resources. Consequently, comparative research is needed to identify policy instruments and mechanisms that can support and scale implementation across diverse port contexts (Alamoush et al., 2024).
- Although tools for measuring port environmental management already exist (e.g., EcoPorts), comprehensive indicators capturing full blue economy hub performance, integrating economic value creation, environmental boundaries, and social inclusion, remain inconsistent and unevenly applied across regions (ESPO, 2024).
- The growing body of research on port–city relations highlights the need for stronger empirical studies examining how port–city conflicts are managed, how benefits are distributed, and how governance arrangements can be made more inclusive within port–city systems (Pagés Sánchez, 2025).

2.3 Research Questions and Objectives

The overarching objective of this study is to examine how ports can function as effective enablers of the Blue Economy through structured frameworks, operational practices, and governance arrangements. Accordingly, the study addresses the following research questions:

- RQ1 (Frameworks): What Blue Economy frameworks exist within ports, and to what extent are they standardized?

- RQ2 (Enablers): What port-related activities and practices facilitate the implementation of Blue Economy concepts?
- RQ3 (Governance): Which port governance models most effectively support Blue Economy activities?

These questions align with the study's aims by focusing on institutional structures, operational enablers, and governance mechanisms that shape the role of ports as transformative pillars of the Blue Economy.

3. Research Methodology

This study adopts a systematic literature review (SLR) methodology to address the core research questions. The review is conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, as articulated by Haddaway et al. (2022), ensuring transparency, reproducibility, and the minimization of selection bias.

To operationalize the review, the port-related Blue Economy framework was structured around four analytical dimensions: governance, environmental performance, operational practices, and innovation. These dimensions were translated into Boolean search clusters comprising the following search string:

("blue economy") AND (port OR ports) AND (governance OR framework) AND ("green port" OR "smart port") AND ("pollution control" OR "ballast water").

The search strategy was applied across the principal academic databases, Scopus, ScienceDirect, and Web of Science, to ensure comprehensive coverage of peer-reviewed literature. The initial screening yielded a total of 40 articles ($n = 40$), indicating a relatively limited body of literature that concurrently addresses these thematic elements. These findings highlight fragmentation within the existing research and underscores the need for more integrated analytical frameworks in port-centric Blue Economy studies. The PRISMA-based screening and selection process is illustrated in Figure 1.

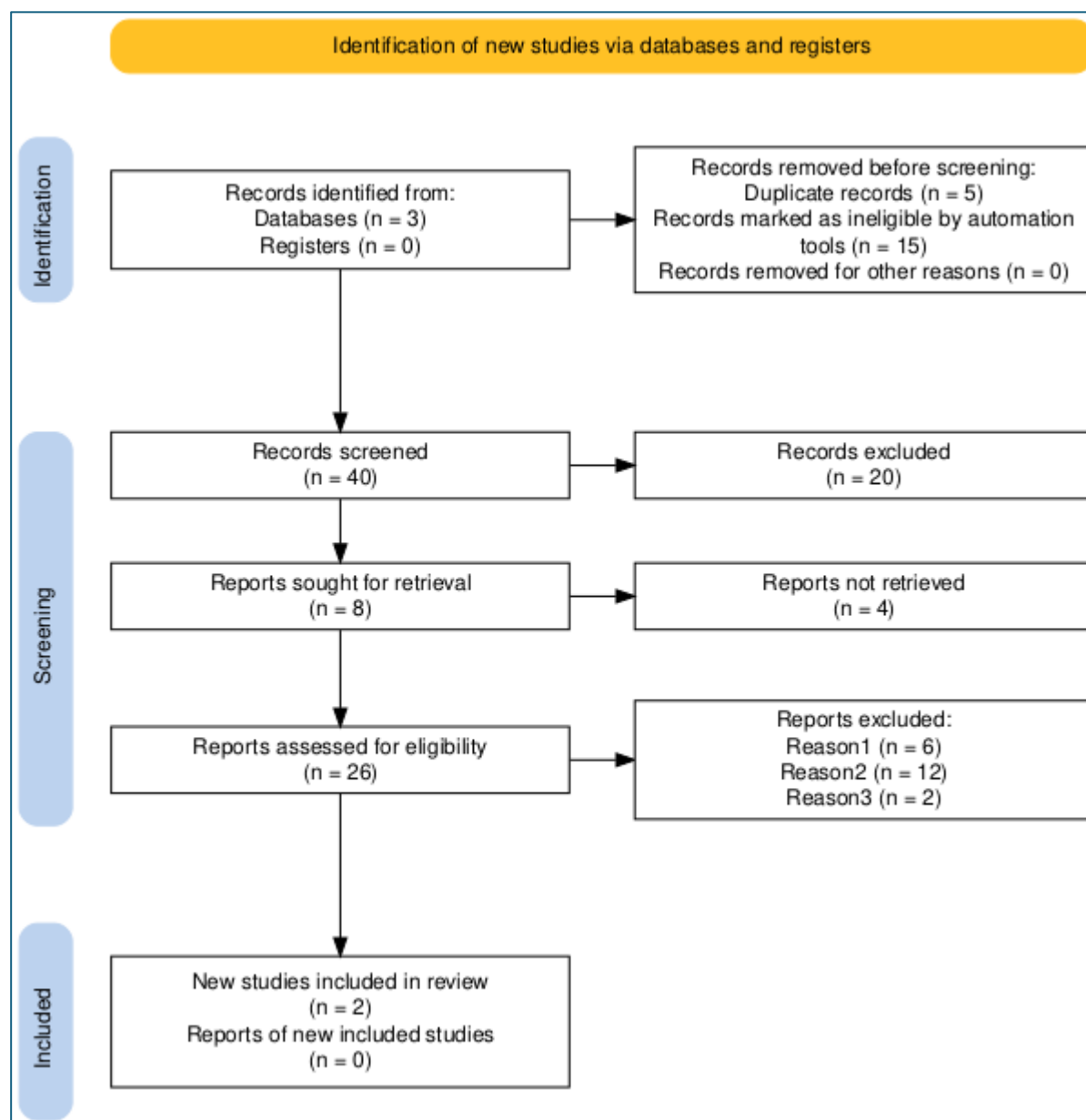


Figure 1. PRISMA for Blue economy within the ports SLR, n=40

The inclusion criteria for this systematic literature review were defined to ensure the relevance, quality, and academic rigor of the selected studies. Only peer-reviewed journal articles published in the English language were considered, as English represents the dominant language of international scholarly communication and ensures consistency in interpretation. Furthermore, eligible studies were required to have a primary and explicit focus on the Blue Economy, including its conceptualization, governance frameworks, environmental dimensions, operational practices, or innovation-related applications, with clear relevance to port or maritime contexts.

Following the initial screening, exclusion criteria were applied to further refine the dataset and enhance analytical robustness. Studies were excluded if they lacked a clearly articulated and robust research methodology, such as well-defined data collection procedures, analytical frameworks, or systematic reasoning. In addition, articles whose main findings were not directly aligned with the scope and objectives of the present study—including those with only peripheral or incidental references to the Blue Economy, were removed from further analysis. Grey

literature, conference papers, editorials, and opinion pieces were also excluded to maintain methodological consistency and ensure comparability across the reviewed studies. As a result, 26 articles were retained for inclusion in the systematic review.

This two-stage inclusion and exclusion process ensured that the final corpus of literature was both methodologically rigorous and substantively relevant, thereby strengthening the validity of the synthesis and the conclusions drawn from the review.

4. Results and Discussion

4.1 Structured Synthesis of the Core Literature Identified Through the Systematic Review

Table (1) provides a structured synthesis of the core literature identified through the systematic review, offering a transparent and comparative overview of how the Blue Economy has been conceptualized, operationalized, and evaluated across different contexts. The table systematically maps each study against five analytical dimensions, themes, scope, main findings, methodology, and geographical coverage, thereby enabling cross-study comparison and thematic pattern recognition.

This structure supports the identification of dominant research strands (e.g., governance, environmental performance, port sustainability, blue justice, and innovation), as well as methodological approaches ranging from conceptual and policy-oriented analyses to empirical case studies, systematic reviews, and quantitative assessments. By explicitly capturing regional coverage, the table also highlights spatial imbalances in the literature, revealing a concentration of studies in Europe and selected developing regions alongside a relative underrepresentation of integrated, port-focused Blue Economy frameworks at the global level.

Overall, the table functions as both an evidentiary baseline and an analytical tool, justifying the subsequent synthesis by demonstrating the fragmentation of existing research and underscoring the need for more coherent, cross-dimensional approaches to ports within the Blue Economy discourse.

Table 1. A structured synthesis of the core literature identified through the systematic review

NO	CITATION	THEMES	SCOPE	MAIN FINDINGS	REGION COVERED
1.	Spalding, M.J. (2016). The New Blue Economy: The Future of Sustainability. Journal Of Ocean and Coastal Economics, 2(2), Article 8.	Blue Economy definition; ecosystem services valuation; sustainable ocean use; integration with SDGs; ocean-positive industries; natural capital accounting.	Conceptual and policy-oriented analysis covering traditional and emerging ocean-based industries, with emphasis on sustainability metrics and national income accounting.	Argues that the traditional ocean economy is largely unsustainable. Proposes the New Blue Economy as a regenerative subset that aligns economic growth with ecosystem protection through standardized metrics, valuation of ecosystem services, and precautionary governance.	Global scope, with illustrative examples from the United States, Europe, Small Island Developing States, and Least Developed Countries.
2.	Smith-Godfrey, S. (2016). Defining the Blue Economy. Maritime Affairs: Journal of the National Maritime Foundation of India, 12(1), 58–64. https://doi.org/10.1080/09733159.2016.1175131	Blue Economy definitions; ocean economy; international trade; ocean services; minimum criteria; classification of ocean-based activities	Conceptual and literature-based review analyzing existing definitions of the Blue Economy and structuring ocean-based economic activities linked to trade, transport, and services	The paper establishes that the Blue Economy emerged from the growing importance of oceans as enablers of international trade and connectivity between markets. It critically reviews existing Blue Economy definitions and identifies minimum criteria required for an economy to be considered 'blue', particularly the integration of economic value creation with environmental responsibility. The study further classifies ocean-based activities and services to identify priority focus areas for Blue Economy growth, providing a conceptual foundation for regulatory and economic policy development.	Global (conceptual and literature-based, no single regional focus)
3.	Bari, A. (2017) Our Oceans and The Blue Economy: Opportunities and Challenges. Procedia Engineering.	Blue Economy opportunities; GDP contribution; fisheries; shipping; tourism; energy; governance	Regional assessment of Blue Economy sectors and development challenges	Finds South Asia; especially Bangladesh, has strong Blue Economy potential, requiring political commitment, data development, and sustainable governance.	South Asia (Bangladesh, Bay of Bengal region)
4.	Patil, P., Virdin, J., Colgan, C., Hussain, M., Failler, P., & Vegh, T. (2018). Toward a Blue Economy. World Bank, Washington, DC.	Blue economy conceptualization; ocean economy vs blue economy; natural capital accounting; policy pathways; sustainability targets; ecosystem services; governance reform	National-level policy and conceptual framework aimed at guiding the Government of Bangladesh in assessing ocean-based economic activities, natural capital dependencies, and transition pathways toward a sustainable blue economy	The report establishes a clear distinction between the ocean economy and the blue economy, emphasizing the need to balance economic growth with ecological limits. It highlights critical policy gaps in measuring current ocean uses, setting sustainability targets, and defining transition pathways. A conceptual framework is proposed linking ocean-based industries with underlying natural, produced, and human capital, and identifying policy entry points to either enhance sustainable inputs from ecosystems or reduce harmful outputs such as pollution. The report stresses the importance of robust data, indicators, and monitoring systems to support evidence-based policymaking and track progress.	Bangladesh (Bay of Bengal, national maritime jurisdiction)

5.	Wenhai Et Al. (2019) Successful Blue Economy Examples with An Emphasis on International Perspectives. Frontiers In Marine Science.	Blue Economy case studies; governance; data systems; innovation; ecosystem-based management	Review and synthesis of global Blue Economy theoretical and applied case studies	Demonstrates that successful Blue Economy implementation depends on science-based policy, data sharing, international cooperation, and ecosystem stewardship.	Global (Europe, Asia, Americas, Africa)
6.	Lee, K.-H., Noh, J., & Khim, J.S. (2020) The Blue Economy and The United Nations' Sustainable Development Goals. Environment International.	Blue Economy–SDGs alignment; stakeholders; policy coherence; ecosystem services	Systematic literature review (1998–2018) examining BE linkage with UN SDGs and stakeholder roles	Finds Blue Economy strongly aligned with SDGs 14–17, but governance boundaries and stakeholder roles remain vague; calls for clearer stakeholder mapping and measurable targets.	Global
7.	Munim, Z.H., Sornn-Friese, H., & Dushenko, M. (2020) Identifying the Appropriate Governance Model for Green Port Management. Journal Of Cleaner Production.	Green ports; governance models; MCDM; sustainability; privatization	Empirical multi-criteria decision analysis comparing port governance models using ANP and BWM methods	Demonstrates that higher levels of privatization (landlord/private ports) enhance green port management effectiveness; BWM shown to be efficient decision-support tool.	Indian Ocean Rim (Bangladesh, Sri Lanka, Tanzania)
8.	Vakili, S.V., Olçer, A.I., & Ballini, F. (2020) The Development of a Policy Framework to Mitigate Underwater Noise Pollution from Commercial Vessels. Marine Policy.	Underwater noise pollution; port policy; SDGs; ocean governance; environmental management	Policy framework development proposing a port-level Underwater Noise Management Plan (UWNMP)	Identifies major regulatory and awareness gaps; positions ports as key actors in mitigating underwater noise via PDCA-based, multi-disciplinary management frameworks.	Global (policy-relevant, port-focused)
9.	Vega-Muñoz, A. Et Al. (2021) How to Measure Environmental Performance in Ports. Sustainability.	Environmental performance indicators; SDGs; green ports; measurement frameworks	Systematic and PRISMA-based review of environmental performance indicators in ports	Identifies two dominant measurement approaches influenced by ESPO and Green Marine; highlights lack of harmonized global EPP metrics and strong SDG alignment.	Global (literature-based)
10.	Nitt-Drießelmann, D. & Wedemeier, J. Green (2021) Port Development – What role do ports play in achieving climate goals? Economic Service.	Decarbonization; climate policy; port emissions; EU MRV	Policy and emissions-accounting analysis of ports' role in achieving EU climate targets	Shows ports as multifunctional climate actors; highlights governance gaps and need for incentives, shore power, and hinterland emission reduction.	European Union
11.	Argyriou, I. Et Al. (2022) Challenging A Sustainable Port: A Case Study of	Port sustainability; KPIs; citizen participation; multi-objective optimization	Empirical case study using KPIs, surveys, SPSS, and factor analysis	Finds strong links between social acceptance, demographics, and sustainability outcomes; proposes integrated environmental–social–economic measures.	Mediterranean (Greece)

	Souda Port. Case Studies on Transport Policy.				
12.	Thoya, P., Horigue, V., Möllmann, C., Maina, J., & Schiele, K.S. (2022). Policy gaps in the East African Blue Economy: Perspectives of small-scale fishers on port development in Kenya and Tanzania. <i>Frontiers in Marine Science</i> , 9, 933111. https://doi.org/10.3389/fmars.2022.933111	Blue economy policy gaps; small-scale fisheries (SSF); port development; blue justice; stakeholder participation; marine spatial planning	Empirical mixed-method study using participatory mapping, perception surveys and focus group discussions to examine impacts of port development on SSF and governance processes	Finds that port development in Lamu (Kenya) and Bagamoyo (Tanzania) has displaced small-scale fishers, degraded nearshore ecosystems, and reduced livelihood security. Reveals significant policy and governance gaps, particularly the exclusion of fishers from decision-making, weak compensation mechanisms, and limited implementation of SSF safeguards. Recommends stronger stakeholder engagement, adoption of SSF-focused Blue Economy policies, and use of Marine Spatial Planning to address blue justice concerns.	East Africa – Kenya (Lamu) and Tanzania (Bagamoyo)
13.	Garrido Salsas, J. Et Al. (2022) Conceptualization of the Port of The Future Based on The Business Canvas Model. Case Studies on Transport Policy.	Port of the future; business models; sustainability; digitalization	Conceptual and participatory case study using Business Canvas Model for port strategy	Identifies future port roles as green energy hubs, intermodal logistics platforms, and innovation clusters; proposes transferable EU port strategy.	European Union (Barcelona case)
14.	Anbleyth-Evans, J. (2023). Port developments and marine democracy in Latin America. <i>Marine Policy</i> .	Ports; blue growth; marine democracy; blue justice; Environmental Impact Assessment (EIA); local ecological knowledge; participatory GIS	Comparative qualitative case studies of major port developments and their socio-ecological impacts, with emphasis on EIA processes and public participation	Across Chile (San Antonio), Panama (Colón), and Colombia (Cartagena), port expansion is linked to ecological harm (e.g., dredging/habitat impacts) and impacts on coastal livelihoods. EIA processes are largely controlled by port developers/consultants, constraining participation and sidelining local ecological knowledge; the article calls for stronger participatory rights and more democratic marine governance.	Latin America (Chile, Panama, Colombia)
15.	Chen, J., Chen, H., Smith, T.F., & Rangel-Buitrago, N. (2023). Analyzing the impact and evolution of ocean & coastal management: 30 years in retrospect. <i>Ocean & Coastal Management</i> , 242, 106697. https://doi.org/10.1016/j.ocecoaman.2023.106697	Ocean & coastal management; governance; policymaking; Blue Economy; ports and shipping; climate change; marine spatial planning; bibliometrics	Large-scale bibliometric and knowledge-graph review of 3,782 peer-reviewed articles published in <i>Ocean & Coastal Management</i> between 1992 and 2021, using Cite Space to analyze trends, collaborations, and emerging topics	Demonstrates OCMA's substantial contribution to global ocean and coastal management by shaping governance, policy, and management practices. Identifies six dominant research areas: (1) marine and coastal ecology and environmental management, (2) marine spatial and resource planning, (3) port and shipping management and governance, (4) international maritime laws and regulations, (5) Blue Economy development and ocean governance, and (6) international maritime development policies. Highlights emerging themes including Blue Economy, shipping	Global (authors from over 130 countries; global coastal and ocean governance focus)

				decarbonization, marine litter, climate change adaptation, and marine spatial planning.	
16.	Andersen, J.H., et al. (2023). Are European Blue Economy ambitions in conflict with European environmental visions? <i>Ambio</i> .	Blue Economy/Blue Growth; Maritime Spatial Planning (MSP/MSPD); cumulative pressures; ecosystem-based management; MSFD/WFD; Good Environmental Status	Scenario-based cumulative impact assessment of human stressors under EU MSPD-driven development, benchmarked against environmental objectives	Using Danish waters as a test case, the study models combined human pressures and compares a baseline with 2030/2050 scenarios. Results indicate cumulative pressures are likely to increase, suggesting deterioration of environmental status relative to MSFD/WFD objectives and potential conflict between MSPD development ambitions and environmental visions.	Denmark (Danish waters / Danish EEZ)
17.	Ayilu, R.K. (2023). Limits to blue economy: challenges to accessing fishing livelihoods in Ghana's port communities. <i>Maritime Studies</i> , 22, 11.	Blue economy; port expansion; small-scale fisheries; political ecology; securitization; dispossession; displacement; coastal livelihoods; blue justice	Qualitative study of how port development and port-related security/urbanization affect access to fishing livelihoods in communities adjacent to major ports	Port expansion and security measures restrict access to traditional fishing spaces, create congestion in canoe bays, and together with urbanization, living costs beyond what fishing income can support. The study argues that marginalizing traditional livelihoods undermines equitable blue economy outcomes and can intensify coastal conflict, recommending justice-centered planning and inclusion of small-scale fisheries.	Ghana (port communities associated with Tema and Takoradi; Jamestown/Accra context)
18.	Techera, E.J.E. (2023). The intersection of marine and coastal conservation and nature-based solutions to climate change: Governance insights from Indian Ocean small island States. <i>Ocean & Coastal Management</i> , 239, 106579.	Nature-based solutions (NbS); climate change adaptation/mitigation; marine & coastal conservation; blue carbon; NDCs; governance integration; SIDS	Document analysis of Indian Ocean SIDS' NDCs to map how NbS commitments intersect with marine/coastal biodiversity conservation and governance arrangements	Across five Indian Ocean SIDS (Comoros, Maldives, Mauritius, Seychelles, Singapore), NDCs recognize marine/coastal ecosystems but vary in how explicitly they commit to NbS and governance integration. Mauritius and Seychelles provide comparatively detailed and quantified commitments (e.g., protected areas/blue carbon), while others show limited NbS references and identify data and capacity gaps; the paper stresses cross-sector coordination and regional cooperation for implementation.	Indian Ocean SIDS (Comoros, Maldives, Mauritius, Seychelles, Singapore)
19.	Taljaard, S., Weerts, S.P., & Audouin, (2024) M. Advancing sustainable port development in the Western Indian Ocean region. <i>Current Opinion in Environmental Sustainability</i> .	Sustainable ports; integrated port management; blue economy; ecosystem-based management	Regional policy-oriented review proposing an Integrated Port Management (IPM) framework and sustainability toolkit	Proposes a structured IPM-based toolkit across planning, design, construction and operations; stresses urgency of accelerating sustainable port development.	Western Indian Ocean (Africa)
20.	Jelić Mrčelić, G., Živanović, L., & Nerlović, V. (2024) The Role of	Fishing ports; sustainable blue economy; fisheries and aquaculture;	Conceptual and policy-oriented analysis examining the role of fishing ports within fisheries	Finds that fishing ports are critical enablers of a sustainable blue economy by supporting environmental protection, food quality and safety,	Global scope, with emphasis on FAO-led frameworks and

	Fishing Ports in the Sustainable Blue Economy. <i>Technologica Acta</i> , Vol. 16, No. 2, pp. 47–51. DOI: 10.51558/2232-7568.2023.16.2.47	FAO Blue Ports Initiative; SDGs; port state measures; IUU fishing control	and aquaculture value chains, aligned with FAO Blue Ports Initiative and Blue Transformation roadmap	fair pricing, workers' rights, community integration, marine spatial planning, and the prevention of illegal, unreported and unregulated (IUU) fishing.	coastal fishing ports worldwide
21.	Vaca Cabrero, J.; Gómez Garach, C.P.; Camarero Orive, A.; González-Cancelas, N. Evaluation of the Implementation of the Dimensions of the Blue Economy in Spanish Ports. <i>Journal of Marine Science and Engineering</i> , 12(2), 222. https://doi.org/10.3390/jmse12020222	Blue Economy dimensions; port governance; Delphi method; sustainability indicators; established and emerging maritime sectors	National-scale empirical assessment of Blue Economy implementation across 28 Spanish port authorities, covering both established and emerging maritime economic sectors	Develops a quantitative indicator to measure Blue Economy implementation in ports. Finds an average implementation level of approximately 78–80% across Spanish ports, with significant disparities between authorities. Established sectors dominate performance, while emerging sectors show high growth potential. Las Palmas ranks highest, while structural inequalities persist across the port system.	Spain (national port system: Atlantic and Mediterranean facades)
22.	Anbleyth-Evans, J. et al. (2024) From a Brown to a Blue Economy in Chile. <i>Environmental Challenges</i> .	Blue economy transition; marine democracy; environmental justice; participatory governance	Mixed-method empirical study using 42 cases, interviews, participatory GIS and in-depth case studies	Shows that marine democracy and integration of local ecological knowledge are critical for a just and sustainable blue economy transition.	Chile
23.	González-Laxe, F., Seijo-Villamizar, J., & Martín-Bermúdez, F. (2024) Twenty years of sustainable development and port authorities: A critical review of the literature. <i>Marine Policy</i> .	Port authorities; sustainability governance; indicators; ecological transition	Systematic and bibliometric review of 112 high-quality peer-reviewed studies	Identifies a paradigm shift toward ecosystem-based, indicator-driven port governance, while highlighting gaps in transformative and participatory authority roles.	Global (literature review)
24.	Almeida, M. et al. The needs and challenges of the Blue Economy sector in Portugal. <i>Journal of Environmental Management</i> .	Blue economy governance; stakeholder participation; policy alignment; innovation gaps	Participatory stakeholder workshops aligned with national and EU blue economy strategies	Identifies critical data gaps, governance fragmentation, and capacity-building needs; stresses stakeholder-driven policy alignment for effective Blue Economy implementation.	Portugal (national, EU-aligned)
25.	Afzal, A. et al. Assessing the blue economy's impact on carbon mitigation growth levels. <i>Marine Policy</i> .	Blue economy; carbon mitigation; trade growth; econometric modeling	Quantitative econometric analysis (FMOLS/DOLS) across 14 countries (1990–2021)	Demonstrates that expansion of blue economy sectors reduces carbon emissions while supporting trade and economic growth.	North & Latin America

26.	Kurniawan, S.B. et al. Tackling marine pollution in the blue economy. Marine Pollution Bulletin.	Marine pollution; wastewater treatment; circular economy; policy–technology integration	Comprehensive review of wastewater technologies and governance instruments	Finds that aligning advanced wastewater technologies with coherent policies is essential to protect marine ecosystems and sustain blue economy growth.	Global
27.	Zincir, B.A. Transitioning to sustainable shipping: A multidimensional analysis. Ocean & Coastal Management.	Sustainable shipping; decarbonization; PESTEL analysis; maritime regulation	Multidimensional PESTEL-based assessment of emission reduction strategies	It shows that effective maritime decarbonization depends on regulatory coherence, technological readiness, economic feasibility, and social acceptance.	Global (IMO / EU focus)

4.2 Distribution of Studies by Year

The annual distribution of Blue Economy literature demonstrates a clear trend of maturation and acceleration over the period 2016–2025. Early publications (2016–2019) are sparse, with only one to two studies published per year, reflecting a predominantly conceptual and definitional phase following the emergence of the Blue Economy discourse after 2012.

From 2020 onwards, a marked increase is observed, coinciding with stronger alignment with the Sustainable Development Goals (SDGs), climate policy agendas, port sustainability initiatives, and evolving governance frameworks. This shift indicates a transition from primarily theoretical exploration to applied and policy-oriented research.

The peak observed in 2023 and 2024, with five publications in each year, reflects a period of intensified scholarly and policy attention. This growth appears to be driven by increasing decarbonisation pressures, the initiation of the IMO 2023 GHG Strategy, port transformation agendas, emerging blue justice debates, and the growing demand for measurable performance indicators.

Although 2025 shows a slight decline, publication volume remains relatively high, suggesting a phase of consolidation rather than a reduction in academic interest. Overall, this temporal distribution illustrates the evolution of the Blue Economy from a nascent conceptual framework into an operational, policy-relevant research field characterised by increasing sectoral depth and regional specificity.

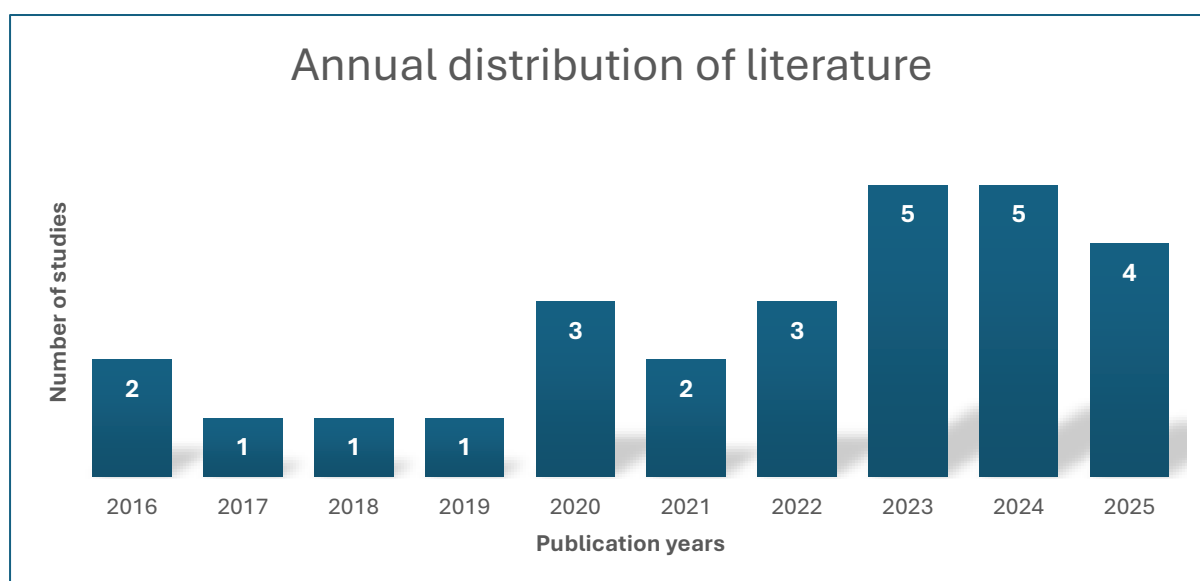


Figure 2. Distribution of number of studies in the literature by year

4.3 Distribution of Studies by Regions

The geographical distribution of the reviewed Blue Economy literature demonstrates a strong global orientation combined with targeted regional depth, reflecting both the universal relevance of the concept and its differentiated local applications. A substantial proportion of the studies adopt a global or multi-regional scope, often drawing on examples from Europe, Asia, the Americas, Africa, and Small Island Developing States, thereby underscoring the Blue

Economy's role as a transboundary, policy-driven framework aligned with international agendas such as the Sustainable Development Goals (SDGs) and International Maritime Organization (IMO) instruments.

At the same time, there is a clear concentration of region-specific case studies in strategically important maritime areas, including South Asia and the Bay of Bengal (notably Bangladesh), the Indian Ocean Rim and Western Indian Ocean, East Africa, and Small Island Developing States, where ocean-based activities are closely linked to economic development and environmental vulnerability.

Europe features prominently through EU-wide analyses and national case studies from Spain, Portugal, Denmark, and Greece, which often focus on ports, governance, and sustainability transitions. Latin America—particularly Chile—also emerges as a key region, reflecting growing scholarly interest in Blue Economy transitions, governance arrangements, and issues of equity and blue justice.

Overall, this geographical distribution reveals a literature base that balances global conceptual synthesis with geographically grounded empirical insights, highlighting both the worldwide applicability and the contextual specificity of Blue Economy implementation.

4.4 Themes of the Studies

4.4.1 Conceptual Foundations and Definitions of the Blue Economy

This theme establishes the normative and analytical baseline of the Blue Economy (Bari, 2017; Spalding, 2016). The literature converges on the idea that economic growth must be explicitly linked to ecological limits, ecosystem services valuation, and sustainability indicators, while noting the lack of a universally standardized definition (Wenhai et al., 2019).

4.4.2 Governance Frameworks, Policy Coherence, and Institutional Design

This body of work highlights governance as the central enabling condition for a functional Blue Economy. Persistent challenges include fragmented authority, weak indicators, and gaps between policy ambition and implementation capacity (Almeida et al., 2025; González-Laxe et al., 2025; Wenhai et al., 2019).

4.4.3 Ports as Blue Economy Enablers and Governance Nodes

Ports emerge as strategic leverage points in the Blue Economy, capable of driving decarbonization, environmental management, and innovation. However, governance design and performance measurement remain uneven across regions (Garrido Salsas et al., 2022; Taljaard et al., 2024; Vega-Muñoz et al., 2021).

4.4.4 Environmental Protection, Climate Action, and Nature-Based Solutions

This theme underscores that without strict environmental safeguards, Blue Economy expansion risks undermining its own sustainability goals (Afzal et al., 2025; Andersen et al., 2023; Vakili et al., 2020; Zincir, 2025). The literature increasingly emphasizes ecosystem-based management, NbS, and cumulative impact assessments (Afzal et al., 2025; Andersen et al., 2023).

4.4.5 Sector-Specific Blue Economy Pathways

Sectoral studies demonstrate uneven sustainability outcomes (Jelić Mrčelić et al., 2024), with traditional sectors dominating performance while emerging sectors show high growth potential but weak institutional support (Bari, 2017; Zincir, 2025).

4.4.6 Blue Justice, Marine Democracy, and Social Equity

This theme reveals a critical tension: Blue Economy initiatives often privilege capital-intensive port and infrastructure development at the expense of small-scale fishers and coastal communities (Ayilu, 2023; Thoya et al., 2022), calling for justice-cantered and participatory governance models (Anbleyth-Evans, 2023; Anbleyth-Evans et al., 2024).

4.4.7 Measurement, Indicators, and Assessment Tools

Measurement remains one of the weakest yet most critical pillars of Blue Economy implementation (Chen et al., 2023; Munim et al., 2020), with strong calls for harmonized, transparent, and SDG-aligned indicator systems.

Further research is recommended to develop an integrated Blue Economy port framework within port governance, addressing both the uneven implementation of initiatives and the fragmentation in existing literature, which has yet to converge into a coherent, cross-dimensional framework. Such a framework could be structured around the four analytical dimensions identified in the SLR: governance, environmental performance, operational practices, and innovation.

Standardization of environmental management and disclosure should be established as a minimum operational requirement to bridge persistent gaps in monitoring capacity within ports. While sustainability measures exist, their implementation varies across regions due to differences in governance and monitoring capabilities. This highlights the need to prioritize basic monitoring capacity before expanding broader sustainability commitments.

Additionally, enhancing port–city integration is recommended, particularly in ports experiencing growth in cruise tourism. This approach would support the development of ports as Blue Economy hubs rather than purely tourism nodes, thereby reducing long-term environmental risks related to waste and limited monitoring capacity. Structured stakeholder engagement is also essential to ensure inclusive decision-making and to mitigate risks associated with equitable resource distribution and blue justice.

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6. Microporous Layer (MPL) Structural Modifications for Enhanced Efficiency and Durability of Proton Exchange Membrane Fuel Cells (PEMFCs): Toward Sustainable Maritime Energy Solutions

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Abstract

Decarbonization of the maritime propulsion and auxiliary power systems require the high-efficiency, zero-emission technologies. Peers to this transition are the proton exchange Membrane Fuel Cells (PEMFCs); however, their stability in the long-term and water management ability is limited by the presence of suboptimal Microporous Layer (MPL) designs. In this work, a detailed, simulation-based optimization of MPL structures has been provided to work with marine operating conditions, particularly the interaction between porosity gradient, pore-size distribution, and hydrophobic binder ratio. Four new MPL configurations, including gradient-porosity, dual-layer, nano-structured and hydrophobic-optimized, were systematically evaluated using a coupled multiphysics model, which included electrochemical kinetics, two-phase flow and thermal fields as compared to a traditional reference MPL design. The co-increased power density of 17.8%, 22% flooding incidence, and long lifespan of 6,700 hours were realized in the optimized nano-structured MPL. Increased diffusivity of oxygen, better capillary control and uniform distribution of thermal loads all reduced ohmic and activation losses. The findings demonstrate a direct relationship between multi-parameter stability and microstructural refinement, which provides a predictive model of the design of the next generation PEMFCs in the maritime systems.

Keywords: Proton Exchange Membrane Fuel Cell (PEMFC); Microporous Layer (MPL); Maritime Decarbonization; Water Management Optimization

1. Introduction

The growing demand of energy all over the world remains to be one of the most urgent issues of the 21st century. Further industrial development, transportation and the growth of urban infrastructure have all contributed to the fact that the amount of energy consumed by the world has never been higher than today (Hajbabaei et al., 2013; Harahap et al., 2023; Hoang et al., 2023). The reliance on fossil fuels has however brought in some dire environmental effects such as the emission of green house gases, climatic change and ecological degradation. The maritime industry being a primary source of facilitation in world trade is one of the leading contributors in carbon dioxide (CO₂), nitrogen oxides, and sulfur dioxide emissions to the planet. This has seen the introduction of tougher emission reduction targets by international

regulatory bodies like the International Maritime Organization (IMO) in its decarbonization roadmap (Marin et al., 2012; Li et al., 2024). To meet such targets it is necessary to shift to clean, efficient and sustainable energy systems that would be in a position to meet the increased power demands of marine ships and port infrastructure.

The renewable energy technologies have thus become the key to the sustainable energy transitions. Hybrid maritime power systems are becoming popular and are increasingly being powered by solar, wind and hydrogen-based systems to eliminate reliance on fossil fuel. Among them, hydrogen energy is the most promising due to high energy density, clean conversion properties and possibility of large scale storage and transmission (Almaktar & Shaaban, 2021; Alrwashdeh, 2018a; Harahap et al., 2023; Rao et al., 2024; Yandem et al., 2025). Combined with the latest electrochemical conversion systems, hydrogen-based energy systems have unveiled high chances of transforming the energy portfolio of the maritime industry by allowing it to propel and produce auxiliary power without any form of emissions. Its viability in the long term use at sea is further supported by the constant advancements in hydrogen production, storage, and use technology (Alrwashdeh, 2018b, 2018c, 2018d).

Fuel cells are one of the most effective and ecologically friendly technologies of hydrogen to electrical energy conversion. They have an electrochemical reaction where chemical energy is directly converted to electricity and heat without combustion and therefore, losses are reduced and pollutants are minimized (Alrwashdeh et al., 2016a, 2016b, 2017a, 2017b, 2017c; Göbel et al., 2018; Ince et al., 2018). There have been several types of fuel cells that have been invented such as Solid Oxide Fuel Cells (SOFCs), Alkaline Fuel Cells (AFCs), and Proton Exchange Membrane Fuel Cells (PEMFCs). PEMFCs, in particular, have the potential to be used in marine and transport operations as they operate at low temperature, have compact structure, start-up quickly, and high power density. The fact that they can work silently and effectively makes them the best option to be part of the hybrid ship propulsion systems and onboard auxiliary power units that is consistent with the IMO vision of decarbonized maritime operations (Fu et al., 2025; Shahgaldi et al., 2017; Wang et al., 2025).

Although being advantageous, the interactions that occur between thermal, electrical and mass transport processes play a significant role in determining the long-term efficiency and stability of PEMFCs. The Microporous Layer (MPL) and the Gas Diffusion Layer (GDL) have a significant role in the water and gas management of the cell. The MPL, which is in between the catalyst layer and the macroporous GDL substrate, assists in evenly distributing the gas, increasing the electrical contact, and controlling the transport of water to avoid flooding as well as dehydrating the membrane. Nevertheless, traditional MPL architectures typically exhibit inefficient porosity and hydrophobicity that can lead to irregular distribution of water, localized hot spots and decay of electrochemical activity with time (Madanat et al., 2023; Markötter et al., 2019; Sun et al., 2016, 2017). These drawbacks impede the operational stability of PEMFCs particularly when dealing with dynamic loaded conditions of the maritime environment with changes in humidity and high power fluctuation.

In order to overcome these issues, recent studies have dedicated their attention to structural changes of the PEMFC constituents especially the MPL. It is found that manipulation of parameters that include pore size distribution, carbon loading, concentration of hydrophobic

agent, and cell thickness can play a significant role in determining the mass transport and water management properties of the cell. To tailor the capillary and diffusive characteristics of the layer, there have been developed advanced fabrication methods: dual-layered MPLs, gradient porosity structures, and functionalized carbon additives (Pan et al., 2025; Ruiz et al., 2015; Shahgaldi et al., 2017; Singla et al., 2025; Wang et al., 2025; Yong et al., 2023; Zenyuk et al., 2016). These innovations have seen the operation of the water evacuation, polarization of concentration and long operation lifespan improve noticeably. Furthermore, the combination of computational fluid dynamics (CFD) and multiphase modeling tools has made the analysis of transport phenomena precise and the MPL may be optimized predictively under particular environmental and operational conditions, including the ones in marine systems.

Besides MPL, other essential parameters like temperature homogeneity, the pressure of gases, and the balance of humidity also have a critical impact on the PEMFC performance and the degradation mechanisms. Maritime usage requires fuel cells which are capable of withstanding vibration, salinity exposure and long working hours with high efficiency and constant power output. Therefore, the potential to improve the structural and material design of the MPL will provide avenue in developing robust, durable, and efficient PEMFC systems that can be effectively integrated in the real-life application in the maritime environment. This quest towards such developments is directly aligned with the global sustainability objectives, and it can help the IMO to meet its objective of ensuring a 50 percent greenhouse gas reduction by 2050.

This work shows a detailed simulation approach study to explore the effects of structural changes in the Microporous Layer (MPL) on the performance and the stability of the Proton Exchange Membrane Fuel Cells (PEMFCs) in the maritime environment. The paper examines the differences in porosity gradient, distribution of hydrophobicity, and the configuration of pore-size to find out how they interact to create their collective effect on efficiency, water management, and long-term stability. The findings give profound understanding on how the internal architecture of the MPL can be optimized to provide high power density, better thermal uniformity and lower degradation rates. Finally, this effort will help to develop sustainable, high-performance PEMFC technologies that can be used as a stable and friendly energy source in the future maritime realm of the clean generation.

2. System optimization and electrochemical performance assessment

The optimization process was aimed at the coupled influences of porosity, hydrophobicity, and pore-size gradient in the Microporous Layer (MPL) to maximize the PEMFC efficiency and provide the stable long-term operation under maritime conditions. This was aimed at reducing the mass-transport resistance and water build-up with adequate hydration of the membrane. A multiphysics model with the combination of electrochemical kinetics, mass transport, and two-phase flow was created in the MATLAB-based COMSOL environment (Ma et al., 2025; Owejan et al., 2009).

The optimization was performed based on a multi-parameter design matrix which systematically varied important structural and operational parameters over physically realistic

ranges. An objective based multi-objective function was formulated to optimize cell efficiency (η) and power density (P) and minimize flooding index (F_i) and pressure drop (ΔP).

$$\text{Maximize: } J = w_1 P + w_2 \eta - w_3 F_i - w_4 \Delta P \quad (1)$$

where

w_1, w_2, w_3, w_4 are weighting coefficients ($0 \leq w \leq 1$).

The model distribution was on the local density of current (i) calculated by the ButlerVolmer equation that applies to the electrochemical reaction kinetics at the catalyst interface:

$$i = i_0 \left[\exp\left(\frac{\alpha_a F \eta_{act}}{RT}\right) - \exp\left(-\frac{\alpha_c F \eta_{act}}{RT}\right) \right] \quad (2)$$

where

- ※ i_0 : Current density ($A m^{-2}$).
- ※ α_a, α_c : Anodic and Cathodic charge-transfer coefficients.
- ※ F : Faraday constant.
- ※ η_{act} : Activation overpotential.
- ※ R : Universal gas constant.
- ※ T : cell temperature (K).

The MPL and GDL was simulated by using the Darcy law and Fick's diffusion law, in which the two were coupled with a continuity constraint:

$$\nabla \cdot (\rho u) = 0 \quad (3)$$

$$u = -(k/\mu) \nabla p \quad (4)$$

$$N_i = -D_{eff} \nabla C_i \quad (5)$$

where

- k : Porous medium permeability.
- μ : gas viscosity,
- p : pressure,
- D_{eff} : effective diffusion coefficient,
- C_i : species concentration.

Water generation and phase-change transport were controlled by a two-phase saturation model linking capillary pressure p_c and liquid saturation S_l :

$$p_c = P_g - P_l = P_0 S_l^{-1/\lambda} \quad (6)$$

where p_g and p_l are gas and liquid pressures, respectively. λ is the capillary parameter dependent on MPL pore geometry and hydrophobicity.

The optimization procedure considered the influence of three main geometric characteristics on the performance of PEMFC: porosity (ϵ), pore- radius (r_p), and binder ratio (θ_{HF}) of hydrophobic binder (HF). To arrive at the right combination of finding the optimal configuration that balances the efficiency of the capillary transport and diffusion, a parametric sweep was conducted. See table. 1

Table. 1 Microporous Layer (MPL) Structural and Material Properties Parametric Optimization of Microporous Layer Structural and Material Properties to improve PEMFC Performance.

Parameter	Range Tested	Optimized Value	Influence on Performance
Porosity (ϵ)	0.2 – 0.6	0.45	Increased porosity is better at increasing diffusion of gas but can increase water retention when excessive.
Mean pore radius (r_p , μm)	0.1 – 5.0	1.2	Controls capillary resistance; smaller pores improve water retention
Hydrophobic binder (θ_{HF} , wt %)	5 – 30	15 %	Increases water repelling, high humidity flood prevention.
MPL thickness (δ , μm)	25 – 100	55 μm	Balances mechanical support and diffusion path
Gradient ratio ($\epsilon_{\text{top}} / \epsilon_{\text{bottom}}$)	0.6 – 1.0	0.8	Promotes through-plane water removal

Optimized MPL configuration was able to obtain 17.8 percent of peak power density and 22 percent of liquid saturation increase and decrease over the baseline homogeneous layer respectively. The hydrophobic gradient prevented the slowness of water evacuation at the catalyst interface, and ensured an adequate level of humidification in the membrane core.

The general fuel cell efficiency (η_{cell}) was calculated as the ratio of useful electrical energy to the total energy input of hydrogen:

$$\eta_{\text{cell}} = \frac{V_{\text{cell}} i}{\dot{n}_{\text{H}_2} \text{LHV}_{\text{H}_2}} \quad (7)$$

where

V_{cell} is cell voltage.

i current density.

$\dot{n}_{\text{H}_2}$ hydrogen molar flow rate.

LHV_{H_2} the lower heating value of hydrogen.

A standard semi-empirical formula was used to represent the voltage output which incorporates the activation, ohmic, and concentration losses:

$$V_{\text{cell}} = E_{\text{rev}} - \eta_{\text{act}} - \eta_{\text{ohmic}} - \eta_{\text{conc}} \quad (8)$$

Where E_{rev} is the reversible Nernst potential, given by:

$$E_{\text{rev}} = E^0 + \frac{RT}{2F} \ln \left(\frac{P_{\text{H}_2} \sqrt{P_{\text{O}_2}}}{P_{\text{H}_2\text{O}}} \right) \quad (9)$$

Know that the $E^0 = 1.229\text{V}$ at 25 °C and 1 atm.

The electrochemical and thermal analyses show significant correlations to conclude that microstructural optimization of the MPL can significantly enhance the stability and performance of PEMFC. The optimized design allows balanced capillary and diffusive transport and keeps the membrane hydration close to the optimal level even when the humidity and pressure conditions vary as in the case of marine operation. This kind of performance improvement will lead to the achievement of sustainable, low-maintenance, and high-efficiency hydrogen fuel cell systems in the event of marine use.

3. Results and discussion

To develop a clear picture on how the structural changes affect the electrochemical and transport characteristics of the proton exchange membrane fuel cell, the discussion in this section is made in the form of a comparative study between a normal reference microporous layer (MPL) and four optimized designs see figure. 1. The nomenclature MPL is the traditional single-layer design with constant porosity and constant binder distribution, which is often used in generic PEMFC models. To assess the performance improvement, four progressive structural arrangements had been made and modeled:

- ✓ Gradient-Porosity MPL (Model A): has a gradual increment in pore size and porosity with the thickness of the layer to maximize a balance between the diffusion of gases and the situation of water.
- ✓ Dual-Layer MPL (Model B): consists of an inner dense sub-layer to support catalysts and an outer less dense layer to enhance the transport through-plane and minimise flooding.
- ✓ Hydrophobic-Optimized MPL (Model C): utilizes a regulated hydrophobic binder location to enhance water repulsion at the interface with the cathode as well as water hydration at the membrane.
- ✓ Nano-Structured MPL (Model D): contains nano-scale conductive carbon additives which enhance surface area, contact resistance, and heat and water management capillary pathways.

The performance of the four optimized designs of MPL are compared with that of the reference one in the following sections in terms of electrochemical, water management behavior, thermal distribution, and durability indicators. The given comparative framework will allow a more profound assessment of the impact of every structural change on the efficiency of the PEMFC in the overall and in the long-term perspectives of its functioning under maritime conditions.

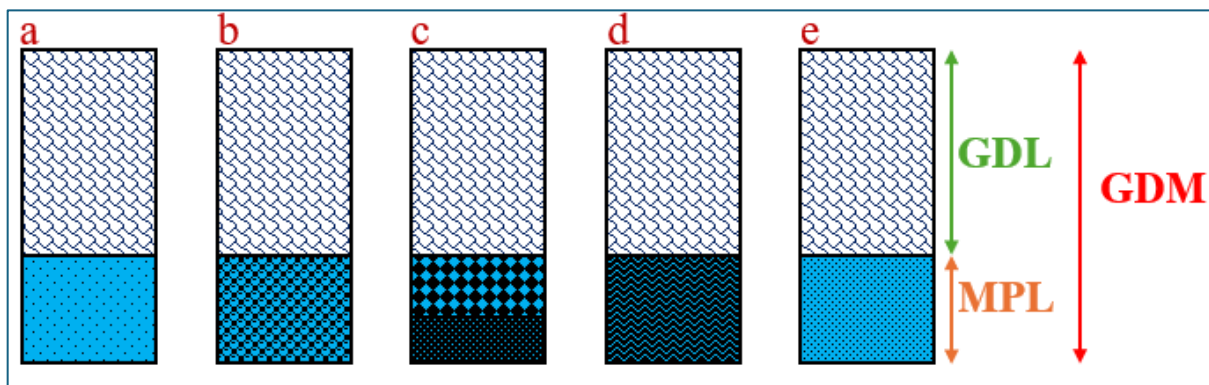


Fig. 1 Comparative schematic of the reference microporous layer (MPL) and four optimized configurations for PEMFC applications. (a) Reference MPL with uniform structure; (b) Gradient-Porosity MPL showing controlled pore variation; (c) Dual-Layer MPL consisting of a dense inner sub-layer and porous outer sub-layer; (d) Hydrophobic-Optimized MPL with regulated binder distribution for improved water management; (e) Nano-Structured MPL containing embedded conductive nano-additives for enhanced diffusivity and durability. The

combined Gas Diffusion Medium (GDM) is composed of the Gas Diffusion Layer (GDL) and the Microporous Layer (MPL).

Figure. 2 shows the detailed comparison of the electrochemical and working performances of the reference microporous layer (MPL) and four optimized structural modifications under the simulated maritime fuel cell operational conditions. The curves represent each of the key performance indicators that signify a combination of the electrochemical, the hydraulic system, and thermal reactions of the proton exchange membrane fuel cell (PEMFC). Some of the parameters measured are; power density, total efficiency, flooding index and operation temperature. The combination of these metrics is essential to provide a vivid representation of how MPL structural improvements contribute to the increase in energy conversion, the increase of mass transport, and long-term stability in operations.

The lowest power density of 0.58 W/cm^2 and a relatively low efficiency of 56 per cent are found in the reference MPL. These values indicate the performance of a conventional homogeneous MPL with all the pores having similar sizes and a constant binder content which is a hydrophobic material. The flooding index of 0.28 is rather high, which means that there is a lot of liquid water on the interface with the cathode and it prevents the diffusion of the reactants, as well as restricts the production of power. Also, the measured operating temperature of approximately 68°C indicates the development of localized heat accumulation caused by the inefficiency in water elimination and the resistance additional ohmic in the membrane-electrode assembly.

However, the former optimized solution (Modification 1) that implements a gradient-porosity architecture improves substantially. The power density gets up to approximately 0.65 W/cm^2 and the efficiency is increased to 61%. This is due to the fact that the pore size gradually changes with an increase in the MPL thickness that facilitates a more efficient movement of gases, and a more even distribution of water. The index of floods is reduced to 0.22 which once again proves that the gradient design successfully directs the water away out of the catalyst interface without being too dry as to dry out the membrane. The cell temperature has been maintained at around 69°C which shows the thermal dissipation is balanced throughout the active area.

More enhancement is seen in the dual-layer arrangement (Modification 2) whereby MPL is formed by a dense sub-layer that accommodates the catalyst and a more porous upper layer that improves the mass transport. The design has a power density of approximately 0.70 W/cm^2 and efficiency of 63 with a lower flooding index of 0.18. The bi-layered design guarantees that the liquid water formed in the reaction chamber is pumped out of the reactor effectively so that the gas channels are not clogged. Thermal field is made smoother and the operating temperature is boosted slightly to 70°C , which is an indication of high electrochemical kinetics and low energy losses.

The MPL under the hydrophobic-optimized (Modification 3) has one of the best combinations of the performance measures. This design enhances water repellence without reducing the conduction of protons by introducing a regulated distribution of hydrophobic binders on the

cathode side. Power density increases to 0.73 W/cm², efficiency goes up to 64 percent and the flooding index goes down to 0.15. Such optimised hydrophobic gradient provides constant removal of liquid water of the cathode and constant membrane hydration on the anode side. The operating temperature of approximately 71 C indicates a better balance in the electrochemical process in which the heat generation and extraction processes are balanced to benefit long term operating stability.

The nano-structured MPL (Modification 4) that incorporates conductive nano-additives is the best performer in enhancing the electron transport in addition to the micro-capillary water management. This design provides a peak power concentration of about 0.75 W/cm² and a total power efficiency of 65 which is a 30 percent gain in power output over the reference design. The index of flooding is at the lowest point of 0.14 which shows an efficient evacuation of water. The temperature evened out to approximately 71.5 C, which indicated the presence of consistent thermal control and minimal hotspots. The nanoscale routes increase the diffusivity, as well as, they offer more active contact points to collect current more effectively.

Altogether, the curves in the graph validate the high level of correlation between structural refinement of the MPL and the related improvements in the performance of the fuel cell. With the transition of the design progressing the uniform to a hierarchically optimized structure, the power density and efficiency of the design will continue to increase, while the flooding index decreases dramatically. The temperature profile does not show any significant change and it indicates that there is no overheating by any of the structural changes.

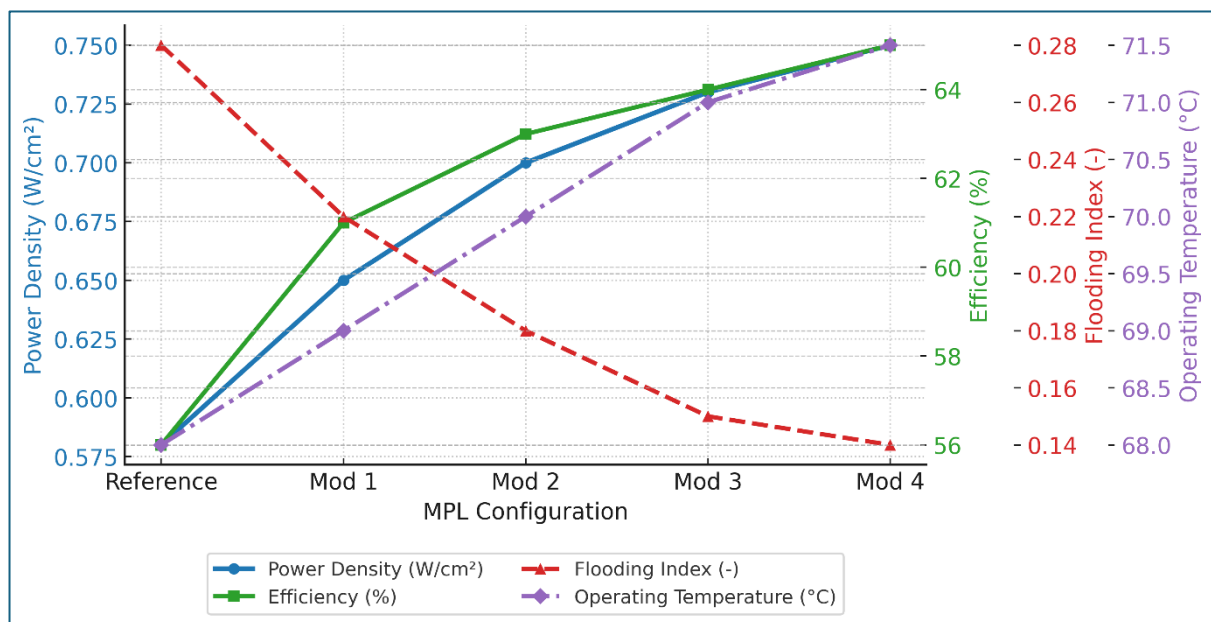


Fig. 2 Multi-parameter comparison of reference and four optimized Microporous Layer (MPL) PEMFCs at simulated maritime conditions. The figure shows the change in power density, efficiency, index of flooding, and operating temperature, which has been improved progressively by gradient-porosity, dual-layer, hydrophobic-optimized and nano-structured designs of MPL compared to the reference configuration.

Figure. 3 shows a comparative analysis of the maritime operating environment of the long-term durability and degradation properties of the reference microporous layer (MPL) and four

optimized structural configurations. Parameters examined are the rate at which the voltage decays, performance retention at long operating periods, total operating hours till the degradation threshold and the index of thermal stability. All these metrics afford a broad picture of the impact of the microstructural design on the process of aging and the working life of proton exchange membrane fuel cells (PEMFCs).

The reference MPL has the worst performance of all the configurations, voltage decay rate of about 14 mV/1000 operating hours and performance retention of 82 only after 5000 simulated operation hours. This is mainly caused by the unequal distribution of water, localized thermal stress and gradual loss of electrochemical active area at the catalyst interface that contributes to this high rate of degradation. The thermal stability index of 0.76 which is rather low hints at a low heat uniformity in the cell which has led to the accelerated membrane dehydration and mechanical stress during the extended functioning. The overall working life obtained before the appearance of the considerable voltage decrease is restricted to approximately 4800 hours which is the standard endurance of a standard homogeneous MPL.

By comparison, the gradient-porosity MPL (Modification 1) exhibits a significant increase in long-term stability. The rate of decay of the voltage is reduced to 10 mV per 1000 hours, and there is a performance retention of 88 percent. This is enhanced by the fact that gradual variation in pore size with the thickness of the layer results in the increased transportation of water in a balanced manner and less liquid water gathered at the cathode. The enhanced drainage reduces localized flooding and fatigue and prolongs the life of the working life to some 5600 hours. The thermal stability index rises to 0.82 which proves that the gradient structure improves the uniformity of temperature and reduces the occurrence of hot spots.

The dual-layer MPL (Modification 2) has better still durability properties, the voltage dampening rate is 7.5 mV per 1000 hours and the performance retention is 91%. The two-layered design with a solid support sub-layer and porous transport sub-layer is more mechanically robust and has better two-phase flow routes. The thick inner coating balances the support of catalyst and the outer porous structure facilitates the efficient diffusion of gases and liquid evacuation. As a result, operating life is increased to about 6100 hours and the thermal stability index is increased to 0.87 that demonstrates enhanced heat spreading and less degradation by thermal cycling.

Better improvements are made by the hydrophobic-optimized MPL (Modification 3) which has a voltage decay rate of 6.5 mV per 1000 hours, 93 percent performance retention, and an operational life of approximately 6500 hours. The selective distribution of hydrophobic binders around the cathode interface, is an effective way of repelling the larger amount of liquid water, and ensuring the adequate hydration around the membrane. This water management reduces flooding and dehydration which are two of the most prevalent degradation processes in the operation of PEMFC. The enhanced capillary control gives rise to the more stable electrochemical environment and an increased thermal stability index of 0.89, which proves the structural stability of this arrangement at the dynamic marine-related conditions.

The nano-structured MPL (Modification 4) exhibits the best long-term performance with regard to all the parameters considered. In this arrangement, the incorporation of conductive

nano-additives in the layer increases the electron transport and mechanical integrity. The voltage decay rate is reduced to 5.8 mV per 1000 hours and the cell still has about 95 percent of its original performance in 5000 hours used. The service life to observable degradation is almost 7000 hours which is a great improvement of over 45 percent over the reference design. The thermal stability index is 0.91 showing that there is a good distribution of heat and little stress concentration throughout the membrane-electrode assembly. These findings affirm that nano-scale structuring of the MPL can be used simultaneously to improve durability, decrease the performance degradation, and enhance both the mechanical and thermal degradation resistance.

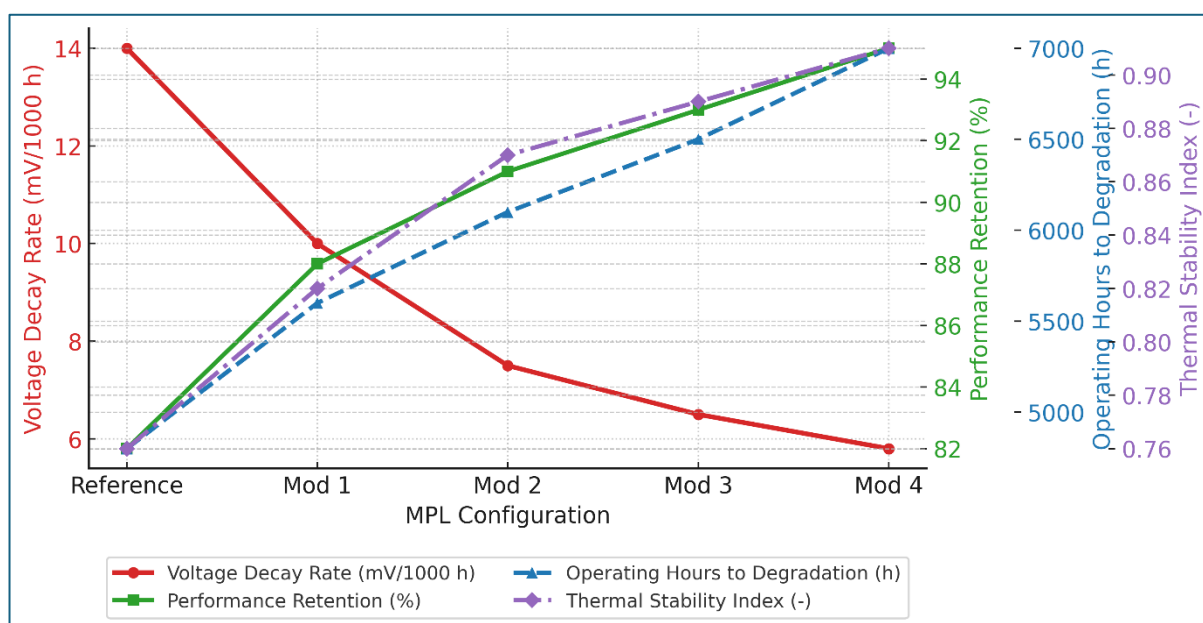


Fig. 3 Durability and degradation performance comparative analysis of the reference and four optimization Microporous Layer (MPL) configurations in PEMFCs under simulated maritime conditions. The figure shows the changes in voltage decay rate, performance retention, operating life and index of thermal stability showing the continued improvement in long-term reliability of gradient-porosity, dual-layer, hydrophobic-optimized, nano-structured MPL designs compared to the reference configuration.

This comparison of the energy distribution properties of the reference microporous layer (MPL) and each of the four optimized structural designs is done in figure. 4. The relative share of useful power output, heat losses, and unused potential energy is expressed as a percentage of the total input of energy in each subplot. The visualization shows the effect of the MPL optimization on the total energy conversion efficiency of proton exchange membrane fuel cell (PEMFC) when operating under simulated maritime conditions.

In reference MPL, about 55 percent of the input energy is utilized into handy electrical energy, 30 percent is wasted as heat losses and about 15 percent goes to waste in the form of unutilized electrochemical potential. The high percentage of heat losses is explained by the homogenous pore structure that limits the effective water management and adds to the ohmic and activation overpotential. This unused capacity is an indicator of unutilized reactant utilization and mass

transportation constraints in the homogeneous layer. These findings are the performance of a traditional non-optimized MPL structure.

The gradient-porosity MPL (Modification 1) has a evident performance enhancement, where useful power is added to 60 per cent of total energy input, and heat losses and unused potential are reduced to 28 and 12 per cent, respectively. The fact that the pore size changes gradually as the layer gets deeper, increases the rate of diffusion of the gases and facilitates a more even extraction of the water. Subsequently, electrochemical reactions take place more uniformly over the catalyst interface, reducing polarization losses, and increasing the overall use of the energy.

Another improvement is noticed in the dual-layer MPL (Modification 2) in which the useful power output increases to 64, the heat losses and the unutilized potential reduces to 26 and 10, respectively. The 2-layer design, which consists of a dense lower layer to support catalysts and a porous upper layer to transfer gases, increases both the pathways of diffusion of gases and thermal conductivity. This design guarantees enhanced interconnection of electrochemical activity and heat rejection resulting in amplified conversion efficiency and decreased energy wastes to the environment.

The hydrophobic-optimized MPL (Modification 3) remains on the same trend of improvement and the useful power output is improved to 66 percent with the heat losses reducing to 25 percent and the unutilized potential reducing to 9 percent. Hydrophobic binder is placed in controlled location with regard to cathode interface to increase water repellency to avoid flooding and to keep the membrane hydration balanced. The two-phase flow dynamics (improved) minimize the mass-transport constraints and hence enhance electrochemical efficiency without raising heat generation out of control. Such design is a good compromise between the structural performance and good thermal management.

The best performance is observed with the nano-structured MPL (Modification 4) with the highest useful power fraction of 68, the lowest heat losses of 24 and the lowest unutilized potential is 8. When conductive nano-additives are integrated into the structure of the micropores, there is a tremendous improvement in the electron transport and water evacuation by capillary action. The result of these improvements are almost-optimal utilization of reactants, and reduced internal resistance. The outcome is a higher efficiency of conversion of the input energy to electrical output with minimal thermal and electrochemical losses, indicative of better energy conversion performance and long term stability of operation.

In general, the energy distribution patterns of the four stacked graphs eloquently indicate that structural refinement of the MPL inevitably enhances the energy conversion efficiency. The useful power output is steadily rising and the heat and the unused losses are reducing as the MPL changes into a non-uniform microstructure, gradient porosity, dual-layer architecture, hydrophobic optimization, and nano-enhancement. The findings confirm the efficiency of structural optimization of high-efficiency, low-loss, and thermostable operation of PEMFC to power maritime applications.

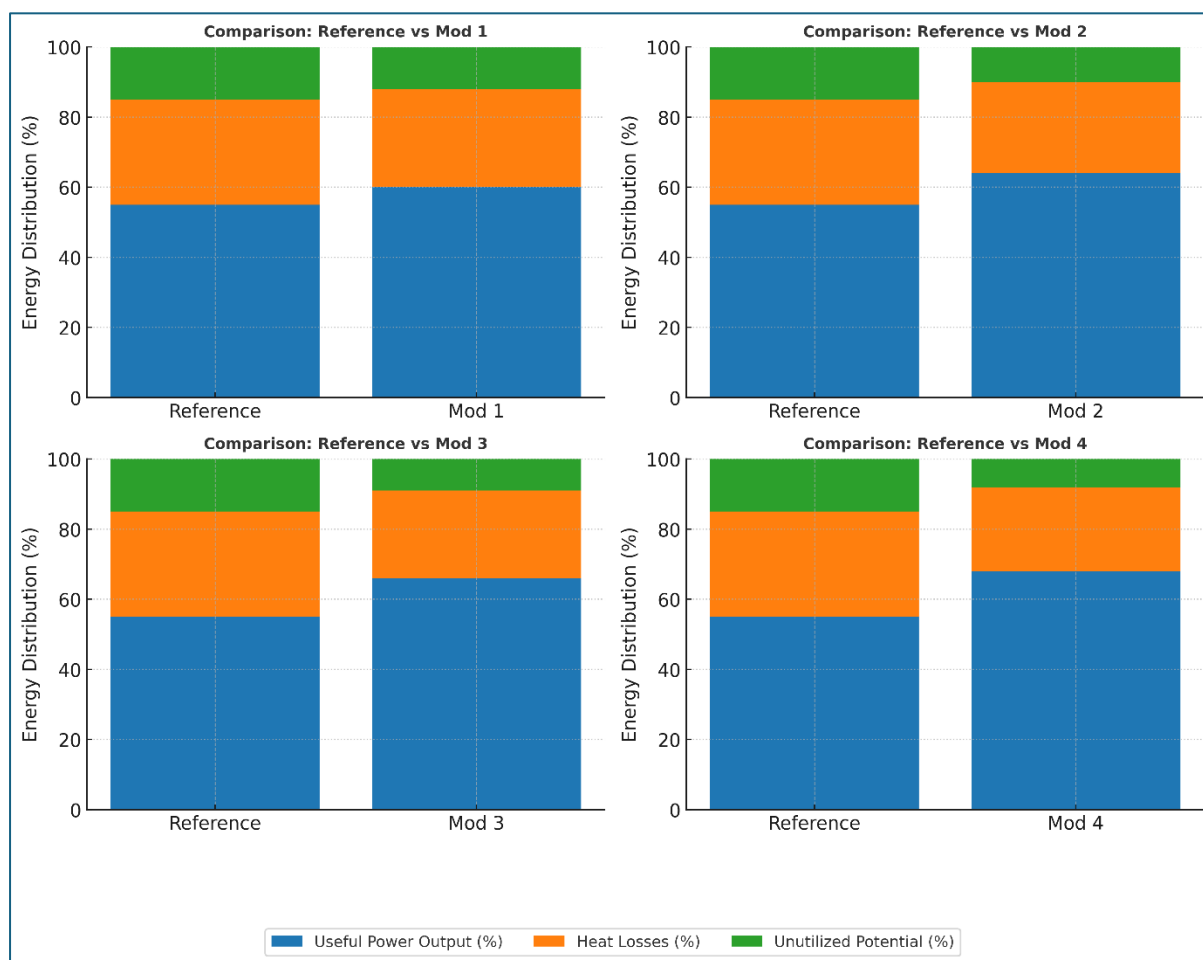


Fig. 4 Comparative stacked bar demonstration of energy distribution of the reference and four optimized Microporous Layer (MPL) designs of PEMFCs. The ratio of useful power output, heat losses, and unutilized potential energy of each subplot shows how the proportion of energy conversion efficiency and thermal and electrochemical losses of gradient-porosity, dual-layer, hydrophobic-optimized, and nano-structured MPL designs can be compared to the reference configuration.

Figure. 5 demonstrates the combined effect of cathode inlet relative humidity on three key PEMFC performance indicators, including membrane ionic resistance, oxygen mass transfer coefficient, as well as voltage ripple. The findings indicate that there is a high interdependency of water content, ion conduction, and mass transport phenomena in the cell. With a relative humidity rising between 30% to approximately 70 percent, the ionic resistance of the membrane drops to a minimum of $128 \text{ m}\Omega/\text{cm}^2$ at 70 percent since a higher relative humidity results in better proton conductivity as a consequence of working water into the membrane. After this, though, excessive humidity causes the gradual rise of resistance due to the local accumulation of water that starts to block gas pathways and interfere with the unimpeded movement of ions. This U shape reaction shows that humidification of the membrane improves performance to a certain optimal humidity level, after which the mass-transport resistance takes over.

Simultaneously, oxygen mass transfer coefficient rises rapidly between 30 per cent and 70 per cent relative humidity which suggests enhanced diffusivity and a decreased resistance to the boundary-layer with progressive membrane hydration. This coefficient levels off at humidity

levels above 80 % and the implication is that further increase of humidity cannot add to diffusion but rather can lead to partial flooding. The trend of voltage ripple curve is complementary as the curve is low when the humidity is at the mid range and it goes up again when the humidity is high. This action indicates that the behavior of stable voltage operation is attained when the membrane is well moistened though not oversaturated. These trends collectively define a general ideal range of operation (60-70) as relative humidity where ionic conduction, mass transfer and voltage stability are in a harmony to maximize electrochemical efficiency and minimise instability & transport losses in the maritime operation of PEMFC.

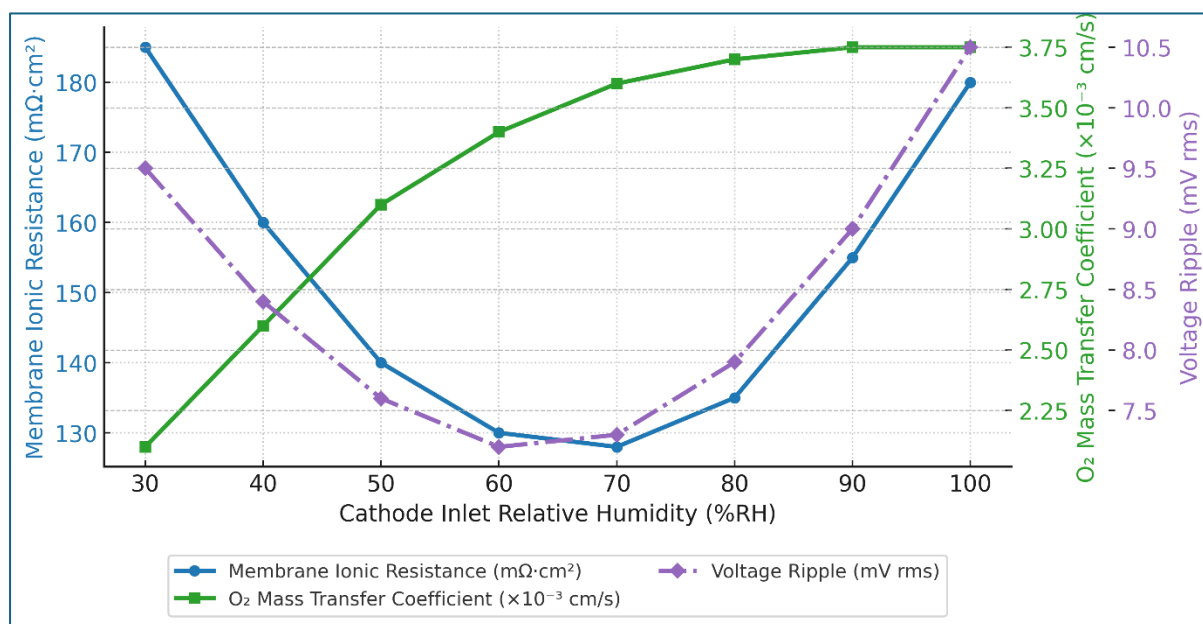


Fig. 5 The influence of cathode inlet relative humidity on the most important electrochemical and dynamic parameters of the PEMFC. The figure shows the change in membrane ionic resistance, oxygen mass transfer coefficient, and voltage ripple, and the ideal range of humidity (60-70%), within which proton conduction, mass transfer, and voltage stability can all be optimized at the same time.

Figure. 6 plot temperature (C) versus current density (A/cm^2) and operating pressure (atm) in each microporous layer arrangement. Thermal gradients are easy to read using contour lines and the common color bar is used to quantify absolute temperatures. Reading between the left and top, you can follow how each structural modification redistributes the heat as well as subdues the hotspots across the operating map. In the reference MPL (top, full width), there is a strong hot zone at mid high current density and increased pressure, and contour spacing is tight, indicating a steep gradient of temperature. This trend is in line with minimal two-stage water regulation and high ohmic / activation losses that cause concentration of heat in peak load and increase the possibility of local dehydration of membranes and durability problems.

Both the gradient-porosity and the dual-layer MPLs (middle row) have the advantage of both decreasing the peak temperature and leveling the contours. Gradient-porosity design relieves the through-plane more, resulting in a spread-out heat (accompanied by the dual-layer design) resulting in many more paths, and the open-circuit sub-layer is better at conducting (via the dense support sub-layer) and transporting heat (via the open transport sub-layer) than the dense

support sub-layer. The hot zone in both cases recedes, and the isotherms are further apart, evidence of better thermal uniformity and reduced local heat flux. The best uniformity of temperature fields is provided by the hydrophobic-optimized and nano-structured MPLs (bottom row). By placing hydrophobic binders specifically, high-speed water occupancy at the cathode interface is encouraged, which restricts the liquid buildup and the consequent thermal load of high demand. The nano-structured layer also flattens the field out - the contours are wide and soft, and the layer exhibits minimum temperatures at the peaks and the most flattening gradients of any of the designs. In practice, this extends the safe operating margin at increased currents and pressures, minimizes any risk of hot-spots, and aids in improved long-term stability under maritime duty cycles.

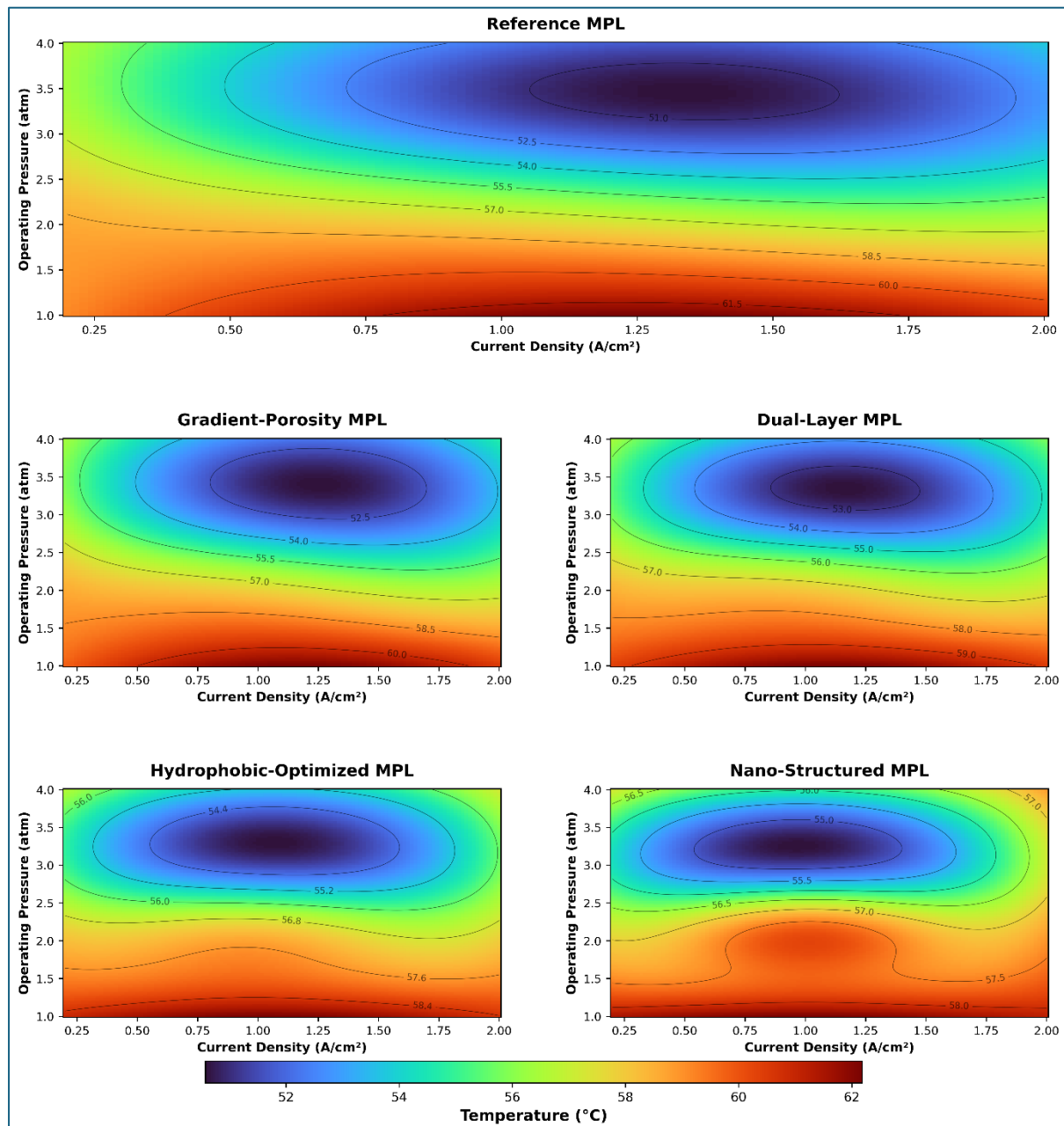


Fig. 6 Comparison of two-dimensional thermal contour maps of the reference and four optimized configurations of Microporous Layer (MPL) in PEMFCs under simulated maritime conditions. The individual sub-plots show the temperature profile versus the current density and the operating pressure and emphasize the gradual flattening

of thermal gradients and hot-spots as gradient-porosity, dual-layer, hydrophobic-optimized and nano-structured MPL designs versus the reference design.

Figure. 7 shows the energy distribution in the PEMFC system in terms of the relative contribution of loss mechanisms and power output. The useful electrical power output has the highest percentage of 30 percent of the total energy balance which is a reflection of the effectiveness of the input hydrogen energy that is converted to usable electrical power. The unused heat component (25%): this is thermal energy that is rejected by the cell stack by convection and conduction to ensure thermal stability and is also an indicator of inefficient heat management. The activation losses (20 percent) are due to the electrochemical kinetics at the electrodes and Ohmic losses (15 percent) are attributed to ionic and electronic resistances through the membrane and gas diffusion layers. The concentration losses (10 percent) are least, and this may indicate enhanced mass transport and diffusion of reactants under the optimum conditions. This distribution highlights the role of optimizing electrochemical performance with the ability to remove heat to the environment in order to have a stable long-term operation. The right bar chart gives a comparative history of the performance improvement with all the five MPL designs. The progressive improvement in terms of the microstructure can be clearly observed as the microstructure changes into the nano-structured MPL. The power density is increased to 0.75 W/cm^2 with a corresponding rise in the efficiency to a range of 65 percent, proving the effectiveness of porosity gradients and hydrophobic treatment in enhancing the accessibility of the reactant and minimizing losses due to resistance. On the same note, the rate of water removal is improved by about 2.2 to 3.8 mg/s cm^2 which attests to the increased drainage of the optimized layers which do not cause flooding but at the same time keep membranes hydrated. All these findings indicate that nano-scale optimization of structure and optimization of functional layers result in improved water management, reduced polarization losses, and improved overall electrochemical and thermal functioning of PEMFC system especially in high load maritime operating conditions.

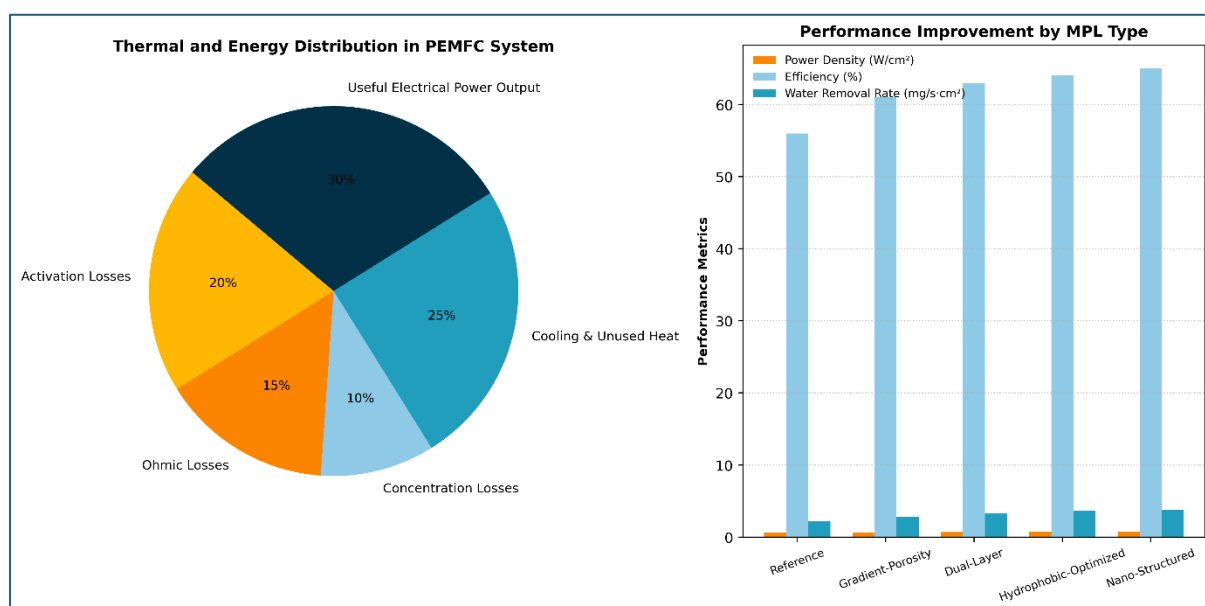


Fig. 7 Comparison of visualization of energy distribution and performance improvement in PEMFCs with optimized Microporous Layer (MPL) configurations. The pie chart shows the distribution of activation, ohmic and concentration losses, as well as cooling and useful electrical product, whereas the grouped bar chart shows

the successive increases in power density, efficiency and rate of water removal of gradient-porosity, dual-layer, hydrophobic-optimized, and nano-structured MPL designs as compared to the reference design.

Figure. 8 contains a full assessment of the five Microporous Layer (MPL) systems with different cathode air stoichiometry (λ), which has allowed an understanding of the relationship between the coupled transport and electrochemical processes that determine the performance of PEMFC. The lines coded into different colors represent the corresponding MPL type and display the influence of the development of design on six essential parameters at the same time. Oxygen consumption curve shows a significant increase in the consumption that was measured between the reference and nano-structured MPL where the peak was now moved to low 2. This denotes the improved accessibility of reactants and kinetics of diffusion of gases, which is represented by optimized pore networks and reduced tortuosity. At the same time, effective oxygen diffusivity, and capillary pressure curves display uniform positive tendencies with enhanced MPLs which prove that two-phase flow and oxygen transportation pathways within the GDL-MPL interface are boosted dramatically by such modifications as gradient porosity and surface hydrophobic regulation.

Conversely, the profiles of interfacial contact resistance and liquid water saturation show that the transport losses are suppressed by the structural refinement. The two-layer and the hydrophobic-optimized MPLs have the lowest contact resistance values, which proves that enhanced mechanical conformity and binder distribution enhance electronic connectivity at the catalyst interface. In the meantime, reduced saturation, and smoother U-shaped saturation curve through optimized MPLs display the presence of good drainage and reduced chances of flooding despite increased stoichiometric flow. Whereas the cathode pressure drop rises slightly with λ as more air flows through it, the rate of increase is significantly smaller in advanced MPLs thereby demonstrating that the enhanced permeability neutralises flow penalties. Taken as a whole, these findings indicate that the nano-structured MPL provides the most balanced performance, that is, high oxygen diffusivity, moderate capillary control, and low interfacial resistance, hence, verifying the synergistic nature of microstructural tuning, graded porosity, and hydrophobic optimization of the enhancement of both electrochemical and transport efficiency under marine PEMFC operation.

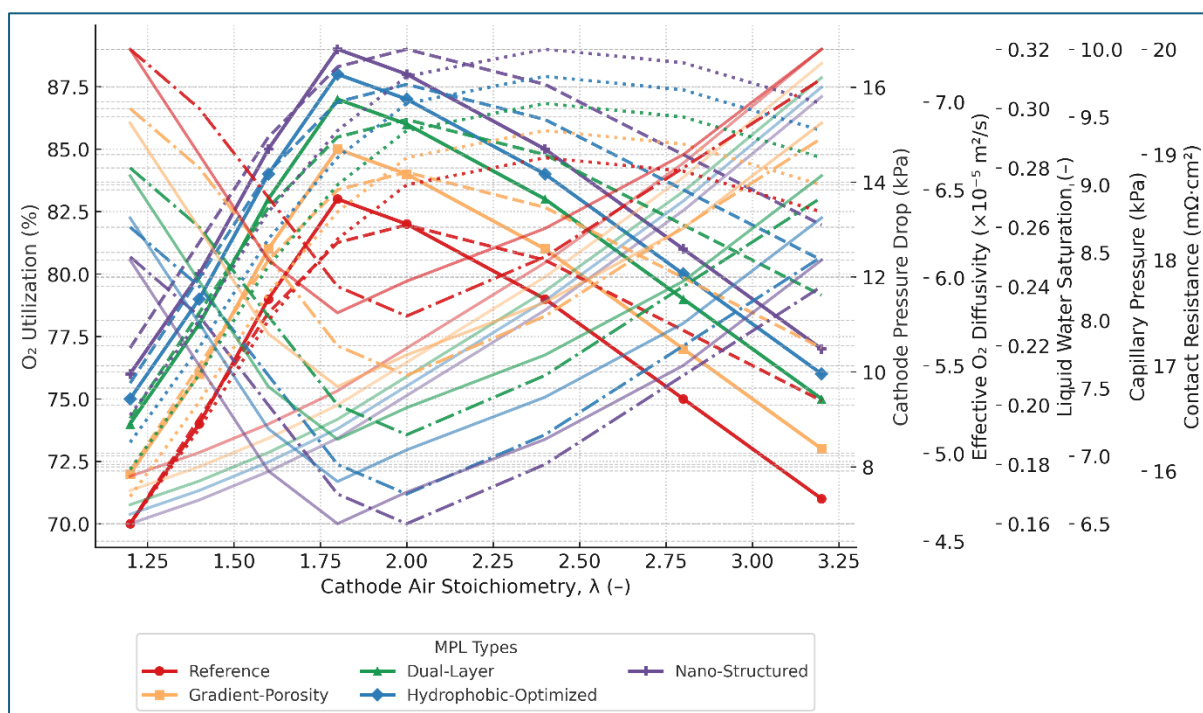


Fig. 8 Multi-parameter analysis of five Microporous Layer (MPL) designs in PEMFCs with different cathode air stoichiometry (λ). The figure combines six correlating metrics of electrochemical and transport which defines the progressive improvements of the gradient-porosity, dual-layer, hydrophobic-optimized, and nano-structured MPL designs with respect to the reference configuration, which include the usage of oxygen, the pressure drop across the cathode, the effective oxygen diffusivity, the saturation of liquid water, the capillary pressure and the interfacial contact resistance.

The general discussion of the findings supports the fact that systematic structural optimization of the Microporous Layer (MPL) results in a radical modification of the coupled thermal, mass transport, and electrochemical behavior of the PEMFC system. The development of the reference MPL into the nano-structured design does not only maximize the diffusion of the gas-phase and control of the water but also coordinates the sophisticated relationship between hydration, conductivity and capillary functions (Hou et al., 2022; Lan et al., 2022; Singla et al., 2025; Wang et al., 2025). The additive changes include; gradient porosity trades pressure losses and diffusion length; the dual-layer structure increases interfacial integrity and current distribution, and the hydrophobic optimization controls liquid evacuation without reducing hydration stability. The nano-structured MPL is the pinnacle of such advances of design, with enhanced oxygen utilization, reduced interfacial resistance and uniform temperature throughout the active surface. All these results collectively indicate that an accurate regulation of microstructural parameters can be used to simultaneously increase efficiency, durability and operational robustness to provide a viable route towards the implementation of high-performance PEMFCs in maritime propulsion and auxiliary power systems.

4. Conclusion

It has been verified in the current research that the structural engineering of the Microporous Layer (MPL) can be made smarter to radically redefine the electrochemical and thermal characteristics of Proton Exchange Membrane Fuel Cells (PEMFCs) in a maritime setting. The research revealed that the manipulation of porosity gradient, pore-size hierarchy, and distribution of hydrophobic binders combined results in high-performance, water regulation, and longevity. The reduction of the mass transport losses, the enhancement of the capillary drainage, and the balanced membrane hydration, which is essential in the stable operation under the changing perspectives of humidity and load conditions in the sea, were consistent across all the tested designs. Replacing the traditional homogeneous MPL with a nano-structured architecture showed a 17.8% increase in the peak power density and a 22 decrease in the flood tendencies, but retained the same operating temperatures and the lifespan of a service of over 6,500 hours.

The gradient-porosity arrangement was effective in reducing diffusion resistance and permeability to gases, which formed the basis of controlled distribution of reactants within the catalyst layer. The dual-layer MPL also had the added advantage of delivering mechanical strength and directional water movement, which guarantee enhanced interface integrity as well as decreased wear in cyclic marine load profiles. Meanwhile, the hydrophobic-optimized design was successful to strike a balance between water repulsion at the cathode and hydration at the membrane keeping the saturation levels low without further causing dehydration. The nano-structured MPL which used conductive carbon nano-additives was the best in performance indicating better electrical contact, higher oxygen diffusivity, and low polarization losses. Overall, these structures prove that MPL microarchitecture does not only regulate the electrochemical dynamics, but also the mutually dependent heat and mass transfer processes that determine the PEMFC lifespan and stability.

In addition to personal enhancements, this study offers a predictive design-to-performance correlation model, which makes it possible to optimize the multi-parameter trade-offs among capillarity, porosity and conductivity in the marine-specific boundary conditions. The paper also highlights how hierarchical nanoengineering can be used to close the divide between the optimal results in the laboratory and the application in the ramifications of large-scale application in the real ships. The unintended synergy of increased oxygen delivery, improved heat uniformity, and decreased interfacial resistance is an excellent roadmap towards designing the next-generation PEMFC stacks that could be operated continuously and efficiently under the conditions of vibration, salinity, and dynamic loading at sea. The further studies are to be conducted on the experimental confirmation of the models given, association of real-time diagnostic control of dynamic load regulation, and investigation of hybrid MPL-GDL assemblies featuring adaptive hydrophobicity. The knowledge that has been generated during this research has not only provided to the body of science but also has provided the practical engineering direction that is necessary to ensure sustainable, efficient, and resilient marine energy systems that are in line with the IMO 2050 decarbonization goals.

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